Economic Impact of Multi-Span, Prestressed Concrete Girder Bridges Designed as Simple Span versus Continuous Span

Final Report
October 2016

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16. Abstract

The objective of this study was to determine the economic impact of designing pre-tensioned prestressed concrete beam (PPCB) bridges utilizing the continuity developed in the bridge deck as opposed to the current Iowa Department of Transportation (DOT) method of utilizing standardized spans treated as simply supported. This work consisted of a literature search and review, survey of other highway agencies, design comparisons, and cost-benefit analysis.

The design review consisted of comparisons of the standard design practices in terms of material use and cost from a review of electronically published design manuals, standards, and practices for state DOTs. Furthermore, the design review examined design cost, as determined by design hours spent to produce final bridge plans using the different design methodologies from state DOT survey respondents.

The cost-benefit analysis was based on construction costs from the Federal Highway Administration (FHWA) National Bridge Inventory (NBI) (with corrections to account for the different years the costs were recorded and the different regional bridge locations) and material and design costs from the design review.

Based on the evidence included in the final report for this project, the researchers concluded that simple span designs have a lower initial cost compared to continuous designs, in terms of construction cost and design time.

The lower construction cost demonstrated by the simple span designs in contradiction to theoretical material efficiencies in continuous design is an indicator that many of the continuous designs utilized are not optimized to the extent possible. While significant recent research has been completed on optimization methods for prestressed concrete bridge design, the majority of them remain undeveloped for practical application.

Due to the lack of strong evidence in favor of either design method in terms of long-term cost and performance, the research team concluded that simple span designs are preferable at this time.

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1. INTRODUCTION

1.1 Background

The current Iowa Department of Transportation (DOT) design method for pre-tensioned prestressed concrete beam (PPCB) bridges utilizes a set of standard span designs, which can be combined to produce single or multi-span bridges. In the development of these standards, the spans are assumed to behave as simple spans for all applied loads. This eliminates any variation in loading and detailing requirements based on adjacent spans lengths.

In addition, the current Iowa DOT preference is for jointless design of bridges. As such, additional reinforcing steel is required in the negative moment regions (i.e., over the bridge piers) to prevent cracking and resist the additional moment. The addition of this reinforcement creates a load transfer mechanism between adjacent spans that results in continuity between adjacent bridge spans.

Other state DOTs utilize PPCB bridge design methods that assume multi-span jointless bridges behave in a continuous fashion, accounting for the continuity developed by the continuous deck and additional reinforcing. Doing so may allow for a more efficient design by accounting for the additional strength provided by continuity and the deck.

However, accounting for the continuity of the deck during design creates a more complex interaction between spans, leading to varying loading on spans. Adopting similar design methods would potentially reduce the effectiveness of using the standardized simple span designs that the Iowa DOT uses and potentially result in longer design times and higher design costs. While other standards utilize smaller precast beams, which may save on material costs, fabrication costs would most likely increase.

The Bridge Engineering Center (BEC) at Iowa State University recently completed an Iowa DOT-sponsored project that investigated the additional negative moment reinforcing bar details (Phares et al. 2015). The focus of that project was the adequacy of the additional reinforcing steel in the negative moment region, especially in light of the fact that current practices may violate American Association of State Highway and Transportation Officials (AASHTO) design provisions with respect to reinforcing bar lengths and layout.

The work detailed in this report expands on that research by evaluating the cost-benefit relationship of designing multi-span, jointless bridges as simple spans versus as continuous spans for all loads.

1.2 Objective and Scope

The objective of this study was to determine the economic impact of designing PPCB bridges utilizing the continuity developed in the bridge deck as opposed to the current Iowa DOT method of utilizing standardized spans treated as simply supported. This work consisted of the following tasks: literature search, survey of other highway agencies, design comparisons, cost-benefit analysis, and this final report.

The literature review consisted of a thorough review and documentation of currently published research on related topics, including other reports on cost analysis and material optimization for the design of prestressed concrete bridges and published information on current design procedures for prestressed concrete bridges throughout the US.

The design review consisted of comparisons of the standard design practices from the literature search in terms of material use and cost. Furthermore, the design review examined design cost, as determined by design hours spent to produce final bridge plans using the different design methodologies.

The cost-benefit analysis was based on construction costs and design costs from the design review and the researchers created a combined cost-benefit model for comparison of the design methods.

The final task was to document the generated information and analysis into a simplified format for dissemination.

2. LITERATURE REVIEW

2.1. Benefits of Jointless Decks

Jointless bridge decks have been utilized in the US since the early 1970s. The primary advantages of jointless bridge design lie in eliminating expansion joints and reducing exposure of the substructure to runoff and deicing salts without those expansion joints.

Expansion joints are designed and implemented to allow for expansion/contraction of the bridge superstructure; however, the joints require periodic maintenance and are prone to failure, leading to higher bridge maintenance costs. Premature failure can also cause increased degradation of the bridge as drainage of water/chloride runoff through joints causes increased corrosion of both the superstructure and substructure elements.

Benefits of utilizing jointless bridges include the following: higher on-average condition rating (Alampalli and Yannotti 1998), reduced maintenance, and, because of the continuity established between spans when the girders act compositely with the continuous deck, generation of a negative moment capacity at the piers, thereby reducing the positive moment in the bridge span (Oesterle et al. 1989). This results in lower moment demands in the girders and the potential for more efficient material use.

2.2. Challenges of Continuous Decks

2.2.1. Abutments for Temperature and Other Displacement Effects

While elimination of joints over piers is relatively simple, further elimination of expansion joints at bridge ends requires special consideration. Completely eliminating expansion joints in a bridge deck requires special attention to developing an alternate method to account for expansion and contraction due to temperature change, creep, shrinkage, settlement, and other miscellaneous causes of relative displacements in a structure (Kunin and Alampalli 2000). Elimination of expansion joints at bridge ends is generally accomplished using either integral or semi-integral abutments (Alampalli and Yannotti 1998) (Burke and Glyod 1997).

Integral abutments are of particular interest as they are cast integrally with the superstructure. This results in integral abutments providing a degree of rotational restraint to the bridge ends. Furthermore, integral abutment bridges provide a resistance to uplift forces in the outer spans that can be caused by deck continuity in combination with specific loading cases (Hassiotis et al. 2006). For these reasons, the use of integral abutments can have significant effect on the load interactions between bridge spans, as well as reduce maintenance at the abutment-bearing locations.

2.2.2. Cracking and Moment Continuity over Piers

Utilizing a continuous deck over multiple beam spans imposes additional restraints to the bridge system, which have a significant effect on the distribution of loads, deflections, and strains in the bridge system. The additional restraint comes in the form of negative moment capacity over the piers and abutments. The addition of negative moment over the piers may result in a concern for cracking of the deck concrete in these negative moment regions, subsequently allowing infiltration of water and deicing salts, and leading to premature onset of reinforcement corrosion, among other issues (Francois and Arliguie 1994).

Furthermore, the additional continuity restraint in the bridge significantly impacts the effects of creep, shrinkage, and temperature. Creep in prestressed girders is known to cause rotation at member ends due to the non-uniform stress distribution in girder sections. After continuity is established, this creep develops a residual positive restraint moment at the piers. This residual moment counteracts the development of negative moment at the support, greatly reducing the effectiveness of the continuity (Oesterle et al. 1989).

Shrinkage also has an impact in the development of residual moments in the bridge. Because the deck is cast after the placement of the girders, the age differential of the girders and deck results in differential shrinkage between the two. The positive moment developed by differential shrinkage in the span may induce residual negative moments at the pier. The magnitude of the resulting moment varies greatly with the age of the girders when the deck is cast, with the reduced shrinkage remaining in older girders leading to a higher differential shrinkage and thus greater residual moment (Oesterle et al. 1989). The side effects of differential shrinkage are highly variable, and have also been observed to have minimal impact even working with decks cast significantly after girders (Miller et al. 2004).

Cracking in the negative moment region is reduced or prevented through the addition of reinforcing steel. Various methods are used for the determination of the amount of steel necessary to prevent cracking, including analytical, empirical, and code-based. This additional reinforcing steel helps prevent cracking by increasing the tension capacity and stiffness of the deck over the piers, which in turn causes an increase in the bridge’s negative moment capacity at the piers. The additional of negative moment steel is also important to ensure the distribution of any cracking that does occur over multiple narrow cracks.

2.3. Cost Optimization of Concrete Bridges

2.3.1. Construction Costs

There have been numerous studies on the computerized optimization of bridge design in terms of material use. This interest stems from the relatively large dollar amount spent on bridges and the high degree of variability in bridge designs, as well as the increased availability of computing power and improved optimization algorithms (Ahsan et al. 2012, Rana et al. 2013, Hassanain and Loov 2003).

Optimization efforts in the past have looked at a variety of design levels, with the majority of the focus being on bridge component and system optimization (Cohn and Dinovitzer 1994). More recent research has utilized more advanced computing and methods for this, as well as looked at developing quantitative methodologies for conceptual design optimization (Malekly et al. 2010).

While there has been significant research into optimizing material use, limited research has been conducted utilizing bridge construction costs in correlation with design and construction methods. This is likely due to the wide variety of bridge design, analysis, and construction methodologies.

2.3.2 Design Costs

Generally, design costs are estimated as a portion of construction costs, typically ranging from 4 to 20% from state to state, with an average of 10.3% (Hollar et al. 2010). Minimal research is available quantifying bridge costs associated with design and other engineering and legal work prior to construction. No research found in the literature review has made an effort to accurately associate design costs and construction costs.

2.3.3 Lifetime Costs

Aging highway infrastructure has prompted significant research on optimization of lifetime maintenance costs of existing bridges (Elbehairy et al. 2006, Okasha and Frangopol 2010, Elbeltagi 2006). However, there is minimal published research on initial designs for lifecycle cost optimization.

3. CURRENT PRACTICES

3.1. Identification of Primary Design Methods

This section defines the various design methods that may be utilized for concrete bridge continuity over piers. A review of state DOT practices was conducted and is described in this Chapter. As a result of this review, the design practices and standards generally used were classified into one of the eight general categories described in this section. In cases where the exact method employed by a state could not be determined, the last two categories are used to convey the information that was provided.

Simple Span (SS)

Bridges designed as SS utilize a joint over the piers to remove continuity. All spans are designed and detailed to act as simple spans.

Simple Span Jointless (SSJ)

SSJ bridges are designed as simple spans, but do not have joints interrupting continuity over the piers. As such, negative moment capacity is induced over the piers, creating a degree of continuity. In general, bridges designed as SSJ will have additional reinforcing steel placed in the deck region over the piers to prevent deck cracking. The amount of reinforcing steel utilized is typically based on a combination of in-house experience and AASHTO specifications.

Continuous for Live Loads (ContLL)

ContLL bridges are designed taking into account bridge continuity over piers for all live loads on the bridge. This has the advantage of reducing design positive moments in the bridge spans, while in exchange creating negative moment demand over the piers. This requires specific design of longitudinal reinforcement in the bridge deck over the piers to generate this negative moment capacity.

Continuous for Composite Loads (ContCL)

ContCL bridges are designed taking into account bridge continuity over the piers for all composite loads placed on the bridge. Composite loads are generally defined as any load applied after the deck has cured, and thus the deck and girders can act as a composite unit to resist said loads. Because more load is resisted by composite action, the design positive moment reduction in the spans is increased, again at the expense of increased negative moment demand over the piers, requiring a specific longitudinal reinforcement design in these regions.

Continuous for All Loads (ContAL)

ContAL bridges are designed taking into account bridge continuity over the piers for all loads acting on the bridge, both dead and live. This procedure greatly reduces positive moments in the bridge spans, while in exchange creating a significant negative moment demand over the piers. In addition to specific longitudinal reinforcement design over the piers, this design method also requires careful detailing to ensure continuous action of the girders prior to the addition of the slab. A benefit of ContAL design, as well as for ContLL and ContCL, is the possible reduction in girder cross-section, required prestressing, and/or in the number of girder lines.

Continuous Envelope (ContE)

ContE bridges are designed for both negative moment over the piers as determined by one of the continuous methods described above, as well as for the full positive moment in the span. This effectively creates an envelope of worst-case conditions, with a large margin of safety and redundancy.

Continuous Deck (ContD)

Classification as ContD indicates that, while it is known that the bridge decks are generally continuous over the piers, it is unknown what assumptions are made for analysis, meaning the bridges could be designed as SS, ContLL, ContCL, or ContAL.

Simple Span Analysis (SSA)

Classification as SSA indicates that, while it is known that the bridges are analyzed as consisting of simple spans, it is unknown whether the decks are continuous over the piers, meaning the bridges could be designed as SS or SSJ.

3.2. Inventory of State Department of Transportation Design Policy

With the above categories defined, a review was completed of electronically published design manuals, standards, and practices for state DOTs. Information collected from this review is presented in Table 1.

Because information gathered from some sources was not all inclusive, some assumptions were made; however, assumptions were limited as much as possible. For that reason, two states were labeled with Provisions during the review. This indicated that the state DOT has provisions for continuous design of PPCB bridges, but does not utilize any language to indicate that continuous design is preferred or required. A number of states had no electronically published documents, or published documents contained no considerations for continuous versus simple span analysis of PPCB bridges. These 12 states and Washington D.C. were omitted from the table, leaving information for 38 states.

Table 1. State DOT published design practices

State	Design Method	Updated	Reference
Alabama	SSJ	Feb 2015	Sec 5 Pg 2 Structural Design Manual
Arizona	ContE	Aug 2011	Sec 5 Pg 23 Bridge Design Guidelines
Colorado	ContE, ContCL	Jul 2012	Sec 9.1 Pg 12 Bridge Design Manual
Connecticut	SS	Feb 2011	Sec 6.3.4.4.2 Bridge Design Manual
Delaware	ContLL	May 2005	Sec 5.5.3 DelDOT Bridge Design Manual
Florida	Provisions	Jan 2015	Sec 4.1.7 Structures Design Guidelines
Idaho	Provisions	May 2014	Sec 5.14.1.14 LRFD Bridge Design Manual
Illinois	ContC, SSA	Jan 2012	Sec 3.4.2 Bridge Manual
Indiana	ContLL	Jan 2013	Sec 402-8.02(05) Indiana Design Manual
Iowa	SS		
Kansas	ContE	Jan 2014	Pg 5-106 KDOT Design Manual
Louisiana	ContE	Nov 2014	Sec 5.14.1 LaDOTD Bridge Design and Evaluation Manual
Maine	ContD	Aug 2003	Sec 6.4.1.2-D MaineDOT Bridge Design Guide
Massachusetts	ContCL	Jun 2013	Sec 3.7.4.1 MassDOT LFRD Bridge Manual
Michigan	ContE	May 1999	Sec 7.02.01, 7.02.18 Bridge Design Manual
Minnesota	SSJ	Jul 2014	Sec 5.4.1, 14 LFRD Bridge Design Manual
Mississippi	ContLL	Mar 2010	Pg 24 Design Manual V6.1
Missouri	ContCL	Jun 2014	Sec 751.22 MoDOT Engineering Policy Guide
Montana	ContLL	Aug 2002	Sec 17.3.2.4 Prestressed Concrete Superstructures
Nebraska	ContLL	Oct 2014	Pg 3.23 NDOR Bridge Office Policies and Procedures
Nevada	ContCL	Sep 2008	Sec 14.5.4.2 NDOT Structures Manual
New Hampshire	ContCL	Jan 2015	Pg 2.3-2 NHDOT Bridge Design Manual 2.0
New Jersey	ContCL	Mar 2010	Sec 15.3.6 NJDOT Design Manual for Bridges and Structures 5th Edition
New Mexico	ContCL	Apr 2013	Sec 5.1 NMDOT Bridge Procedures and Design Guide
New York	ContLL	Apr 2014	Sec 9.15 NYSDOT Bridge Manual
North Carolina	ContLL	Jan 2015	Sec 6.2.2.1 NCDOT Structure Design Manual
North Dakota	ContE	May 2015	Sec IV-02.06.01 NDDOT Bridge Division Operating Policies and Procedures
Ohio	ContE	Jan 2013	Sec 302.5 ODOT Bridge Design Manual
Oregon	ContE	Oct 2014	Sec 1.5.6 Bridge Design and Drafting Manual
Rhode Island	ContCL	Jan 2007	Sec 5.10.1 Rhode Island LFRD Bridge Design Manual
Texas	Empirical		TxDOT Specifications
Utah	ContLL	Mar 2015	Sec 10.2.4 Structures Design and Detailing Manual
Vermont	ContE	Jan 2010	Sec 5.2.3 VTrans Structures Design Manual
Virginia	ContLL	Jun 2010	Vol V Part 4 VDOT Prestressed Concrete Beam Standards
Washington	ContE	Apr 2015	Sec 5.6.2 WSDOT Bridge Design Manual
West Virginia	ContLL	Jan 2003	Sec 3.4.1 WVDOH Division of Highways Bridge Design Manual
Wisconsin	ContCL	Jul 2014	Sec 19.3.2.3.1 WisDOT Bridge Manual
Wyoming	ContCL	Dec 2012	Pg 3-14 Bridge Design Manual

3.3. Survey of Standard Design Practice

In conjunction with the review of policies previously described, a survey was utilized to gain additional information directly from the state DOTs. The results of this survey are presented in Table 2.

Table 2. State DOT survey results

State	Analysis	Design Hours	Cost per ft^2	Negative Steel Area	Notes
Alabama	SSA				
Alaska	ContLL		$400	0.9–2.2	160 hrs. for continuity, 15% cost increase over SS
Arizona	SSA*	1,200	$110	2.3	
Arkansas	SSA	700	$95		
California	SSA, ContCL	500	$175	0.6	
Colorado	ContCL	1,400	$120–140	2.0–3.1	
Georgia	SSA	400	$85	1.3	
Hawaii	ContCL			0.8–1.4	
Lousiana	SSA*			1.1–2.5	
Maryland	ContCL	2,000	$250	1.6	
Michigan	ContLL			0.5–1.1	
Minnesota	SSA	2,500–3,000	$130	1.4–1.5	
Missouri	ContCL	700	$85	0.6	
Montana	SSA*	1,000	$110	0.2	
Nebraska	ContLL	200	$100	2.4	
North Carolina	SSA*	400	$100	0.8	
Pennsylvania	ContLL	2,000		1.1	
South Dakota	ContCL	400–450	$101	0.9	8 hrs. for continuity
Tennessee	ContCL	2,000	$65	1.2–1.6	
Texas	Empirical	82	$65	0.3	
Utah	ContCL				
Vermont	ContCL	1,500–2,000	$250		Cost averaged over non-PPCB bridges

Gray highlighting on rows indicates review of published policies was inconclusive.
* Yellow highlighting indicates published policy shows that bridges designed for continuity, while survey response indicates that bridges analyzed as simple spans.

The survey (included in the Appendix) asked the respondents their PPCB bridge analysis method, which translated into these four categories: simple span for all loads (SS), simple for dead loads/continuous for live loads (ContLL), continuous for all composite loads (ContCL), and continuous for all loads (ContAL). Respondents were then asked a number of questions about typical reinforcement in the deck region over the pier, as well as for a typical number of design hours for a PPCB bridge and a typical cost per square foot.

The researchers received 22 responses (44% response rate), as listed in Table 2, of which, 10 were from states where the review of published policies was inconclusive. These 10 responses are are shown with gray highlighting across the rows in Table 2. Of the 12 respondents for which the policy review yielded results, four of them showed a discrepancy. These are highlighted with yellow in the table. In each case, it was the result of the published policy showing that bridges were designed for continuity, where the survey indicated that they were analyzed as simple spans.

The Texas DOT (TxDOT) is labeled as Empirical in Table 2, as the survey response specifically stated that an empirical method was utilized for design, as opposed to one of the other four options (SS, ContLL, ContCL, or ContAL) indicated by the other 21 respondents. However, the empirical method utilized appears to match well with the simple span (SS) design category, so TxDOT bridges are classified as such for the remainder of the study.

The cost and design hour data presented in Table 2 are discussed in detail later in this report. For now, it is of interest to note the wide range of responses cost and design hours.

3.4. Final Assignment of Design Methods

Based on the information presented in the previous two sections, a single design methodology was assigned to each state. These assignments, presented in Table 3, are used in all subsequent discussions in this report.

In determining final assignments, survey results were considered to be a more reliable determination of actual practice than the review of publications. The exception to this is those states that, by policy, design for a moment envelope (ContE), as there was not such an option available for selection in the survey. Those that responded to the survey as using simple span analysis were generally designated as designing simple span jointless (SSJ) bridges, based on the indicated presence of negative moment reinforcing steel over the piers. The exceptions to this are Alabama and Minnesota, which are known to use jointed designs.

Table 3. Final analysis assignments

State	Design Method	State	Design Method
Alabama	SS	Nebraska	ContLL
Alaska	ContLL	Nevada	ContCL
Arizona	SSJ	New Hampshire	ContCL
Arkansas	SSJ	New Jersey	ContCL
California	ContCL	New Mexico	ContCL
Colorado	ContCL	New York	ContLL
Connecticut	SSJ	North Carolina	SSJ
Delaware	ContLL	North Dakota	ContE
Georgia	SSJ	Ohio	ContE
Hawaii	ContCL	Oregon	ContE
Illinois	ContCL	Pennsylvania	ContLL
Indiana	ContLL	Rhode Island	ContCL
Iowa	SSJ	South Dakota	ContCL
Kansas	ContE	Tennessee	ContCL
Louisiana	SSJ	Texas	SSJ (Empirical)
Maine	ContDL	Utah	ContCL
Maryland	ContCL	Vermont	ContE
Massachusetts	ContCL	Virginia	ContLL
Michigan	ContE	Washington	ContE
Minnesota	SS	West Virginia	ContLL
Mississippi	ContLL	Wisconsin	ContCL
Missouri	ContCL	Wyoming	ContCL
Montana	SSJ		

4. COMPARISON OF CONSTRUCTION COSTS ASSOCIATED WITH VARIOUS DESIGN METHODOLOGIES

4.1. Comparison of Survey Cost Data

Of the 22 respondents to the survey, 15 included a cost estimate for their typical bridges. Among these, the majority were classified as ContCL or SS, with two ContLL responses and a single ContE. Due to the small number of data, for the remainder of this Chapter, the ContCL and ContLL responses will be grouped together, as shown in Figure 1.

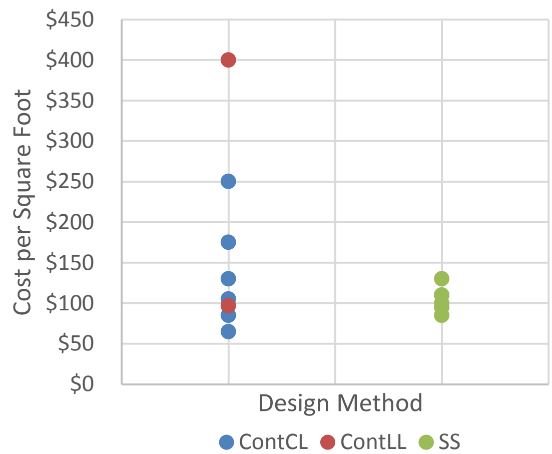

Figure 1. Cost per square foot by design method

A full listing of the reported amounts are included in Table 2. The average reported cost for a simple span designed bridge was $105/ft^2$, as compared to $163/ft^2$ for a continuous span design, with standard deviations of $15.49/ft^2$ and $112.36/ft^2$, respectively. While this indicates a large dispersion, the distribution shown in Figure 1 indicates that there is much more variation in cost than $112.36/ft^2$ with the continuous design method. Furthermore, if the significant outliers are thrown out, the average cost of $163/ft^2$ for the continuous design method would actually be considerably reduced.

The large variance in reported costs for continuous design indicates a wide range in methods and applications, consistent with what was seen in the previous analysis of design methodologies. In terms of both design time and material costs, one would expect ContE to exceed all other methods. Similarly, one would expect a disparity in material to exist between ContCL and ContLL methods, due to the different loading assumptions.

4.2. National Bridge Inventory Cost Data

The Federal Highway Administration (FHWA) National Bridge Inventory (NBI) was used to provide a large dataset for comparison of bridge construction costs. Several key limitations were put in place to ensure the applicability of the results, and several correction factors were applied to account for as many independent factors as possible. An analysis was then performed to determine average cost per square foot for bridges of interest both by state and by design methodology. The researchers reduced the inventory by the criteria in Table 4.

Table 4. NBI bridge criteria

Field	Item #	Allowable Entries	Description
Structure Type	43	5, 6	Prestressed Concrete, Prestressed Concrete Continuous
Deck Width	51	>4 m	No pedestrian or railroad bridges
Primary Spans	45	≥2	
Estimate Year, Year Built	97 27	#27≥#97	Replacement estimate dated prior to the bridge construction date*

*The analysis was performed both with and without this additional criteria.

The limitations were selected to ensure that only bridges applicable to the scope of this study were included in the dataset. Thus, all structures not having a prestressed girder superstructure were eliminated; roadway width was limited to eliminate pedestrian and railroad bridges, which were not included in this study. Also, only bridges that included at least two spans were included to ensure the presence of a pier or piers.

The cost of each bridge was determined using the replacement cost recorded in the NBI. Using these data relies on several assumptions, most importantly that the replacement bridge will be of the same general design as the current bridge, primarily in its total deck area and superstructure system. To minimize such assumptions, a further subset was utilized with the added restriction that the replacement estimate be dated prior to the bridge construction date. It is reasonably assumed that, in this case, the recorded estimate is based on either the engineer’s estimate or construction cost. This indicates a higher quality and more accurate estimate, as well as ensuring that the replacement bridge will match the design parameters given in the NBI. However, this criteria greatly reduces the number of data points available from the NBI. Consequently, the analysis was performed both with and without this additional criteria.

In addition, corrections were applied to the cost estimates to account for variability in the year the costs were recorded and the bridge’s location. Time was accounted for utilizing the US Bureau of Labor Statistics’ Producer Price Index for concrete and related products. This should allow for a more accurate estimate than generic inflation over time, although not as accurate if labor and formwork were taken into account. Regional corrections were accomplished utilizing RSMeans factors based on the nearest zip code to the bridge’s location, determined using the latitude and longitude provided in the NBI. The inclusion of these corrections should minimize, but not eliminate, some the influence of yearly cost variance and location as factors in the bridge cost.

Following the application of these limitations and factors, the results were grouped by state, and the cost per square foot of deck area was determined based on reported width, length, and replacement cost. Among these bridges, there were many outliers, which were assumed to relate to bridges designed for specialized situations, such as crossing navigable waterways or extremely high environmental loads due to geography. To eliminate the effects of these outliers while maintaining consistency, bridges with costs in the top or bottom 10% of each state were eliminated.

Finally, the categorization of design methodology determined for each state was applied to identify each bridge by its design method, allowing computation of the data in Table 5.

Table 5. NBI prestressed girder bridge cost statistics

	Average ($/ft^2)	**Std. Dev. ($/ft^2)**	**Sample Size**	**Max ($/ft^2)**	**Min ($/ft^2)**
Without limitation on estimate date:					
Simple Span:	129	58	360	383	36
Continuous	147	138	1563	688	2
When limited to estimates predating construction:					
Simple Span:	96	34	5	118	36
Continuous	92	62	222	475	4

As can be seen in Table 6, TxDOT bridges account for the majority of the simple span bridges, and have an unrealistically low cost. As such, they are not included in Table 5 statistics.

For additional reference, the bridge data were also separated by state, as shown in Table 6.

Review of the data in Table 5 and Table 6 indicates several major discrepancies. It can be seen immediately that the maximum and minimum costs per square foot provided are well outside the bounds of common judgement. To a certain extent, such discrepancies can be attributed to misinterpretations and data entry errors, as well as special situations. However, the large variation makes one question the validity of the data. As such, these data should be utilized in conjunction with other sources, as well as sound engineering judgement.

That said, the data presented in Table 5 and Table 6 does suggest that bridges designed as simple spans generally have a lower cost per square foot. Despite discrepancies in the data, the sample size presented here is large enough to lend weight to this conclusion. To quantify this difference for later use, a standard P-test was performed based on the data provided in Table 6. Utilizing a significance criteria of 0.05, the P-test indicated no statistically significant difference in average cost when the additional limitation based on estimate date was used. Without this limitation, the data show a statistically significant difference in cost per square foot between simple span and continuous design methods of approximately $10/ft^2, with simple span design having the lower cost. Note, however, that these figures are based on an average between all states, and do not account for any other design and construction differences that could influence costs among states.

Table 6. NBI prestressed girder bridge cost by state

State	# of Bridges	Design Method	Avg. $/ft^2	Std. Dev. $/ft^2
Alabama	22	SS	320	27
Arizona	127	SSJ	87	8
California	126	ContCL	85	5
Colorado	32	ContCL	112	51
Delaware	4	ContLL	109	44
Georgia	203	SSJ	135	25
Idaho	5	–	239	86
Illinois	134	ContCL	93	44
Indiana	262	ContLL	87	80
Iowa	2	SSJ	78	59
Kansas	4	ContE	27	1
Kentucky	119	–	134	25
Maine	3	ContDL	104	119
Maryland	8	ContCL	57	4
Massachusetts	49	ContCL	204	138
Michigan	45	ContE	93	97
Minnesota	6	SS	109	9
Mississippi	2	ContLL	122	7
Missouri	8	ContCL	151	40
Nevada	3	ContCL	86	1
New Jersey	42	ContLL	141	129
New Mexico	7	ContCL	87	78
New York	198	ContLL	182	130
North Dakota	40	ContE	32	15
Ohio	54	ContE	70	36
Oklahoma	20	–	152	84
Oregon	38	ContE	102	27
Puerto Rico	7	–	164	28
Rhode Island	18	ContCL	261	158
Tennessee	241	ContCL	125	62
Texas	523	SS (Other)	3	4
Vermont	1	ContE	218	–
Virginia	63	ContLL	116	125
Washington	135	ContE	472	84
West Virginia	39	ContLL	129	121
Wisconsin	7	ContCL	90	22
Washington, DC	1	SSJ	74	–

The following states had no bridges meeting the criteria: Alaska, Arkansas, Connecticut, Florida, Hawaii, Louisiana, Montana, Nebraska, New Hampshire, North Carolina, Pennsylvania, South Carolina, South Dakota, Utah, Wyoming

Table 6 does allow for comparison among states. As shown in Table 6, both simple span and continuous design methods fall into a similar range of costs on a state-by-state basis, with simple span design having a higher range. If average costs by design method are evenly weighted to each state reporting, the average for simple span design is $100/ft^2 and the average for continuous span design is $147/ft^2. These averages fall within a reasonable range, showing that an acceptable number of states are contributing significantly to the overall average costs presented in Table 5. These figures also continue the trend shown in Table 6 of the average cost per square foot for a continuous span bridge being higher than for a simple span.

4.3. Direct Comparison of Material Use

A comparison of material quantities was completed and used to provide more refined and applicable construction cost comparisons at the expense of a smaller dataset. To achieve this, construction quantities were obtained from a number of bridges in various states. In selecting the states to sample, preference was given to states with topology and conditions similar to those in Iowa. Following this, preference was given based on the number of available data.

For comparison of the simple span design methodology, Iowa, Oklahoma, and Texas were selected. Among these states, the Iowa DOT and Oklahoma DOT (ODOT) utilize a simple span design method, with the Iowa DOT using a jointless design and ODOT utilizing both jointless and jointed bridge design. TxDOT utilizes an empirical design method for deck reinforcement in conjunction with a simple span design methodology. All three of these states have a considerable library of standard bridge plans, consisting of typical abutments, piers, girders, and deck layouts for a variety of bridge lengths, widths, and skews. The quantities provided on these standard plans were used as the basis for comparisons.

Missouri, Nebraska, and Wisconsin were selected to represent the continuous design method based on similarities in topography and climate to Iowa, as well as availability of bridge plans. For each of these states, material quantities were collected for bridges based on a combination of plans and bid tabulations published for projects that were sent to construction contractors.

For all sample bridges, the overall length, span lengths, roadway width, and skew were recorded as key comparison metrics. Material use was broken down into bridge components: girders, deck, abutments, and piers. For several states, separate abutment and pier material quantities were not readily available, and, thus, a combined number was recorded. For each component, quantities were recorded for the cubic yards of concrete and pounds of reinforcing steel required.

Figures 2 and 3 show that the simple span designs are much more consistent, which is attributed to their use of standard designs, given that such standards are not affected by project specific requirements.

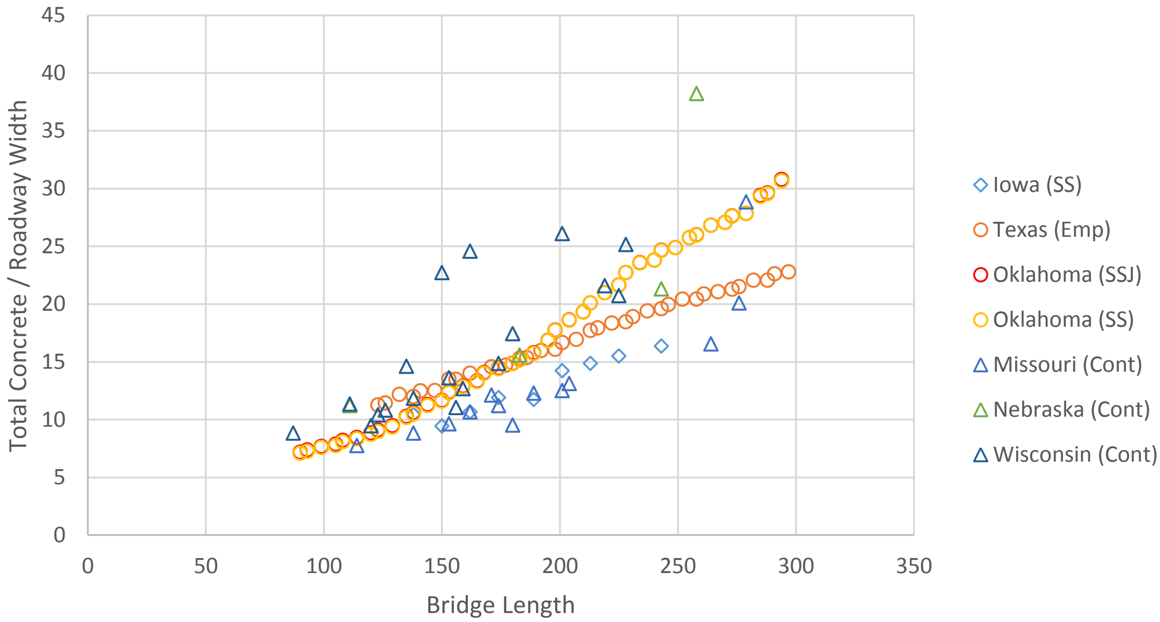

Figure 2. Comparison of total concrete required

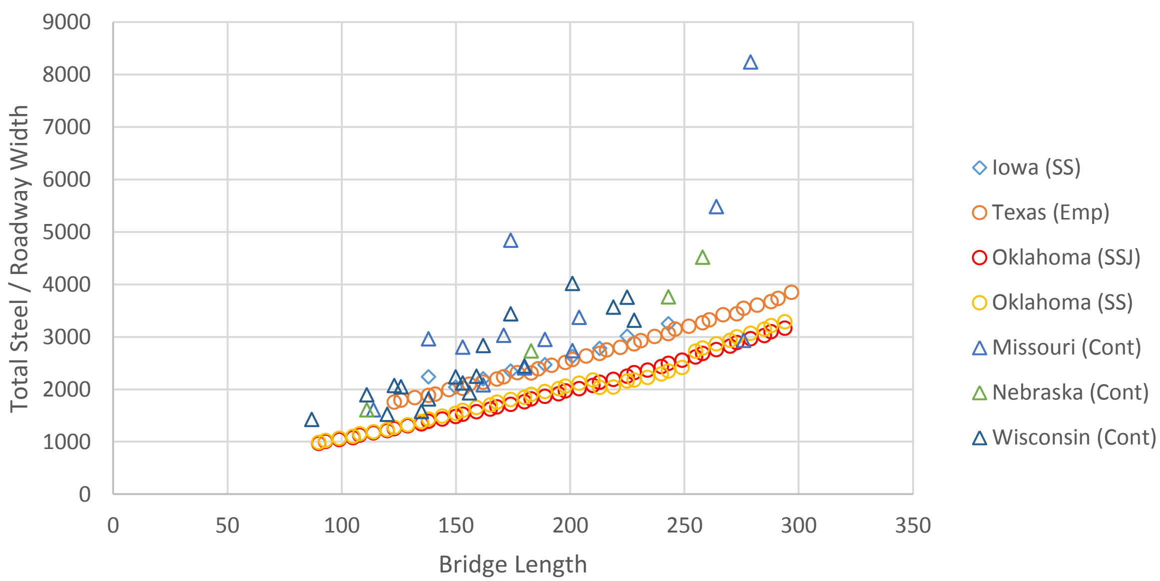

Figure 3. Comparison of total reinforcing steel required

Despite the variance, the continuous designs tend on the average to have slightly lower quantities of concrete required. The simple span designs tend to have lower required amounts of reinforcing steel.

Figures 4 and 5 present the material usage for the deck only.

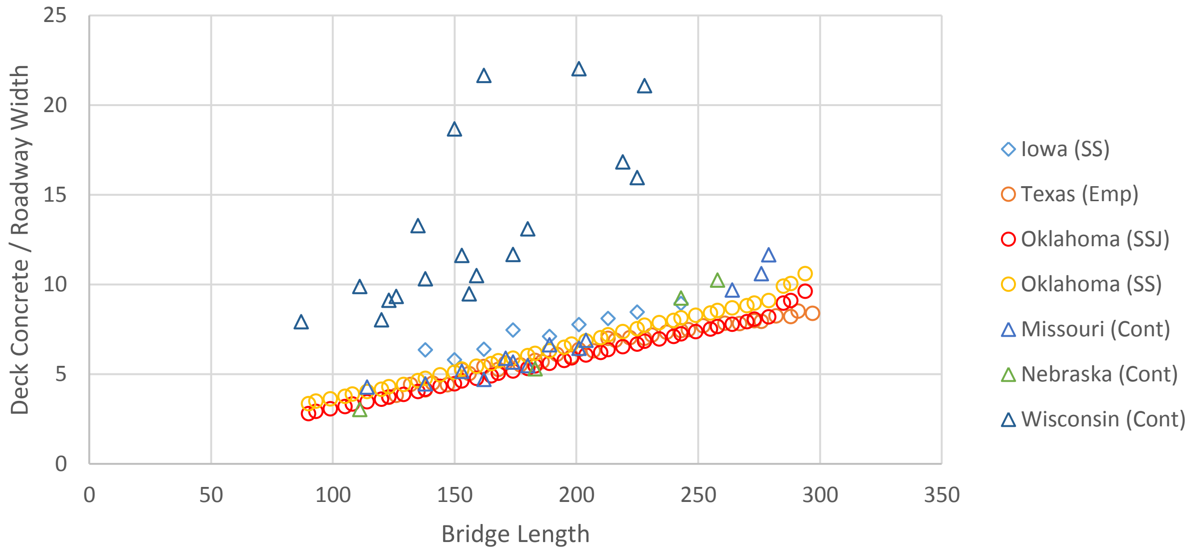

Figure 4. Comparison of deck concrete

Figure 5 clearly shows that the simple span designs utilize less reinforcing steel and concrete for the deck.

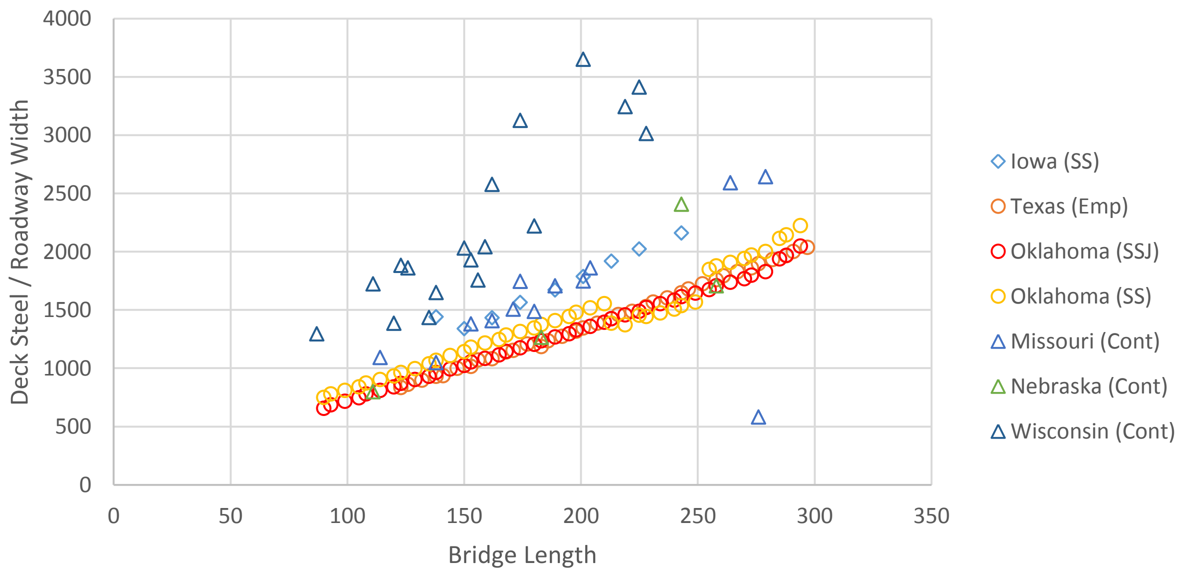

Figure 5. Comparison of deck reinforcing steel required

While deck concrete usage can be affected by numerous factors, the reduction in steel usage is interesting as it can be tied to the amount of negative moment reinforcing over piers and the length of that reinforcing steel into the span. The fact that less deck reinforcing steel is utilized in simple span designs indicates that the design for negative moment resistance at the piers in continuous designs results in an increase in the required reinforcing steel beyond that used in simple span designs for crack resistance.

The bridge girders are another component of interest, as the girders may see the greatest impact from differing longitudinal moment distribution. Figures 6 and 7 show that the continuous designs consistently utilize significantly less concrete and steel in the girders than comparable simple span designs. This shows the potential for material savings with a continuous design.

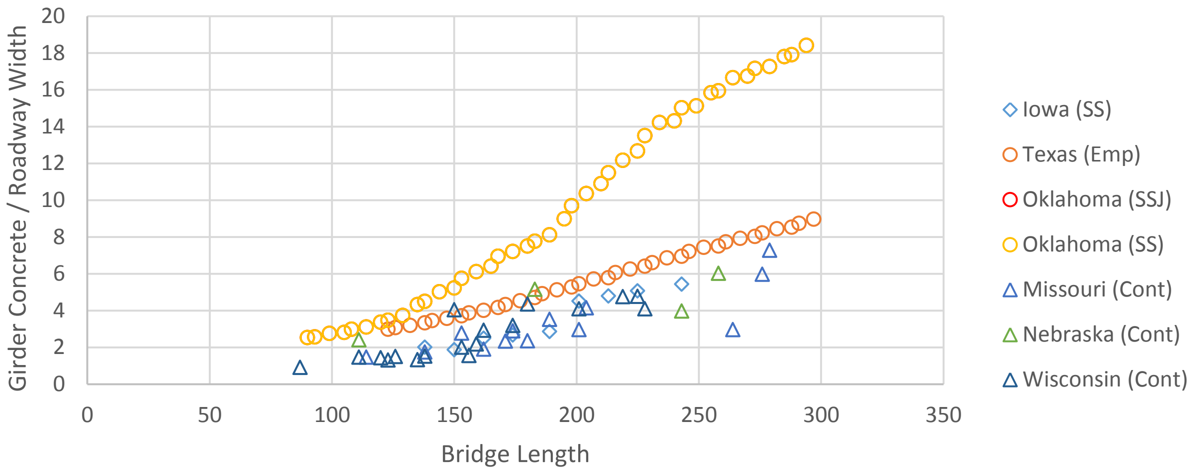

Figure 6. Comparison of girder concrete

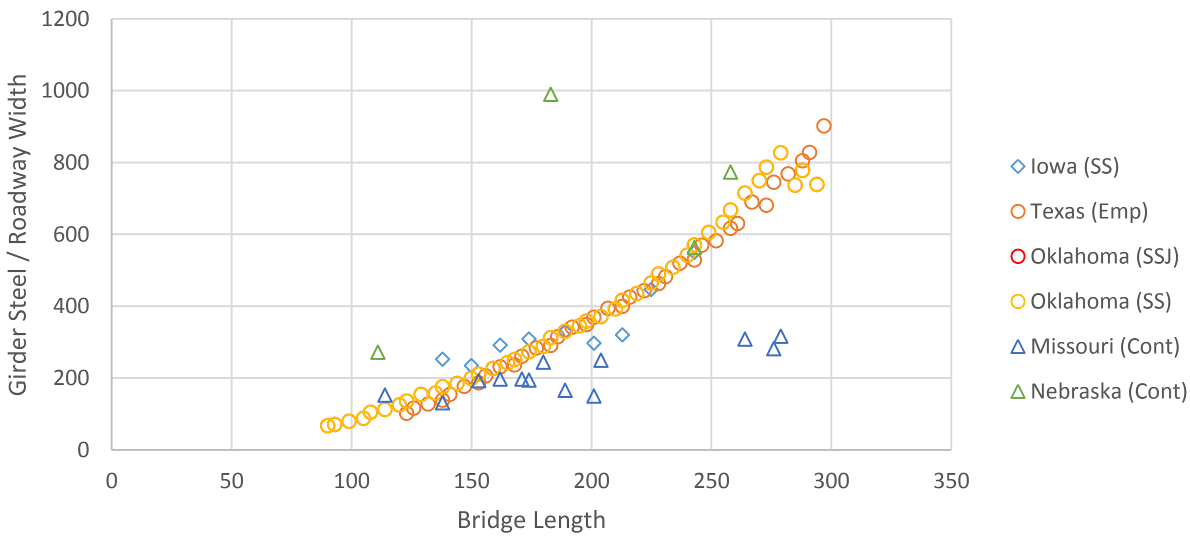

Figure 7. Comparison of girder steel

The notable reduction in concrete usage could indicate a reduced number of beamlines, but this is considered unlikely as the majority of the continuous designs utilize more than 4 beam lines, which is typical for simple span designs. A reduction in beamlines could provide considerable benefit if possible, due to the reduction in not only material, but also in transportation and erection costs associated with precast beams.

Figure 8 provides a direct comparison between the material costs in the deck and girders for continuous and simple span design methods.

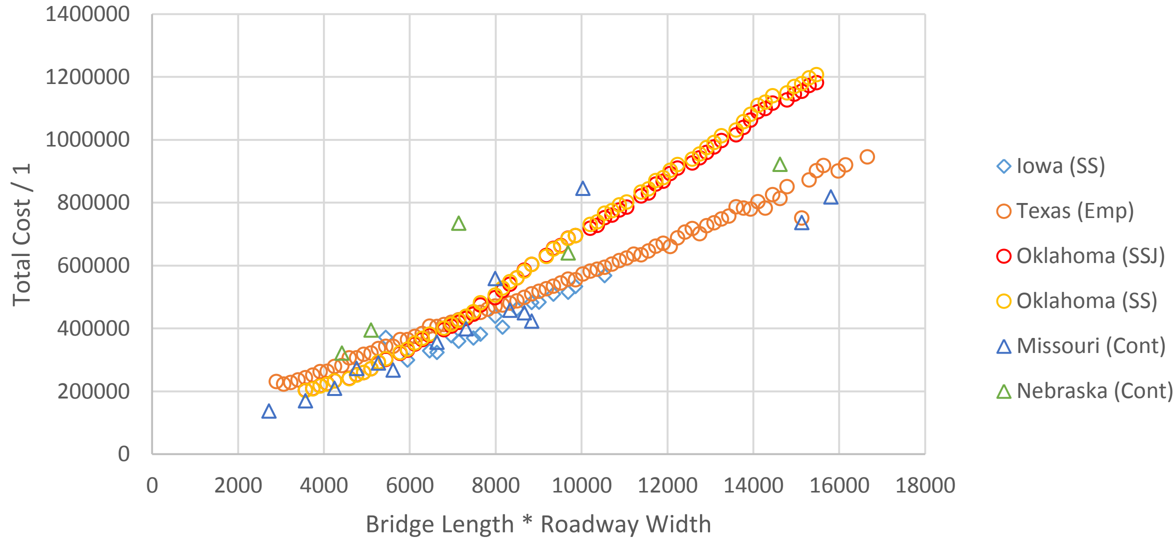

Figure 8. Comparison of material costs

In creating this direct comparison, material prices were determined using the Iowa DOT awarded bid unit prices where available. Unit prices were insufficient for estimating girder material costs, as girders are bid on a per item basis. To fill this gap, rough material cost estimates were obtained directly from a local precaster. A summary of the material costs used is presented in Table 7.

Table 7. Material unit costs

Material	Units	Cost	Source
Concrete (4ksi)	yd^3	$606.90	Iowa DOT Unit Price
Concrete (9ksi)	yd^3	$624.20	[1]
Prestressed Strands	lbs	$ 1.50	[2]
Steel (mild)	lbs	$ 0.50	Iowa DOT Unit Price
Steel (epoxy)	lbs	$ 0.67	Iowa DOT Unit Price

[1] Concrete cost is based on an incremental cost quoted by a prestress manufacturer and is varied linearly with compressive strength
[2] Prestressing steel cost was quoted at $1.00/lb, but was increased to account for the known higher cost in comparison to mild steel

Reviewing data in Figure 8, it can be seen that, despite the overall materials savings in the simple span bridge designs and the reduction in deck concrete and steel, the additional girder requirements at a higher price leaves the overall material costs fairly similar.

To quantify this difference, each continuous design was compared to a baseline formed by averaging the simple span designs. It was found that, on average, the continuous designs have 99% of the cost associated with simple span designs, with the range being from 69% to 180%.

To obtain a square foot cost for comparison to the previous results, the researchers used linear regression on the grouped simple span and continuous bridge designs shown in Figure 8. With a forced y-intercept of 0, the simple span designs had a material cost of $65.20/ft^2$ with an R^2 value of 0.96 and the continuous designs had a material cost of $59.36/ft^2$ and an R^2 value of 0.76.

4.4. Overall Material Cost Comparison

In two of the three methods utilized to compare construction costs between simple span and continuous designs, simple span designs were demonstrated to be less expensive. Only the direct material comparison indicated a lower construction cost for continuous designs, and the reduction was minimal and with significant variance. That simple span designs would have a lower material and construction cost is counterintuitive from a material usage standpoint, as typical expectations would be that simple span designs would be more conservative and thus less efficient. However, the combination of three independent sets of data lends a reasonable degree of credibility to this conclusion.

A comparison of the square footage construction costs obtained in Sections 4.1, 4.2, and 4.3 is shown in Table 8.

Table 8. Construction cost comparison compilation

				Deviation	
Source	**Simple Span**	**Continuous**	**Difference**	**Simple Span**	**Continuous**
DOT Survey	$105.00	$163.00	$ 68.00	$ 15.49	$112.36
NBI data	$129.00	$147.00	$ 18.00	$ 58.00	$138.00
Material Comparison	$ 65.20	$ 59.36	$ –5.84	R^2=0.95	R^2=0.76

All costs are per square foot of roadway area

Based on the data in this table, an average construction cost savings of $20/ft^2$ for simple span designs was selected, based on both the differences and measures of deviation listed. In addition to this average savings, bounding values of $70/ft^2$ and $–10/ft^2$ were identified to move forward in the cost-benefit analysis.

5. ENGINEERING COST COMPARISON

5.1. Comparison of Survey Cost Data

Table 9 shows a comparison of the design hours from the state survey responses.

Table 9. Simple span vs. continuous design hours by state

Simple Span Designs		Continuous Designs	
State	**Hours**	**State**	**Hours**
Arizona	1,200	California	500
Arkansas	700	Colorado	1,400
Georgia	400	Maryland	2,000
Minnesota	2,750	Missouri	700
Montana	1,000	Nebraska	200
North Carolina	400	Pennsylvania	2,000
Texas	82	South Dakota	425
		Tennessee	2,000
		Virginia	1,750
		Wisconsin	450
Average:	**933.1**	**Average:**	**1,142.5**
Standard Deviation:	**887.3**	**Standard Deviation:**	**755.2**

Specifically, respondents were asked for an approximation of design/drafting hours in the production of construction documents for a typical three span bridge (see the Appendix). Note that these numbers include foundation, environmental, and traffic design among other things in addition to superstructure design costs. From the responses, simple span design methods took less time on average; however, the variance is so large in the reported design time that significant conclusions cannot be reached from these data alone.

In addition to the responses listed in Table 9, three DOTs responded to the survey with direct estimates on the time required to detail for continuity. The Alaska Department of Transportation & Public Facilities (ADOT&PF) estimated a requirement of an additional 160 hours; the South Dakota DOT (SDDOT)estimated an additional 8 hours; the Iowa DOT estimates that the design of continuous girders would take an additional 2.5 hours.

5.2. Hourly Cost for Engineering

To convert the average design time estimates into dollar amounts for inclusion into the cost-benefit analysis, a typical hourly pay rate is needed. Several studies have been reviewed for this, usually for purposes of comparing in-house design costs to consultant costs. Among these, a technical report by Texas State University-San Marcos based on TxDOT was chosen, as it is the most recently published (Morris et al. 2012). In this report, it was determined that the total hourly cost of an in-house engineer, inclusive of fringe benefits, averaged approximately $120 per hour.

5.3. Bridge Design Cost

Based on an average hourly cost of $120 for design personnel, in combination with the data from Table 9, the additional design cost of a continuous design can be roughly estimated at $24,000 per bridge. This figure is based on averages with large variances. As such, to account for the range of possibilities, analysis was also performed with bounding values of $1,000 and $60,000, corresponding to an additional approximately 8 hours and 500 hours respectively. These are based on what is believed to be a reasonable minimum and maximum differential based on the collected data.

6. COST-BENEFIT COMPARISION OF DESIGN METHODS

Figure 9 shows the expected continuity cost, consisting of the added expense of continuous design and construction over a simple span baseline ($0 Continuity Cost), for a 24 ft wide roadway at varying bridge lengths.

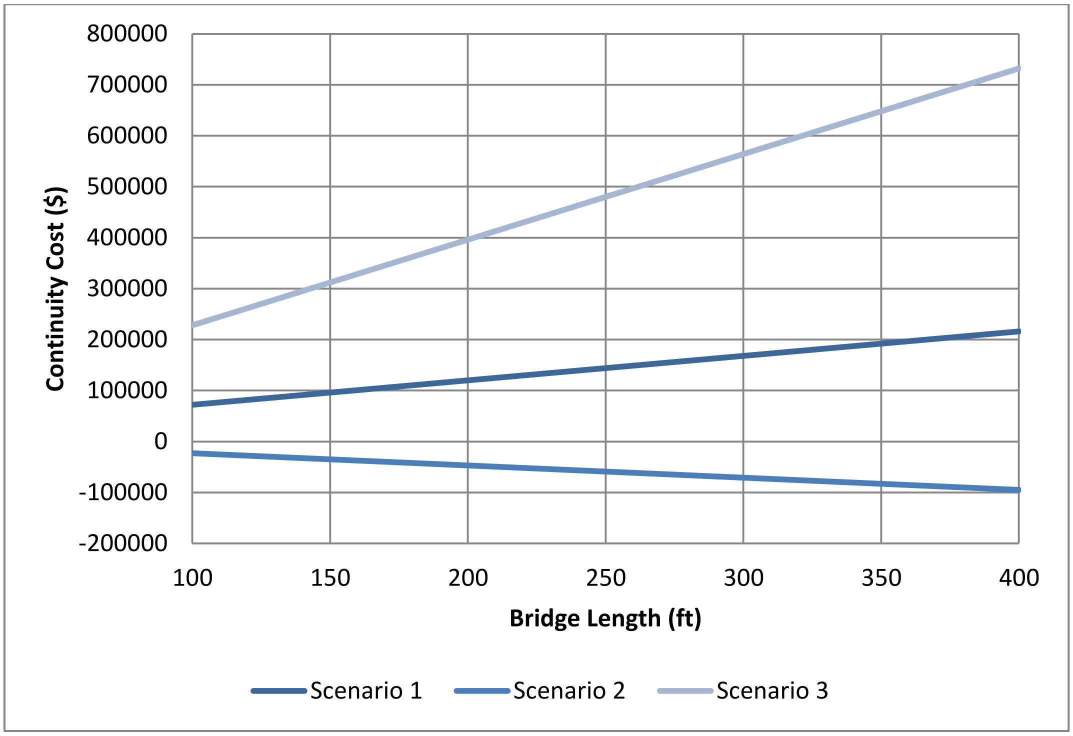

Figure 9. Continuity design and construction costs vs. simple span for three scenarios depending on bridge length

Scenario 1 is associated with the expected values as determined in Sections 4.4 and 5.3. Scenarios 2 and 3 utilize the bounding values determined to demonstrate the maximum and minimum continuity cost considered realistic or reasonable. Table 10 shows the additional costs used for each of the scenarios in the graph.

Table 10. Continuity cost scenarios

Scenario	Additional Design Cost	Additional Const. Cost (per ft^2)
1	$ 24,000	$ 20
2	$ 1,000	$ −10
3	$ 60,000	$ 70

As shown in Figure 9, while the range of possible costs is large, only the Scenario 2 continuity costs (which included savings on construction costs) result in overall savings compared to simple span design and construction costs (the $0 baseline). This is a strong indication that, overall, simple span designs have a lower initial cost.

7. CONCLUSIONS AND RECOMMENDATIONS

The cost-benefit comparison presented in Chapter 6 points fairly conclusively to simple span designs having the lower initial cost of the two design methods. This conclusion is based on savings in both construction and design costs. However, some evidence was also found for continuous designs having a lower cost.

Based on the variations in the data, several continuous design bridges fell significantly below the average simple span bridge in terms of construction cost. Even with relatively high design costs, if a reasonable savings per square foot of deck area can be achieved, the design costs are easily offset for larger bridges. For example, at a reasonable $10/ft^2 savings, a $24,000 design cost differential is offset for a 100 ft long bridge with a 24 ft roadway width.

The lower construction cost demonstrated by the simple span designs in contradiction to theoretical material efficiencies in continuous design is an indicator that many of the continuous designs utilized are not optimized to the extent possible. While significant recent research has been completed on optimization methods for prestressed concrete bridge design, the majority of them remain undeveloped for practical application. It is suggested that with the maturity of such design optimization methods, this study be updated to account for the potential material and time savings suggested by these optimization methods.

This study also did not look into the long-term costs associated with these design methods. Subjects of relevance for which additional research would be needed include the effects of design for continuity on deck cracking in negative moment regions, as well as long-term benefits of the reserve capacity and redundancy available in simple span jointless designs due to the unutilized continuity over the piers.

However, based on the evidence included in this report, the researchers concluded that simple span designs have a lower initial cost compared to continuous designs, in terms of construction cost and design time. Due to the lack of strong evidence in favor of either design method in terms of long-term cost and performance, the research team concluded that simple span designs are preferable at this time.

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APPENDIX: STATE DOT SURVEY

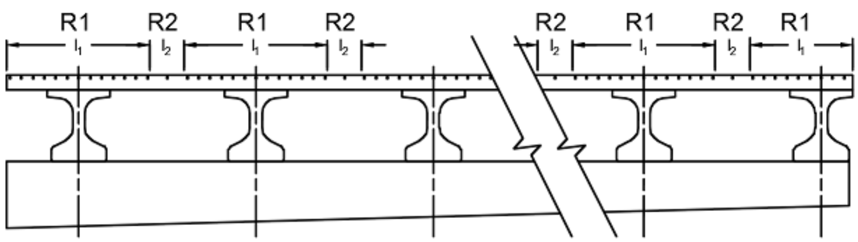
Introduction

While filling out this survey, please describe quantities is the most relevant manner per design ideology, such as rebar cutoffs at 20% of span length or 20 ft, as appropriate.

Agency:	____________________________	Name:	__________________________
Address:	____________________________	Title:	_____________________________
Telephone:	____________________________	Email:	_____________________________
Fax:	____________________________		

What would best describe the analysis assumptions made for a typical design:

- ❍ Simple spans for all loads
- ❍ Simple spans for all dead loads
- ❍ Continuous for all composite loads
- ❍ Other: ____



Region 1 = R1   Region 2 = R2

Basic Deck Longitudinal Reinforcing (Top and Bottom)

Typical Bar Size: _____________________

Typical Bar Spacing: _____________________

Is this steel in addition to negative moment steel over the pier? _____________________

Additional Negative Steel Zones Over Girders (Region 1)

Is additional negative moment steel used over girders? _____________________

Over what effective flange width l1 is this differing steel used? _____________________

What is the typical length of these bars into the end span? _____________________

What is the typical length of these bars into the center span? _____________________

Typical Bar Size: _____________________

Typical Bar Spacing: _____________________

Additional Negative Steel Zones Not Over Girders (Region 2) _____________________

What is the typical length of these bars into the end span? _____________________

What is the typical length of these bars into the center span? _____________________

Typical Bar Size: _____________________

Typical Bar Spacing: _____________________

Approximately how many design/drafting hours would be required to produce construction documents for a typical three span bridge per this procedure?

Approximately what is the cost per square foot for a typical three span bridge designed per this procedure?