Bridge Formula Development

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ABSTRACT

The objective of this research was to review the existing bridge formula to determine whether modifications could be suggested to make it more rational. The intent was to more fully use the capacity of existing bridges without significantly shortening the service life of any. A formula, independent of the number of included axles, was developed to accomplish the objective. As is the current formula, it is applicable both to the overall wheelbase and to all included subgroups of axles. The maximum weights for single and tandem axles were assumed to be unchanged. If enforced, the proposed formula assures that HS 20 bridges will not be loaded to more than 1.05 times the design stress, nor will H 15 bridges be loaded to more than 1.30 times the design stress. The formula reduces the maximum weight allowed on four or more closely spaced axles. However, for most practical lengths, the formula is less restrictive than the current law. A brief study of the influence the proposed formula would have on pavement fatigue was accomplished. For most practical heavy vehicles, the formula would result in a greater number of equivalent axle loads per vehicle. One equivalent axle load causes the same pavement fatigue damage as a single 18,000-lb (80.06-kN) axle. The number of equivalent axle loads is commonly used as a measure of the fatigue damage a heavy vehicle inflicts on the pavement. A detailed study of the effect that the adoption of the proposed formula would have on pavements is recommended. Such a study should consider costs, benefits, and potential formula modifications.

In this paper is described a study of the bridge formula currently prescribed in the Surface Transportation Assistance Act (STAA) of 1982 for regulating truck weights on certain federally funded roadways. This bridge formula, often referred to as Table B (or Formula B), has received criticism from both users and transportation officials for being basically unfair in terms of the stress levels generated in various bridge spans and types by different axle combinations. The most compelling criticism concerns its applicability to long, many-axled vehicles, which are also being studied under the STAA of 1982, for which the formula would allow unreasonably high loads should the current 80,000-lb (355.7-kN) maximum gross weight be increased.

The problem is complicated by the variability in bridge carrying capacities. This is primarily because different bridges were originally designed to different strength levels. Two of the most common of these strength levels are termed H 15 and HS 20 by the AASHTO bridge specifications, in which the HS 20 is significantly stronger than the H 15. This notation for strength levels actually refers to the hypothetical truck loading used for the bridge design. The HS 20 design truck, which has a semitrailer, actually weighs more than twice the weight of the H 15. About 95 percent of the bridges on the Interstate system are rated as HS 20 or better. In general, none are classified as less than H 15. The percentage of HS 20 bridges on the primary and secondary highway systems, however, is significantly lower.

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HISTORIC BACKGROUND

The first significant federal legislation concerning truck weights was contained in the Federal Aid Highway Act of 1956, which initially provided for the planning, financing, and construction of the National System of Interstate and Defense Highways. This bill provided that no funds would be used for the Interstate system in any state that allowed vehicles with a single axle weighing more than 18,000 lb (80.06 kN), a tandem axle of 32,000 lb (142.3 kN), and a gross weight of 73,280 lb (325.9 kN). However, a "grandfather clause" provided that any vehicle that operated legally within a state before the passage of the law could continue to operate legally afterwards.

In 1964 the Highway Research Board prepared and submitted to Congress, via the Secretary of Commerce, House Document 354. This document contained a detailed review of the trucking industry and of the regulations governing the operation of heavy vehicles. Further, it recognized the large capital investment the nation had in these heavy vehicles, their importance to the nation's commerce, and their wear and tear on the nation's highway system. Findings of the document were partly based on results of AASHO Road Tests performed in the late 1950s. Probably the most important recommendation made in that document was that Table B, a tabulation of permissible weights of axle groups, depending on the number of axles and the overall length of the group, be adopted for the Interstate system. In addition, it suggested that the single axle limit be increased to 20,000 lb (88.96 kN) and the tandem axle limit to 34,000 lb (151.2 kN).

It is important to note that a footnote to Table B flatly prohibited the operation of certain short-wheelbase, multiaxle trucks over H 15 bridges. The point was clearly made in the document that such vehicles would overstress the H 15 bridges by more than 30 percent, a situation the authors of the document clearly viewed as intolerable.

Little happened in response to these recommendations, however, until 1975, when the U.S. Congress enacted legislation allowing the states to increase the weight limits on the Interstate system to those of Table B. The allowable single axle weight was increased to 20,000 lb (88.96 kN) and the tandem axle weights increased as recommended in the document. Further, the allowable gross vehicle weight was increased to a maximum not to exceed 80,000 lb (355.8 kN) from 73,280 lb (325.9 kN). It is generally believed that this legislation was passed in an attempt to restore to the industry the productivity lost because of the imposition of the 55-mph (88.5-km/hr) speed limit in December 1973.

The most recent legislation is referred to as the Surface Transportation Assistance Act of 1982 (Act of Jan. 6, 1983, Pub. L. No. 97-424, 96 Stat. 2097-2200).The vehicle weight limitations sections (2123-2124) of the act read as follows:

> VEHICLE WEIGHT, LENGTH, AND WIDTH LIMITATIONS
>
> Sec. 133. (a) Section 127 of title 23 of the United States Code is amended to read:
> [Section] 172. Vehicle weight limitations--Interstate System
>
> "(a) No funds authorized to be appropriated for any fiscal year under provisions of the Federal-Aid Highway Act of 1956 shall be apportioned to any State which does not permit the use of the National System of Interstate and Defense Highways within its boundaries by vehicles with a weight of twenty thousand pounds carried on any one axle, including enforcement tolerances , or with a tandem axle weight of thirty-four thousand pounds, including enforcement tolerances, or a gross weight of at least eighty thousand pounds for vehicle combinations of five axles or more. However, the maximum gross weight to be allowed by any State for vehicles using the National System of Interstate and Defense Highways shall be twenty thousand pounds carried on one axle, including enforcement tolerances, and a tandem axle weight of thirty-four thousand pounds, including enforcement tolerances and with an overall maximum gross weight, including enforcement tolerances, on a group of two or more consecutive axles produced by application of the following formula:
>
> $$W = 500 \left(\frac{LN}{N-1} + 12\ N + 36 \right)$$
>
> where W equals overall gross weight on any group of two or more consecutive axles to the nearest five hundred pounds, L equals distance in feet between the extreme of any group of two or more consecutive axles, and N equals number of axles in group under consideration, except that two consecutive sets of tandem axles may carry a gross load of thirty-four thousand pounds each providing the overall distance between the first and last axles of such consecutive sets of tandem axles is thirty-six feet or more: Provided, That such overall gross weight may not exceed eighty thousand pounds, including all enforcement tolerances, except for those vehicles and loads which cannot be easily dismantled or divided and which have been issued special permits in accordance with applicable State laws, or the corresponding maximum weights permitted for vehicles using the public highways of such State under laws or regulations established by appropriate State authority in effect on July 1, 1956, except in the case of the overall gross weight of any group of two or more consecutive axles, on the date of enactment of the Federal-Aid Highway Amendments of 1974, whichever is the greater. Any amount which is withheld from apportionment to any State pursuant to the foregoing provisions shall lapse. This section shall not be construed to deny apportionment to any State allowing the operation within such State of any vehicles or combinations thereof which the State determines could be lawfully operated within such State on July 1, 1956, except in the case of the overall gross weight of any group of two or more consecutive axles, on the date of enactment of the Federal-Aid Highway Amendments of 1974. With respect to the State of Hawaii, laws or regulations in effect on February 1, 1960, shall be applicable for the purposes of this section in lieu of those in effect on July 1, 1956. With respect to the State of Michigan, laws or regulations in effect on May 1, 1982, shall be applicable for the purposes of this subsection.
>
> "(b) No State may enact or enforce any law denying reasonable access to motor vehicles subject to this title to and from the Interstate Highway System to terminals and facilities for food, fuel, repairs, and rest."

The equation is Formula B from which the weights of Table B are calculated. These limitations are the same as those in Table B, with the 80,000-lb (355.8-kN) gross weight cap. An exception to the bridge Formula B was instituted in the 1974 act and this permitted the maximum weight of tandems spaced 36 ft (10.97 m) to be 68,000 lb (302.5 kN).

FORMULA DEVELOPMENT

An important first step in deriving a new bridge formula to assure specified stress ratios are not exceeded in any H 15 or HS 20 bridge is to identify the lightest and therefore critical bridges. This means finding, for each span, the bridge type that has the least dead load moment and shear. Data were collected from the files of the FHWA and from standard designs of state highway departments to find these minimum weight bridge types. When these lightest weight bridges had been found, it was possible to define the loads that would cause specific stress levels in each span length. This procedure was followed for bridges of both H 15 and HS 20 design.

For example, uniformly distributed loads of every length between 8 and 120 ft (36.58 m) were placed on the lighest weight bridges of every span to evaluate what total load would cause 1.3 times the design stress in H 15 bridges and 1.05 times the design stress in HS 20 bridges. This multitude of calculations was expeditiously completed with a microcomputer and resulted in a unique weight for each uniform load length and each bridge design. These maximum loads were then plotted versus length. It was determined that the H 15 bridges with the 1.3 factor dictated the lesser loads up to lengths of about 70 ft (21.34 m). For the longer lengths, the HS 20 bridges with the 1.05 factor controlled.

Two straight lines were drawn near these results and yielded the formula shown in Figure 1. These two straight lines are shown superimposed over a plot of Table B as modified by the STAA of 1982. The equaequations of the two lines are

$$W = (34 + L)\ 1{,}000 \text{ lb} \qquad 8 \text{ ft} \leq L \leq 56 \text{ ft}$$
$$W = (62 + L/2)\ 1{,}000 \text{ lb} \qquad 56 \text{ ft} \leq L$$

Figure 1 shows that the suggested formula would reduce the loads allowed on the shorter axle groupings as was originally recommended by the footnote to Table B in House Document 354.

Application of the proposed formula is to all contiguous subsets of axles in the vehicle. When calculating the allowable weight of such a subset of axles, the wheelbase (L) is the extreme axle spacing in that subset.

In addition, the current limits for single axles [20,000 lb (88.96 kN)] and tandem axles spaced 4 ft (1.219 m) [34,000 lb (151.2 kN)] are retained. Although a rigorous economic study of the costs of pavement damage compared with the increased transportation productivity was beyond the scope of this study, a brief review of the AASHTO Road Test results led to the conclusion that if these limits were retained and the proposed formula were adopted, some additional pavement fatigue damage would result.

ASSUMPTIONS

The assumptions used to make the calculations described previously are, in general, those made by the analyst during the design of a bridge. For example, the impact formula used in the current AASHTO Standard Specifications for Highway Bridges was assumed to be valid. Similarly, the number and weight of trucks on the bridge in the direction of travel and in adjacent lanes were all as dictated by the design specifications. Finally, the detailed distribution of the load to the several types of members supporting the deck was assumed to follow the design rules.

It is recognized that there is continuing debate about the validity of each of these assumptions, but it is doubtful that the resolution of any one of these debates would alter the results of this study.

One other assumption worth noting is that all bridge design ratings were assumed to be as new. No allowance was made for deterioration due to age or prior service.

STRESS LEVELS CAUSED BY PRACTICAL VEHICLES

The effectiveness of the proposed formula for limiting weights of practical vehicles for specified overstress ratios 1.05 for HS 20 bridges and 1.30 for H 15 bridges is evaluated by comparing the calculated critical weights of selected practical vehicles with the curve defined by the proposed formula. The proposed formula is effective in allowing significantly more weight than does the present formula for many practical vehicles. This is done without exceeding the design total stress, dead load plus live load plus impact (DL + LL + I), by more than a specified percentage: 30 percent in the case of H 15 bridges and 5 percent in the case of HS 20 bridges.

FATIGUE CONSIDERATIONS

The fatigue behavior of highway bridges is influenced primarily by stress range. The stress range is equal to the (LL + I) stresses; therefore any changes in truck weights will result in increased fatigue loading on highway bridges and a corresponding increase

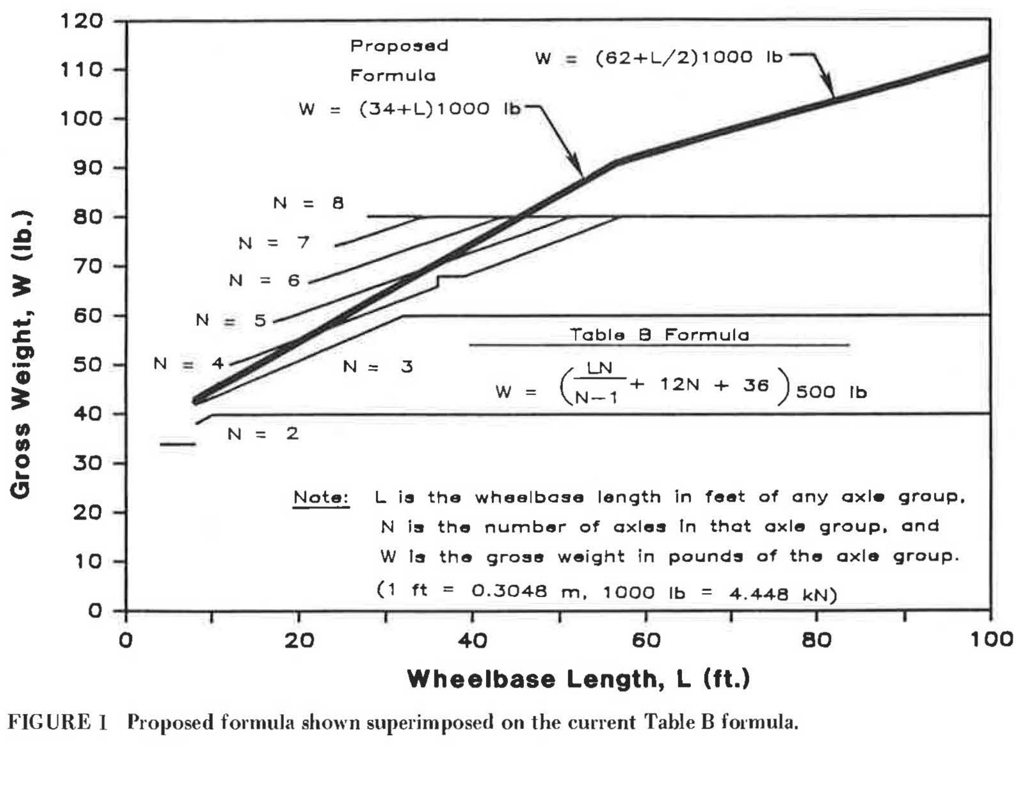

FIGURE 1 Proposed formula shown superimposed on the current Table B formula.

in maintenance costs if the increased fatigue loading causes stresses that are above the fatigue endurance limits. To evaluate the significance of the proposed formula for the fatigue lives of highway bridges, it is necessary to make several simplifying assumptions. It is assumed that existing bridges are loaded in flexure to design allowable stresses by design vehicles. Design allowable stresses are a function of the design lifetime in loading cycles and the weld detail category. It is assumed that flexure governs, and shear is not checked. Because existing single-, tandem-, and triple-axle bogies are not changed, shear stresses are not expected to increase as significantly as flexure stresses. Further, only simple spans were evaluated.

For each span checked, the maximum moment caused by the maximum legal weight vehicles and the maximum moment due to the design live load were calculated. With the assumption that the stress range due to the design loading equals the allowable stress range, the stress range due to the maximum weight vehicles is calculated by multiplying by the appropriate moment ratio.

The calculated stress ranges are compared with the allowable fatigue stress ranges. The ratio of the calculated stress range to the allowable stress range does not exceed 1.05, except for a small range of spans for all the practical vehicles considered for commonly used structural steels. For most spans and details, the increased stress range is still well below the allowable stress range. Span-detail combinations that are most affected by the proposed formula are the more critical details in maximum moment regions of longer, 120- to 160-ft (36.57- to 48.77-m), spans.

PAVEMENT CONSIDERATIONS

In recognition that the passage of heavy vehicles causes fatigue damage to pavements as well as to bridges and that the country's investment in pavement is several times larger than that in bridges, no change should be made in the bridge formula without considering the consequences of the change for the pavements. The analytical assessment of the impact of such a change on pavement life is not as straightforward as it is for bridges. It is generally accepted that heavy axles, and very short groupings of axles, are more damaging to pavements whereas gross vehicle weights, or longer groupings of axles, are more damaging to bridges.

One measure of the fatigue damage heavy vehicles exert on pavements is termed the "equivalent axle load." The equivalent axle load compares the fatigue damage done by a single axle, or grouping of axles, with the damage done by an 18,000-lb (80.06-kN) axle. So an 18,000-lb (80.06-kN) single axle is arbitrarily assigned an equivalent axle load value of 1.0. A single axle, or grouping of axles, that causes twice as much damage as an 18,000-lb (80.06-kN) axle is given an equivalent axle load value of 2.0. Tables of equivalent axle loads for single and tandem axles, on different types of pavement surfaces, have been tabulated and published. These tables are based primarily on the results of the AASHO Road Test completed in the late 1950s, during which the deterioration of various pavement surfaces under repeated heavy truck loadings was observed.

These tables make it possible to estimate the number of equivalent axle loads that results from the passage of any given heavy truck. If a truck has two widely spaced axles weighing 18,000 lb (80.06 kN) each, for example, it could be said that the passage of that truck generated 2.0 equivalent axle loads. Another truck with three 18,000-lb (80.06-kN) axles would generate 3.0 equivalent axle loads and would be considered 50 percent more damaging to the pavement. Closely spaced axles have an interactive effect, but equivalent axle loads for tandem axles (groups of two axles jointly suspended) are also tabulated. This makes it possible to calculate the

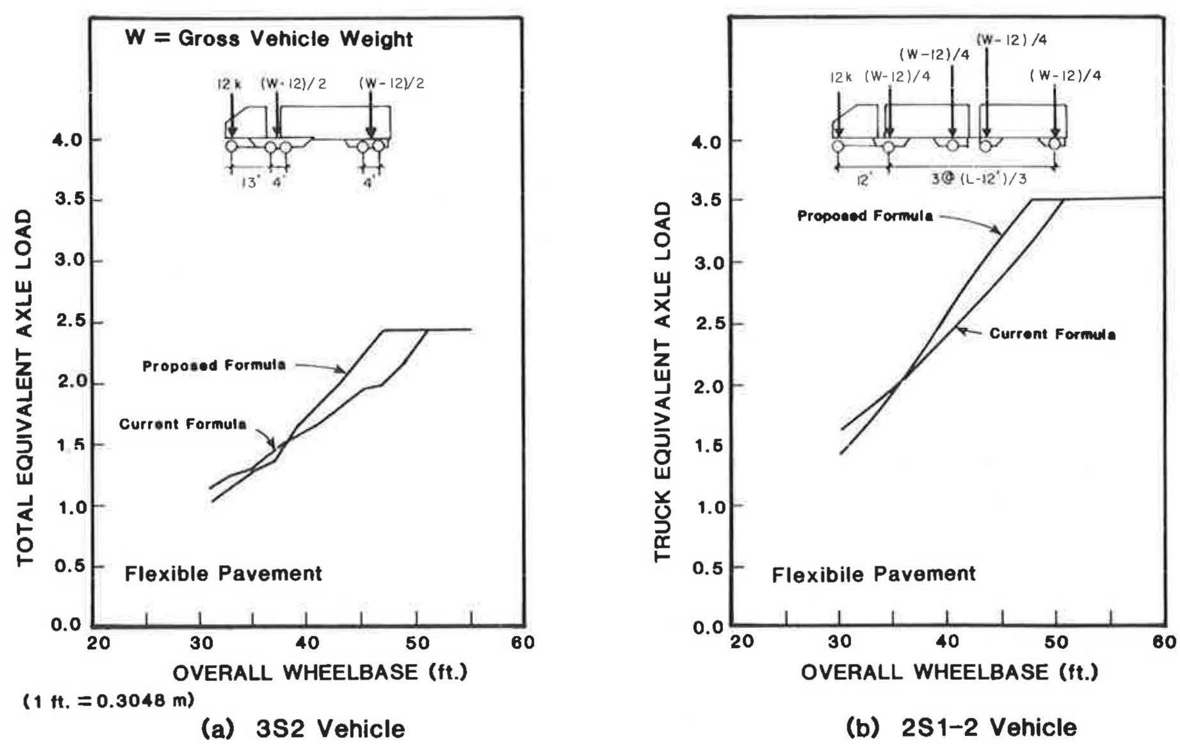

FIGURE 2 Equivalent axle loads per vehicle for proposed and existing formulas.

number of equivalent axle loads generated by most of the heavy truck configurations currently in use.

These calculations were made for trucks that conform to the current bridge formula and for trucks that conform to the proposed bridge formula and the results were compared. These comparisons for two common truck configurations are shown in Figures 2a and 2b. Figure 2a is for the 3S2, a semitrailer truck with a steering axle and two tandems (commonly referred to as the 18-wheeler). Figure 2b is for the 2S1-2, a semitrailer truck with a full trailer on two axles; it has a steering axle with four widely spaced single axles.

For very short and very long vehicles, the equivalent axle loads per truck are about the same. For the short ones, those with wheelbases less than about 36 ft (10.97 m), the proposed formula would lead to smaller equivalent axle loads per truck. If the 80,000-lb (355.8-kN) maximum gross weight per vehicle is maintained, the proposed and current formulas come together at wheelbases just over 50 ft (15.24 m) and are identical for all longer lengths. However, in the intermediate lengths, the equivalent axle loads per truck are significantly greater, in some instances by as much as 20 percent. These intermediate truck lengths, 36 to 50 ft (10.97 to 15.24 m), are common, and the increase in equivalent axle loads would certainly have a detrimental effect on the wear-out rate of pavements.

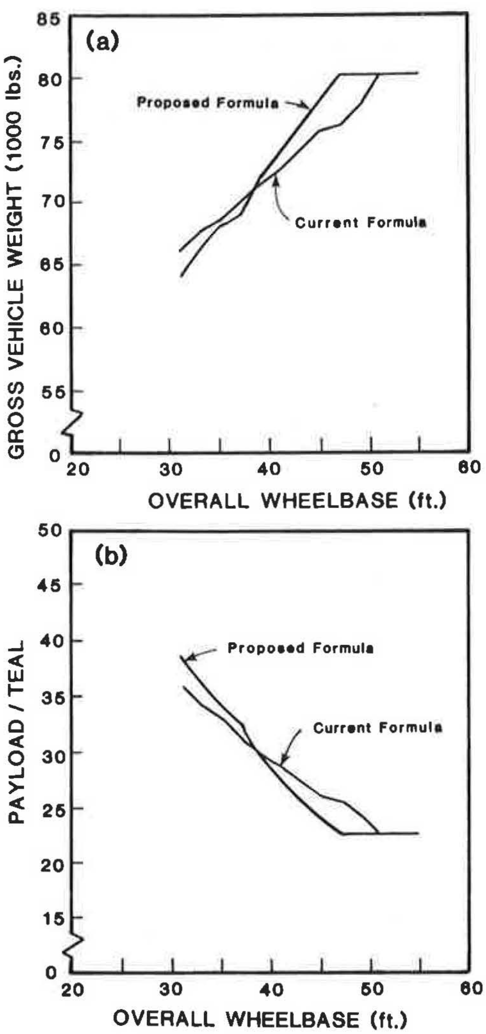

FIGURE 3 Curves illustrating gross vehicle weight and payload per equivalent axle load for 3S2 vehicles complying with proposed and current bridge formulas (1,000 lb = 4.448 kN and 1 ft = 0.3048 m).

It appears that the average equivalent axle load per vehicle will probably increase if the proposed formula is adopted. Even so, this increase would be more acceptable if it could be shown that the payload per equivalent axle load increased as a result of the change. Figures 3a and 3b show the gross vehicle weights versus wheelbase and plots of the assumed payloads divided by vehicle equivalent axle loads. These payloads were calculated by subtracting an arbitrary vehicle empty weight of 25,000 lb (111.2 kN) from the gross vehicle weights. Disappointingly, the payload per equivalent axle load was found to decrease, if only slightly, for vehicles that comply with the proposed formula.

The calculations and comparisons of the equivalent axle loads per truck are evidence that the new bridge formula, as stated and without further modification, would indeed be detrimental to pavements. Currently, pavement deterioration rates are higher than ever, and a change in the bridge formula should not be allowed to magnify that problem. As a result, it is recommended that a detailed study of the influence of a bridge formula change on pavements be initiated with the goal of suggesting additional modifications that would permit the formula to be used without causing unacceptable pavement deterioration. One alternative such a study could consider would be to reduce the allowed maximum single and tandem axle loads to coincide with the adoption of the new formula.

CONCLUSIONS

The adoption of the proposed bridge formula would bring some changes to the geometry and distribution of truck loads on the axles and bogies. In many cases higher payloads would result without bringing excessively higher stresses to structural bridge members. If overall length limits or maximum gross weights should ever be increased, the formula would continue to be effective for protecting bridges against damaging overstresses, not necessarily a feature of the current formula.

The proposed formula is independent of the number of included axles and as such should be simpler to understand and easier to enforce than is the present formula.

The proposed formula is based on engineering rationale, although several controversial assumptions are used.

If the proposed bridge formula is not enforced, irrespective of what form of the formula is being used, bridges are apt to have foreshortened service lives because of fatigue.

The indiscriminate issuing of overweight truck permits, especially those issued on a periodic or annual basis, is equally apt to result in foreshortened bridge service lives.

Adoption of the proposed bridge formula, without any change in the maximum single and tandem axle loads, will cause an increase in the average equivalent axle load per truck. This is often considered the primary measure of the fatigue damage a vehicle causes to pavement. So, although the proposed formula will satisfactorily protect the bridge structures, there is real concern about its effect on pavements, a consequence that should be carefully evaluated before any changes are made.

Publication of this paper sponsored by Committee on General Structures.