An Incremental Cost Study Of Highway Structures In Ohio

JOHN F. LINDLEY, *Assistant Professor of Civil Engineering, Ohio University, Athens, Ohio*

This paper is an interim report of a study which is still in progress. The principal objective is the presentation of the philosophy underlying, and the techniques employed in the conduct of, a study of the relationships between the cost of highway structures in Ohio and the characteristics of the vehicles which those structures are designed to accommodate. Because the study is as yet incomplete, the results included merely exemplify the objectives toward which the work has been directed.

The study is one phase of a large-scale study currently being conducted by personnel of the Engineering Experiment Station of The Ohio State University in an effort to establish the relationships between total highway costs in Ohio and vehicle characteristics. The results will be presented in a bulletin to be published by the Experiment Station toward the end of 1957.

The concept of minimum and maximum relationships between cost and vehicle characteristics, which has been applied by Prof. Robert F. Baker to an incremental cost study of highway pavements, has been incorporated as an integral part of the underlying philosophy, making it somewhat unique among incremental cost studies relating to highway structures.

• THE ULTIMATE OBJECTIVE of this study is the determination of the minimum and maximum relationships between the cost of highway structures in Ohio and the characteristics of the vehicles which the structures are designed to accommodate. Since the design of a structure, and consequently its cost, is directly related to such vehicle characteristics as length, axle arrangement, gross weight, and distribution of the gross weight among the vehicle axles, the relationships are to be established for these characteristics.

Underlying the entire study is the incremental cost philosophy of highway finance; that is, a vehicle operator should share in paying for that portion of an actual highway system which would be provided if his and similar vehicles were the only ones using the system. Since the cost of structures is an appreciable portion of the total cost of a highway system, the bases for vehicle tax structures should incorporate considerations of the influence on structure cost of the vehicle characteristics.

Application of the incremental cost philosophy involves the preparation of theoretical designs for highway systems, which would be adequate for traffic composed of vehicles with assumed characteristics, and the estimation of the costs of these theoretical systems. This is the basic technique which has been applied.

Because the results of this study are to be integrated into a large-scale study, the costs represent the cost (per lineal foot of structure) of structural items only, including concrete, reinforcing steel, structural steel, foundation piling, and bridge railing; the costs of all other items (approach slabs, wearing surface, etc.) will be included in other categories of highway costs, such as earthwork, drainage, paving, etc.

All costs established here are estimated quantities; therefore, attempts to pinpoint the relationships sought were inadvisable. The study has been directed toward the "bracketing" of theoretically exact relationships by determining the minimum and maximum values which the relationships could reasonably be expected to have, with resultant confidence that the exact relationships lie somewhere between these extremes.

The study has been limited to a determination of the relationships for structures representative of those built in Ohio. Accordingly, the bridge construction program during a 6-year period was studied; representative types were selected on the basis of relative expenditures for various types of structures built during this period.

BRIDGE CONSTRUCTION IN OHIO

During a 6-year period (1950-1955) the Ohio Department of Highways let contracts for the construction of 686 bridges with lengths of 20 ft or more, located on state highways outside the corporate limits of towns and villages. Of this number, 280, or 41 percent, were steel beam bridges; 372, or 54 percent, were concrete slab bridges; and 34, or 5 percent, were of other types (steel girder, arches, trusses, etc.). Of the total expenditure of $54,996,173.73 for the structural portions of these bridges, 55.8 percent was for steel beam bridges, 31.4 percent was for concrete slab bridges, and 12.8 percent was for other types.

The percentages of total annual expenditures for structures which were assigned to steel beam and concrete slab bridges varied considerably (from 39.6 to 66.9 for steel beam bridges, and from 24.0 to 38.3 for concrete slab bridges). This variation can be largely accounted for by the shortages of critical materials during the Korean War, which forced the Highway Department to use other types of structures wherever possible, in addition to curtailing the highway construction program generally.

Single-span structures are of little significance in the bridge construction program. During the 6-year period, 11 single-span steel beam and 44 single-span concrete slab bridges were built, accounting, respectively, for 1.5 and 2.3 percent of the total expenditure for structures. Three-span structures dominate the multiple-span bridge construction program; 176 steel beam and 279 concrete slab bridges with 3 spans were built during the period.

The above information, supplied by the Ohio Department of Highways, convincingly establishes steel beam and concrete slab bridges as representative structure types in Ohio. This study has been limited to these two types, with consideration given to both single-and 3-span structures.

PROGRAM OF THE STUDY

The cost per lineal foot of a highway structure (referred to as unit cost) may be considered to be a function of (a) characteristics of the vehicles which the structure is designed to carry; (b) type, length, width, and number of spans of the structure; (c) characteristics of the site of the structure; and (d) the costs of labor and material in the structure.

Highway structures are designed to accommodate traffic composed of an assumed procession of 3-axle combination vehicles with lengths of 28 ft and maximum gross weights of 27 tons, assumed to be distributed among the axles as follows: 1/9 (3 tons) on the front axle, and 4/9 (12 tons) on each of the other 2 axles. Three-axle combination vehicles for which the gross weight is distributed in this manner have been designated as Type I vehicles, as shown in Figure 1, and are referred to as standard combination vehicles.

This vehicle is one of many types

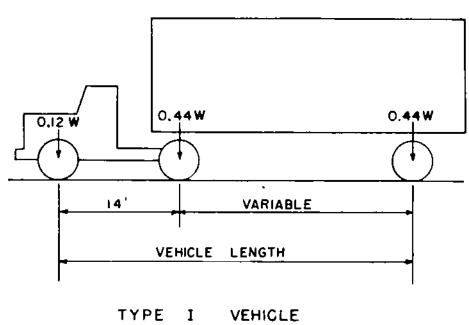

Figure 1. The standard combination vehicle.

which are permitted to travel over the highway systems; eight other vehicle types have been defined in terms of axle arrangement and distribution of the gross vehicle weight among the axles. Some of these types have as few as 2 axles, and others have as many as 5 axles. For some tandem-axle vehicles, the load carried by each of the axles has been assumed to be 2/3 of that carried by a single axle, corresponding to the tandem-axle vehicle designated by the AASHO design specifications; for other such vehicles, the load carried by each tandem axle was assumed to be the same as that carried by a single axle.

Because the maximum vehicle axle load is often a principal criterion in the design of highway structures, the gross weights of vehicles of all types have been defined in terms of the maximum vehicle axle load, which was assumed to vary from 1 to 20 tons. Although an axle load of 20 tons is far in excess of the legal axle loads (19,000 pounds on a single axle or 31,500 pounds on tandem axles), the establishment of the relationships desired was advisable in view of the trend toward increasing legal load limits.

The unit cost of a highway structure is assumed to vary according to both the length and width of the structure. For structures of a given type, with a specified width and number of spans, designed to carry vehicles of designated characteristics, there will be certain lengths for which the unit costs will be, respectively, minimum and maximum. It is also assumed that an increase in the width of a structure will be accompanied by an increase in the cost of the structure. Consequently, the determination of minimum and maximum relationships involves the determination of the influences on cost of both the width and length of the structure.

Site conditions were assumed to be as follows:

1. Structures are located on straight portions of 2-lane highways.
2. Crossings are at right angles, with clearances of 15 ft.
3. Structures are supported on pile foundations.
4. Structure width and roadway width are identical.
5. Separate wearing surfaces are provided.
6. End spans of multiple-span structures are 8/10 the interior spans.
7. The total length of a structure is 2 feet greater than the sum of individual span lengths.

Although the costs of labor and material vary, the estimated costs established by this study are based upon the current average costs of the items considered. Thus, the minimum and maximum costs ultimately established will, in effect, be average quantities, and not necessarily the absolute minimum and maximum costs of structures in Ohio.

Another factor which influences the design and cost of highway structures is the frequency with which traffic is expected to move across the structures, because allowable material stresses are defined in terms of this frequency, expressed as the number of vehicles per lane per day. Correspondingly, the study includes a consideration of the influence on structure cost of traffic frequency, which is assumed to vary from 100 to 2,000 maximum-sized vehicles per lane per day.

Within the framework outlined, the study was resolved into the design of a series of single- and 3-span steel beam and concrete slab bridges of variable length and width, designed to carry traffic composed of vehicles of various types, lengths, and gross weights, passing across the structures with various frequencies. These designs constituted the basis for estimates of material quantities required, and of total structure costs, which were translated into unit structure costs.

In recognition of the fact that the number of possible combinations of specific values of the variables considered would be of astronomical proportion, the program of the study was limited as follows:

1. The design of single- and 3-span steel beam and concrete slab bridges of variable length and width, to accommodate standard combination vehicles of variable gross weight,

passing across the structures with a frequency of 400 per lane per day.

2. The design of single- and 3-span steel beam and concrete slab bridges of representative lengths and widths to accommodate standard combination vehicles of variable gross weight passing across the structures with variable frequencies.
3. The design of single- and 3-span steel beam and concrete slab bridges of representative lengths and widths to accommodate vehicles of various types, lengths, and gross weights passing across the structures with a frequency of 400 per lane per day.

All designs were prepared in accordance with the requirements of the *Design Specifications for Highway Structures*, formulated by the Bureau of Bridges of the Ohio Department of Highways. All structures were assumed to be similar to those being built in Ohio at the present time.

Representative single- and 3-span steel beam bridges were assumed to have lengths of 57 and 158 ft, respectively; the lengths of corresponding representative concrete slab bridges were assumed to be 42 and 106 ft. All representative bridges were assumed to have widths of 28 ft. Minimum and maximum structure widths considered were 24 and 32 ft. The ranges of structure lengths considered are representative of the ranges of lengths usually built in Ohio, and are as follows: single-span steel beam bridges, 42 to 72 ft; 3-span steel beam bridges, 106 to 210 ft; single-span concrete slab bridges, 32 to 52 ft; and 3-span concrete slab bridges, 80 to 132 ft.

MINIMUM AND MAXIMUM UNIT STRUCTURE COSTS

There are many possible bases for the designation of minimum and maximum unit structure costs. It can reasonably be argued that the minimum (or maximum) cost should be established on the basis of the absolute minimum (or maximum) costs of labor and materials. Such theoretical values could be established, but would be of little more significance than would be the average of those values, as established here. Further, minimum labor costs are not necessarily accompanied by minimum material costs, so that such estimated quantities would perhaps be even more fictitious than those based on average costs of labor and materials.

For purposes of this study, minimum and maximum unit structure costs are defined as follows:

> The minimum unit cost of a given type of structure shall be the least estimated cost per lineal foot for which that type of structure could be built to accommodate traffic composed of vehicles of specified characteristics passing across the structures with a frequency of 100 such vehicles per lane per day. The maximum unit cost of a given type of structure shall be the greatest estimated cost per lineal foot for which structures of that type would be built to accommodate traffic composed of vehicles of specified characteristics passing across the structures with a frequency of 2,000 such vehicles per lane per day.

Eventually, for different widths of each type of structure considered, the desired minimum and maximum relationships between unit cost and different vehicle characteristics will be established for all structures of each type, regardless of the number of spans, by proper weighting of corresponding minimum and maximum costs in accordance with relative expenditures for structures with different numbers of spans. Thus formulated, the results will be most easily integrated into the over-all study.

REPRESENTATIVE RESULTS

The study has progressed sufficiently on the basis of which the nature of the to permit the inclusion of some results, relationships involved can be defined in general terms. The curves in Figures 2-11 indicate the relationships between unit structure cost and structure width, structure length, traffic frequency, vehicle length, and vehicle gross weight, for

3-span steel beam and concrete slab bridges designed to accommodate standard 3-axle combination vehicles.

Both the width and length of a structure have appreciable influences on unit structure cost (Figures 2, 3, 4, and 5). The relationship between unit cost and structure width is, for all practical purposes, linear for both types of structures considered, regardless of the gross weight of the vehicle which the structures are designed to carry. The variation of unit structure cost which accompanies variation in structure length deviates appreciably from a linear relationship. For all structures, with the exception of steel beam bridges designed to carry lightweight vehicles, increased structure length results in increased unit cost throughout the range of lengths considered. For the exceptions noted, there would appear to be "economical" lengths, lying between the extreme lengths, for which the unit cost is a minimum.

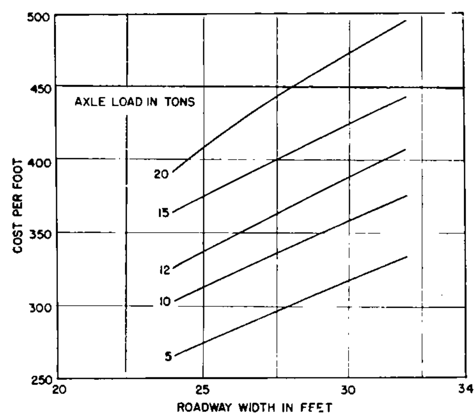

Figure 2. Relationships between unit structure cost and roadway width for 3-span steel beam bridges of representative length (158 ft) designed to accommodate (CF = 400) standard combination vehicles.

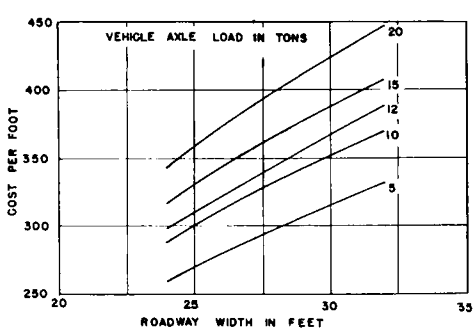

Figure 3. Relationships between unit structure cost and roadway width for 3-span concrete slab bridges of representative length (106 ft) designed to accommodate (CF = 400) standard combination vehicles.

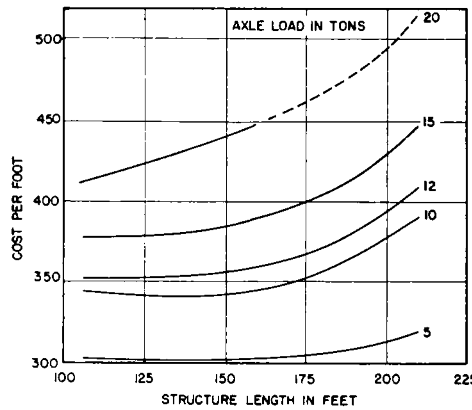

Figure 4. Relationships between unit structure cost and structure length for 3-span steel beam bridges of representative width (28 ft) designed to accommodate (CF = 400) standard combination vehicles.

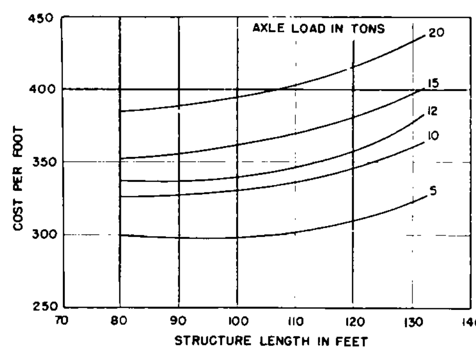

Figure 5. Relationships between unit structure cost and structure length for 3-span concrete slab bridges of representative width (28 ft) designed to accommodate (CF = 400) standard combination vehicles.

The frequency of traffic has a discernible influence on structure cost within the range of 100 to 400 vehicles per lane per day; further increases in frequency result in slight increases in unit cost, discernible principally for structures designed to accommodate quite heavy vehicles (Figures 6 and 7). This arises from the fact that the function of frequency

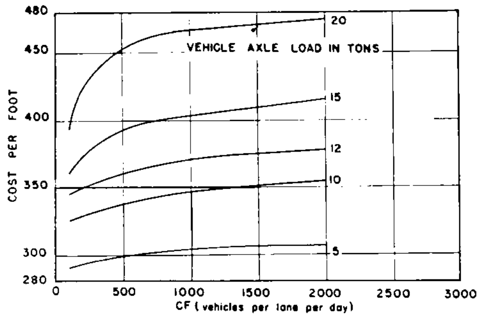

Figure 6. Relationships between unit structure cost and traffic frequency for representative 3-span steel beam bridges (158 ft long, 28-ft roadway) designed to accommodate standard combination vehicles.

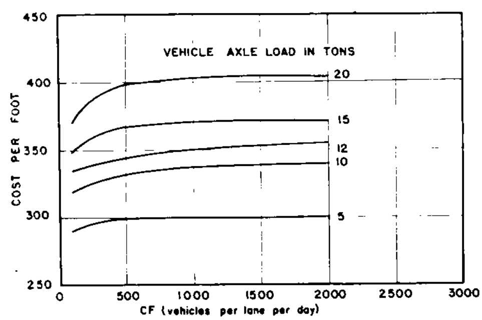

Figure 7. Relationships between unit structure cost and traffic frequency for representative 3-span concrete slab bridges (106 ft long, 28-ft roadway) designed to accommodate standard combination vehicles.

which defines allowable material stresses for values of frequency between 0 and 400 is different from that for values of frequency in excess of 400 vehicles per lane per day.

It would appear that the unit costs of structures designed to accommodate standard 3-axle combination vehicles are not influenced greatly by the length of the vehicles. However, preliminary study of the influence of this vehicle characteristic on unit costs of structures designed to carry other types of vehicles, particularly those having tandem axles, indicates that increases in vehicle length may result in appreciable reduction in unit structure cost. Naturally, generalizations concerning this factor must be formulated only after completion of the study.

The relationships between unit structure cost and gross vehicle weight deviate somewhat from a linear relationship (Figures 8 and 9). In general, the rate of change of unit cost with respect to gross vehicle weight diminishes with

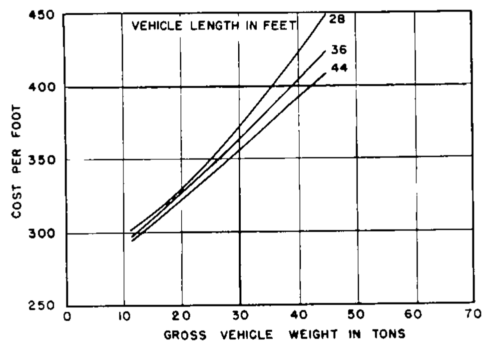

Figure 8. Relationships between unit structure cost and gross vehicle weight for representative 3-span steel beam bridges (158 ft long, 28-ft roadway) designed to accommodate (CF = 400) standard combination vehicles (Type I) of various lengths.

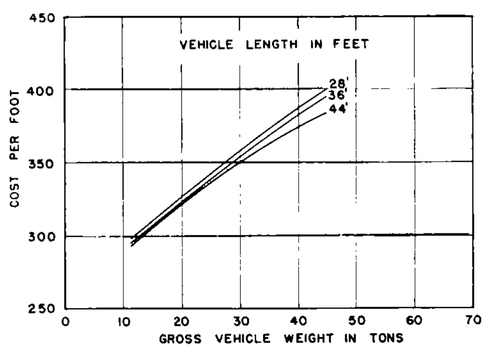

Figure 9. Relationships between unit structure cost and gross vehicle weight for representative 3-span concrete slab bridges (106 ft long, 28-ft roadway) designed to accommodate (CF = 400) standard combination vehicles (Type I) of various lengths.

increasing vehicle weight, this being especially true for concrete slab bridges. The relationships for steel beam bridges could be assumed to be linear without introduction of appreciable error (Figure 8).

The curves in Figures 10 and 11 are exemplary of the types of relationships ultimately sought for the structure and vehicle characteristics considered. No effort has yet been made to integrate other variables into "weighted" minimum and maximum relationships, as will eventually be done. The ranges defined by the minimum and maximum relationships shown

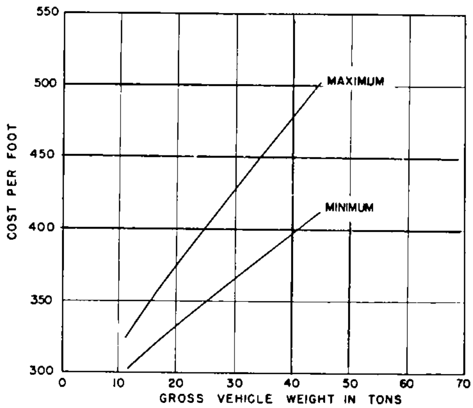

Figure 10. Minimum and maximum relationships between unit structure cost and gross vehicle weight for 3-span steel beam bridges (28-ft roadway) designed to accommodate (CF = 400) standard combination vehicles (Type I).

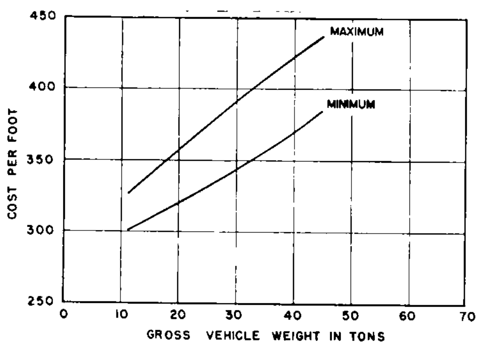

Figure 11. Minimum and maximum relationships between unit structure cost and gross vehicle weight for 3-span concrete slab bridges (28-ft roadway) designed to accommodate (CF = 400) standard combination vehicles (Type I).

are appreciable, considered from the standpoint of dollars per foot, but not great on a percentage basis.

CONCLUSION

The study has been formulated to facilitate the integration of results into the large-scale study. Whereas the results of the study are of interest, they are of value only as they are related to over-all highway cost-vehicle characteristic relationships.

It is believed that the underlying philosophy and the techniques employed in the conduct of this study would be adaptable, without appreciable modification, to similar studies in other states. Despite the limitations necessarily imposed, the results, although far from exact, should be far more indicative of the relationships involved than would be the results of less comprehensive studies.

Upon the completion of the general study, there should be established a reasonable "yardstick" by which the suitability of the present vehicle tax structure in Ohio can be judged, and by which the effect upon highway costs and vehicle taxes of any proposed changes in the present vehicle laws might be evaluated.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the invaluable assistance rendered by Professors Robert F. Baker and Charles B. Smith of The Ohio State University, Mr. D. H. Overman and other personnel of the Ohio Department of Highways Bureau of Bridges, and Mr. James Eberhart, assistant on the staff of the Engineering Experiment Station of The Ohio State University, each of whom has contributed materially to the development of the study.