Incremental Bridge Construction Costs for Highway Cost Allocation

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The procedures and results of an incremental load analysis of bridge construction costs that consisted of the design and pricing of 960 bridges were documented. These 960 bridge type, load, and span combinations were composed of 11 different bridge types ranging in span from 9 to 72 m (30 to 240 ft) and designed for loads ranging from H2.5 to HS25. The bridge type and span combinations included in this factorial reflect current national design and construction practices, as revealed by statistical summaries obtained from the National Bridge Inventory data base. The incremental bridge cost results are important inputs for the highway bridge cost allocation procedures carried out at the federal and state levels. In addition to the bridge cost results, moment ratios of live load to dead load were recorded during this bridge design exercise. The moment ratios obtained in such an exercise can contribute significantly to policy evaluations—especially those that attempt to define the economic impacts of vehicle size and weight changes on bridges at the highway network level.

Cost allocation studies traditionally have been used to provide a logical basis for relating highway tax structures to highway program costs. There is no doubt that the proper allocation of highway costs is very important in providing adequate resources for the various components of a highway program. One important component of the highway system are the bridges, and the proper allocation of bridge costs relies on the incremental analysis of bridge construction costs.

INCREMENTAL DESIGN OF STRUCTURES

This paper summarizes the results published in a report prepared for an FHWA study, Impacts of Heavy Trucks on Bridge Investment (*1*). The results are aimed at allocating the construction costs of typical bridges to the various vehicle classifications that operate on the nation's highways. The incremental design of highway structure methodology is based on the difference in design costs that results when various classes of vehicles are applied as loadings. In this typical incremental cost allocation approach, as described in FHWA's cost allocation guide (2), each of the typical bridges was designed for several AASHTO (H and HS) vehicle configurations representative of the vehicle traffic operating on the nation's highway system. The work reported herein expands considerably on the results previously available for highway bridge cost allocation exercises and documented elsewhere (*3*).

The cost results of this massive bridge design exercise, consisting of 960 bridge type, design load, and span combinations, as summarized by the factorial presented in Table 1, are presented in tabular format in the appendix of the FHWA report (*1*); some of the tables are included in this paper to illustrate the results.

RATIOS OF LIVE LOAD TO DEAD LOAD

The FHWA report (*1*) also documents important results on moment ratios of live load to dead load for the various bridge combinations documented in the factorial presented in Table 1. These results are of significant importance for fulfilling one of the main objectives in the study, as quoted from FHWA's specifications for Study DTFH61-92-C-00099 "to improve the analysis of the impacts on bridges of larger and heavier trucks." The lack of simplified ratios of live load to dead load in the National Bridge Inventory (NBI) (*4*) is one of the major limitations in the process of analysis of impacts of larger and heavier trucks. Modeling of bridge impacts in the available literature (*5–8*) has been limited to the comparison of live load bending moments of the larger and heavier trucks with the live load moments of the rating vehicle recorded in the NBI data base (Items 64 and 66 of the NBI). This process could be significantly improved by the addition of the dead load effects to the analysis.

The comparison of bending moments is the key element in applying simplified methods for determining bridge deficiencies to heavier trucks using the NBI. This makes the results reported in the FHWA report (*1*) on ratios of live load to dead load of great importance for the analysis of the impacts of changes in vehicle size and weight on bridges. These ratios are presented in the report for the bridge type, load, and span combinations described in the Table 1 factorial.

FACTORIAL OF BRIDGES TO BE DESIGNED AND PRICED

To design a factorial of bridge combinations that reflects the current bridge design and construction practices nationwide, the entire NBI data base was analyzed—a total of 665,743 bridge records. The NBI analysis involved scanning the complete nationwide NBI data for 1992 and extracting all bridges having spans less than or equal to 72 m (240 ft) (the range of spans required by the FHWA study). In addition, only bridges having a structure type (second and third digits of Item 43 of the NBI structure type) less than or equal to 6 to restrict the bridge types to the ones required by the FHWA study and also the first digit of Item 43 of the NBI (to avoid timber, aluminum, wrought iron, cast iron bridges, etc.) greater than 6 were extracted. This procedure produced a data set of approximately 381,000 bridges.

This nationwide bridge population was categorized into the 15 span lengths required by the study. The main structure types were

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TABLE 1 Factorial of Bridge Type and Span Combinations

	Reinforced Concrete Slab														
Simple	9	12	15												
Continuous	9	12	15	18											
	Prestressed Concrete Slab														
Simple	9	12	15												
Continuous	9	12	15	18	21										
	Reinforced Concrete T-Beam (C.I.P.)														
Simple	9	12	15	18	21										
Continuous	9	12	15	18	21	24	27	30							
	Prestressed Concrete Beam (Precast)														
Simple	9	12	15	18	21	24	27	30	36	42					
	Prestressed Concrete Multi-cell Box Girder (C.I.P.)														
Continuous						24	27	30	36	42	48	54	60	66	72
	Steel I-Beam														
Simple	9	12	15	18	21	24									
	Steel I-Girder														
Simple			15	18	21	24	27	30	36	42	48	54	60	66	72
Continuous			15	18	21	24	27	30	36	42	48	54	60	66	72

(1 m = 3.3 ft)

categorized using Item 43 of the NBI. The resulting frequency distributions of spans by bridge type are summarized in Table 2 for these 381,000 bridges. From the frequency distributions included in Table 2, it is clear that simply supported slab bridges are typically built with spans up to 15 m (50 ft). The same rationale may be applied to the multibeam concrete simply supported span distribution presented in Table 2 to demonstrate that this type of bridge is built with spans up to 21 m (70 ft).

These frequency distributions were used, in conjunction with experienced engineering judgment, to establish the factorial of bridge type and span combinations to be designed and priced. This factorial, presented in Table 1, establishes a study of incremental

TABLE 2 Distribution of Spans by Bridge Type

NATIONWIDE BRIDGES FOR SPANS UNDER 72 m (240 ft)

Span category (feet)	30	40	50	60	70	80	90	100	120	140	160	180	200	220	240	Cumulative Percent per Type (%)	Total Bridges by Bridge Type
(meters)	9	12	15	18	21	24	27	30	36	42	48	54	60	66	72		
Concrete Slab	81	14	3	1	0	0	0	0	0	0	0	0	0	0	0	100	39,430
Contin. Concr. Slab	39	27	22	8	3	1	0	0	0	0	0	0	0	0	0	100	25,472
Prestress Concrete Slab	28	34	24	7	4	1	0	0	0	0	0	0	0	0	0	100	6,786
Multi-beam Concr.	35	36	20	4	2	1	1	0	0	0	0	0	0	0	0	100	18,386
Multi-beam Concr. Contin.	24	16	13	14	15	8	5	2	2	1	0	0	0	0	0	100	3,256
Multi-beam Steel	32	22	14	9	7	5	4	2	3	2	1	0	0	0	0	100	129,844
Multi-beam Steel Contin.	9	4	6	10	12	12	11	8	12	7	4	2	1	1	0	100	41,470
Multi-beam Prestress	3	7	12	14	18	14	12	8	9	3	0	0	0	0	0	100	34,638
Multi-beam Prestress Contin.	0	4	11	14	16	15	13	9	12	5	1	0	0	0	0	100	5,494
Tee Beam Concr.	27	40	22	9	2	1	0	0	0	0	0	0	0	0	0	100	24,252
Tee Beam Concr. Contin.	7	10	18	19	18	16	6	3	2	0	0	0	0	0	0	100	7,329
Tee Beam Prestress Concr.	23	28	19	13	6	4	2	2	2	1	0	0	0	0	0	100	6,025
Box Beam Concr.	19	20	11	8	10	7	8	4	7	3	1	1	0	0	0	100	2,197
Box Beam Concr. Contin.	0	0	1	4	11	13	17	14	22	10	4	1	0	0	0	100	5,542
Box Beam Steel	19	0	3	3	6	6	5	3	5	13	14	7	7	4	1	100	201
Box Beam Steel Contin.	1	0	2	1	2	4	5	4	18	16	12	16	12	7	1	100	324
Box Beam Prestress	13	20	21	17	12	6	3	2	2	1	1	0	0	0	0	100	27,417
Box Beam Prestress Contin.	4	7	10	7	6	5	5	4	12	13	11	8	5	3	1	100	3,157

Total number of bridges considered in the nationwide bridge population, approximately 381,000 (Source NBI 92) bridge construction costs for 11 structure types of various span lengths for a total of 80 combinations designed for 10 live loading levels (HS25, HS22.5, HS20, HS17.5, HS15, H20, H15, H10, H5, H2.5) for widths of 11.4 m (38 ft) [two 3.6-m (12-ft) lanes; two 1.8-m (6-ft) shoulders] and, for the lightest live load, designed also for three different widths—11.4, 9.6, and 7.8 m (38, 32, and 26 ft) for a total of 12 load-width combinations. The 12 load-width combinations multiplied by the 80 bridge-type span combinations resulted in 960 bridges to be designed and priced.

METHODOLOGY FOR BRIDGE DESIGN FACTORIAL

The continuous bridges were designed for three equal spans of the span lengths specified in the factorial. The decision to use three span configurations for the continuous bridges was justified by the summary statistics analysis of the NBI nationwide population, which shows that about 80 percent of the continuous bridges nationwide have three or more spans. The detailed documentation of the analysis and design results are available in the files of the contractor for this research study. This documentation includes all tables and handwritten calculations performed by the project team to arrive at the quantities and costs presented in the FHWA report (*1*).

Analysis

For continuous spans, envelopes for the various live load configurations for the moments, shears, and reactions were computed using the program BMCOL51 (*9*), with the results summarized using an electronic spreadsheet. Uniform load values were computed for a distributed load intensity of 15.13 kN/m (1 kip/ft) (also using BMCOL51), and the results were subsequently used for the calculations of the dead load moments, shears, and reactions in an iterative procedure that depended on the weight of the various elements selected by the design engineer. Simple spans were analyzed manually for the dead loads and with the help of BMCOL51 for live loads.

Control Sketches and Bridge Design Details

Sketches showing the details and dimensions of the various types of spans specified in the bridge design factorial were prepared on the basis of the project staff's experience in bridge design. The superstructure sketches showed the details of deck dimensions, beam spacing, and railing for the various bridge types included in the study.

In general, the various dead loads, design moments, and shears for the superstructure were obtained by estimating slab, beam, or girder weights, adding the constant weights distributed equally to each beam/girder and multiplying times the appropriate unit value from the moment, shear, and reaction tables generated in the analysis phase. Live load design moments and shears and reactions were obtained by determining the portion of a lane required to be resisted by one beam/girder/meter of slab, then multiplying by the appropriate value from the moment, shear, and reaction tables.

Section properties for calculating stresses resulting from design moments were computed and tabulated as appropriate. Designs proceeded for the various types of bridges specified in the factorial. The service load method was used for all designs (although other methods were used to check for column adequacy).

Abutment sketches depicted all details except variable dimensions, which were dependent on the beam depths determined during the design procedures. The sketches for the interior bents showed cap size and column spacing for various span lengths.

Sketches for abutments and interior bents established the type of foundation (drilled shaft) and the spacing of columns and drilled shafts. Size and minimum length of drilled shafts were established by experience for the abutments. The size of round columns and drilled shafts for interior bents were established in 15-cm (6-in.) increments for grouped span lengths.

Drilled shaft loads were obtained by multiplying the dead load times the reaction tabulated value and the number of design lanes times the tabulated live load reaction, adding the weight of the interior bent and dividing by the number of columns. Structural adequacy of the proposed sizes was verified, and compatibility with shaft loads was noted.

Drilled shaft lengths were calculated to resist the shaft loads without exceeding allowable soil stresses for point bearing and skin friction.

COST ANALYSIS AND RESULTS

Quantities were calculated on the basis of the design sections and the guidelines outlined by the control sketches and using the methodology presented previously. For reinforced concrete slabs and girders, cubic meters of concrete and kilograms of reinforcing were calculated after the design process was completed. For prestressed concrete slabs and box girders, cubic meters of concrete, kilograms of reinforcing steel, and kilograms of prestressing steel were calculated as the design was completed. For steel I-beams and I-girders, kilograms of beam/girder steel, including miscellaneous steel (diaphragms, shoes, expansion joints) and kilograms of shear connectors were calculated when the design was completed. For abutments, cubic meters of concrete and linear meters of drilled shafts were calculated. The same methodology was applied to interior bents.

After the design was completed, bridge costs were obtained by multiplying quantities by unit costs obtained from the Texas Department of Transportation (TxDOT) using an electronic spreadsheet. All quantities resulting from the design of the 960 bridge span, load, and type combinations are summarized on a bridge-by-bridge basis and are available in electronic spreadsheet format.

The electronic spreadsheet format facilitates updates with the costs originating from a nationwide cost survey carried out by the project. This cost survey could be repeated periodically to maintain the updated results. The initial costs used to perform the calculations (surveyed at TxDOT) reflect the average bid prices for the various items for FY 1992. Because TxDOT uses "mobilization" as a separate bid item, 15 percent of the total cost for the superstructure and substructure was added to the total costs to account for mobilization costs.

Included in the FHWA report (*1*) are 11 tables, one for each bridge type included in the factorial presented in Table 1; these tables summarize construction cost, cost per square meter of deck, and cost ratios in relationship to the HS20 bridge design separated for the superstructure, substructure, and total bridge cost. An example of the results summarized in the report is presented in Table 3. In addition, while the design was being performed, dead load and live load design moments were noted and summarized in the form of ratios of the live load to the total moment (live load plus dead load).

Plots of total structure cost per square meter versus design live loading revealed a tendency toward linear variation, as observed in Figure 1. This tendency is logical because live load moment variations are linear between HS15 and HS25 and between H2.5 and H20. Any discontinuous results observed were attributed to the designer's selection of discrete sections that would satisfy the stress requirements. Although all cost results may not be economically optimized, the costs reported are considered close enough to establish the proper incremental load cost relationships for the various bridge types and span lengths specified by the factorial described in Table 1.

It appears that all curves resulting from this bridge design and costing exercise could be logically normalized as straight lines between the costs at H2.5 and H20 loads and between the HS15 and HS25 loads or adjusted by regression analysis with no significant effects on the results.

RESULTS OF RATIOS OF DEAD LOAD TO LIVE LOAD

An important by-product of this massive bridge design exercise (960 bridges of various types, loads, and spans) is the ratios of dead load to live load. These ratios were recorded as the design progressed for each of the bridge types. The ratios were calculated using the design moments induced by the dead load and the live load and followed the formulation presented by the following equation:

$$R_{DL} = \frac{M_L}{M_L + M_D}$$

where

R_{DL} = ratio of live load moment to total moment,
M_L = live load moment, and
M_D = dead load moment.

Results were reported in terms of design moments [kN*m (kip*ft)] and in terms of a ratio of the live load design moment to the total design moment (represented by the dead plus the live load effect), as defined by the equation. A sample of the tables available in the FHWA report (*1*) is presented in Table 4.

The AASHTO specifications (*10*) for the design of highway bridges permits a simplified method for obtaining longitudinal moments and shears resulting from live loads. According to this method, a longitudinal girder (or a strip of unit width in the case of slabs) is isolated from the rest of the bridge structure and treated as a one-dimensional beam. This beam is subjected to loads comprising one line of wheels of the design vehicle multiplied by a load fraction *S/D*, also known in the literature (*11*) as a load distribution factor. *S* is the girder spacing and *D* is specified to have a certain value by the AASHTO specifications for each bridge type.

On the basis of this AASHTO methodology, which was used throughout the analysis and design of the 960 bridges of the factorial, one must recognize that the results for the moment ratios reflect the geometry of the bridges used in the incremental cost exercise. This bridge geometry was established by the control sketches. In other words, the moment ratios reported are specific to the load distribution factors determined during the design phase for each bridge type. Nevertheless, these ratios are still a good approximation and very useful inputs for the modeling of economic impacts on bridges, at the network level, of changes on vehicle size and weight.

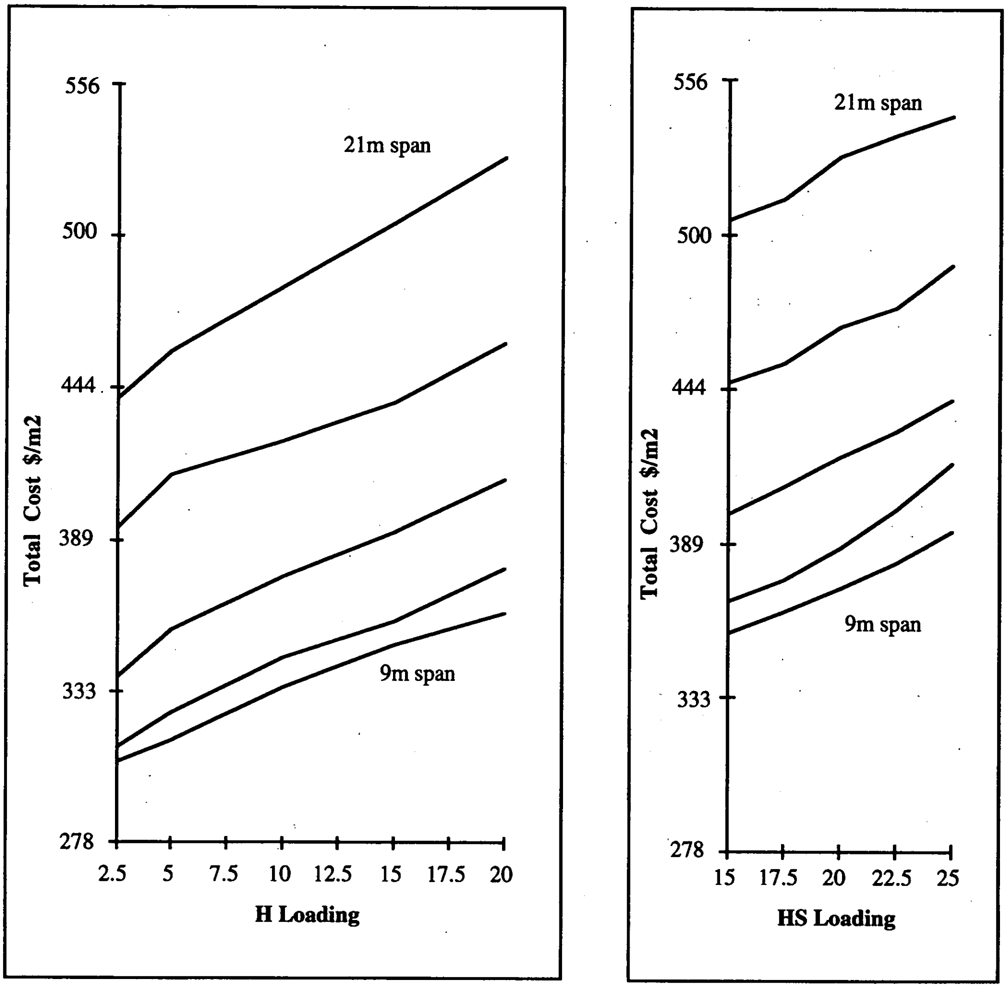
CONCLUSIONS

The procedures and results of an incremental load analysis of bridge construction costs that consisted of the design and pricing of 960 bridges have been documented. These 960 bridge type, load, and span combinations are composed of 11 different bridge types ranging in span from 30 to 240 ft and designed for loads ranging from H2.5 to HS25. The bridge type and span combinations included in the factorial presented in Table 1 represent the current design and construction practices used nationwide, as reflected by statistical summaries obtained from the NBI data base reported in Table 2.

TABLE 3 Example of Cost Tables for Steel I Girder Bridges (Simple and Continuous) (*1*)

	15 m Span Steel I Girder Simple		21 m Span Steel I Girder Simple		21 m Span Steel I Girder Continuous		30 m Span Steel I Girder Continuous	
Loading	Total Cost ($/m^2)	Total Cost HS20 Ratio	Total Cost ($/m^2)	Total Cost HS20 Ratio	Total Cost ($/m^2)	Total Cost HS20 Ratio	Total Cost ($/m^2)	Total Cost HS20 Ratio
HS 25	308.9	1.049	362.2	1.041	345.9	1.034	398.6	1.035
HS 22.5	305.4	1.038	355.1	1.021	340.2	1.017	392.0	1.018
HS 20	294.3	1.000	347.9	1.000	334.6	1.000	385.1	1.000
HS 17.5	287.0	0.975	340.7	0.979	329.1	0.984	378.7	0.983
HS 15	279.4	0.949	333.4	0.958	323.9	0.968	372.2	0.967
H 20	280.3	0.952	333.9	0.960	330.9	0.989	382.4	0.993
H 15	267.0	0.907	324.2	0.932	318.8	0.953	368.1	0.956
H 10	259.4	0.881	312.8	0.899	306.6	0.916	353.3	0.917
H 5	253.9	0.863	302.6	0.870	294.0	0.879	339.0	0.880
H 2.5(11.4m)	253.1	0.860	296.6	0.852	286.6	0.857	331.7	0.861
H 2.5(9.6m)	267.1	0.764	307.1	0.743	285.4	0.718	333.7	0.730
H 2.5(7.8m)	342.4	0.796	322.4	0.634	301.0	0.616	349.8	0.621

(1 m = 3.3 ft)



(1 m = 3.3 ft).

FIGURE 1 Incremental cost analysis results for prestressed continuous concrete slabs (1 m = 3.3 ft).

TABLE 4 Moment Ratios for Simple Concrete Slab Bridges (Moments in kN*m)

	Span 9m			Span 12m			Span 15m		
Loading	Moment Dead	Moment Live	Ratio Live/Total	Moment Dead	Moment Live	Ratio Live/Total	Moment Dead	Moment Live	Ratio Live/Total
HS 25	44.95	54.48	0.548	100.79	77.63	0.435	194.77	98.06	0.335
HS 22.5	43.58	49.03	0.529	98.06	69.46	0.415	194.77	88.53	0.313
HS 20	43.58	43.58	0.500	98.06	62.65	0.390	190.68	79.00	0.293
HS 17.5	42.22	38.14	0.475	93.98	54.48	0.367	179.78	68.10	0.275
HS15	39.50	32.69	0.453	91.25	46.31	0.337	179.78	58,57	0.246
H 20	42.22	38.14	0.475	91.25	47.67	0.343	179.78	55.84	0.237
H 15	39.50	28.60	0.420	87.17	35.41	0.289	174.34	42.22	0.195
H 10	35.41	19.07	0.350	84.44	24.52	0.225	163.44	27.24	0.143
H 5	32.69	8.17	0.200	77.63	10.90	0.123	157.99	13.62	0.079
H 2.5(11.4m)	29.96	4.09	0.120	73.55	5.45	0.07	157.99	6.81	0.04
H 2.5(9.6m)	31.33	4.09	0.120	74.91	5.45	0.07	159.35	6.81	0.04
H 2.5(7.8m)	31.33	4.09	0.120	76.27	5.45	0.07	162.08	6.81	0.04

(1 kN*m = 1.375 kips*ft)

The methodological procedures, designed to accommodate the limited resources available for performing the monumental task of designing and pricing 960 bridge combinations, relied heavily on computerized procedures and on the significant bridge engineering expertise available within the project staff. The incremental bridge cost results should support highway bridge cost allocation procedures carried out by FHWA and state agencies.

The results of periodic cost surveys will ensure that the cost data, tentatively reported using Texas costs, reflect the variability of bridge construction costs nationwide.

In addition to the cost results, moment ratios of live load to dead load were recorded during the design phase. These are an important contribution for the policy evaluations of the economic impacts of changes of vehicle size and weight on bridges at the highway network level. If these moment ratios were available, the results of the analysis of longer combination vehicle impacts on bridges, such as those reported elsewhere (*5–8,12,13*), would have been significantly improved. The moment tables reveal how the cost sensitivity to load increments is attenuated by the effect of the dead load.

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