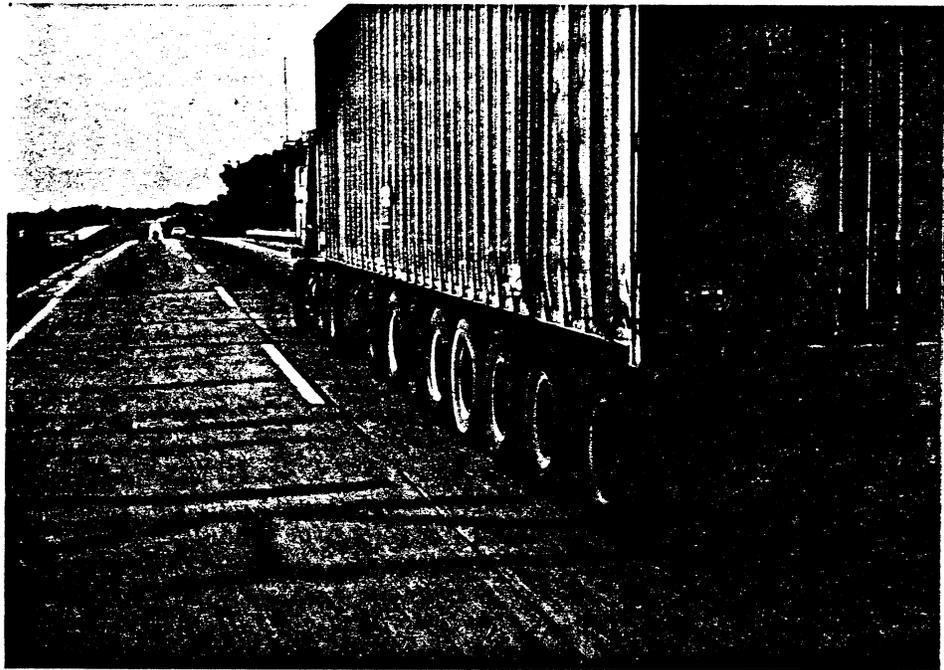"BRIDGE FORMULA DEVELOPMENT - EXECUTIVE
SUMMARY"   James S. Noel, Ray W. James,
Howard L. Furr and Francisco E. Bonilla

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BRIDGE FORMULA DEVELOPMENT

Executive Summary

June 1985

Final Report

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16. Abstract

The objective of this research was to review the existing bridge formula to find if modifications could be suggested to make it more rational. The intent was to more fully utilize 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 with 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 HS20 bridges will not be loaded to more than 1.05 times the design stress nor will H15 bridges be loaded to more than 1.30 times the design stress. The formula reduced 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 imposes on the pavement.

A detailed study of the effect the adoption of the proposed bridge formula would have on pavements is recommended. Such a study should consider costs, benefits, and potential formula modifications.

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INTRODUCTION

This report describes 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 as being basically unfair in terms of the stress levels generated in various bridge spans and types by different axle combinations. But the most compelling criticism concerns its applicability to very long, many axled vehicles, also being studied under the STAA of 1982, where 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 results primarily from the fact that they were originally designed to different strength levels. Two of the most common of these strength levels are termed H15 and HS20 by the AASHTO Bridge Specifications, where the HS20 is significantly stronger than the H15. This notation for strength levels actually refers to the hypothetical truck loading used for the bridge design. The HS20 design truck, which has a semitrailer, actually weighs more than twice the weight of the H15. About 95% of the bridges on the Interstate System are rated as HS20 or better. In general, none are classified as less than H15. The percentage of HS20 bridges on the primary and secondary highway systems, however, is significantly lower.

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HISTORICAL

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 allowing vehicles having 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 No. 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 has 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 partially based on results of AASHO Road Tests performed in the late 1950's. 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 under Table B flatly prohibited the operation of certain short wheelbase, multiaxle trucks over H15 bridges. The point was clearly made in the Document that such vehicles would overstress the H15 bridges by more than 30%, a situation the authors of the Document clearly viewed as intolerable.

Little happened in response to these recommendations, however, until 1975, at which time the U.S. Congress enacted legislation directing 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

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tandem axle weights increased as recomended in the Document. Further, the allowable gross vehicle weight was increased to 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 due to the imposition of the 55 mph (88.50 km/hr) speed limit in December, 1973.

The most recent legislation is referred to as the Surface Transportation Assistance Act of 1982. The Vehicle Weight Limitations section of the Act is reproduced verbatim below.

VEHICLE WEIGHT, LENGTH, AND WIDTH LIMITATIONS

Sec. 133. (a) Section 127 of title 23 of the United States Code is amended to read:

127. 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:

$$W = 500 \left(\frac{LN}{N-1} + 12N + 36 \right)$$

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 States 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

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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."

Equation 1 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, except for the relaxation on the
maximum weight of tandems spaced 36 ft (10.97 m) or more.

FORMULA DEVELOPMENT

An important first step in deriving a bridge formula to assure specified stress ratios are not exceeded in any H15 or HS20 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 was collected from the files of the Federal Highway Administration and from standard designs of state highway departments to find these minimum weight bridge types. Once these lightest weight bridges were found, it was then possible to define the loads that would cause specific stress levels in each span length. This procedure was followed for bridges of both H15 and HS20 design.

For example, uniformly distributed loads of every length between 8 and 120 ft (36.58 m) were placed on the lightest weight bridges of every span to evaluate what total load would cause 1.3 times the design stress in H15 bridges and 1.05 times the design stress in HS20 bridges. This multitude of calculations was expeditiously completed with a micro-computer 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 H15 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 HS20 bridges with the 1.05 factor controlled.

Two straight lines were drawn near these results and yielded the formula as shown in figure 1. These two straight lines are shown superimposed over a plot of Table B as modified by the Surface Transportation Assistance Act of 1982. The equations of the two lines are

$$W = (34 + L) \, 1000 \, \text{lb} \qquad 8 \, \text{ft} \leq L \leq 56 \, \text{ft}$$
$$W = (62 + L/2) \, 1000 \, \text{lb} \qquad 56 \, \text{ft} \leq L$$

Figure 1 shows that the suggested formula would reduce the loads allowed on the shorter axle groupings just as was originally recommended by the footnote of Table B in House Document No. 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
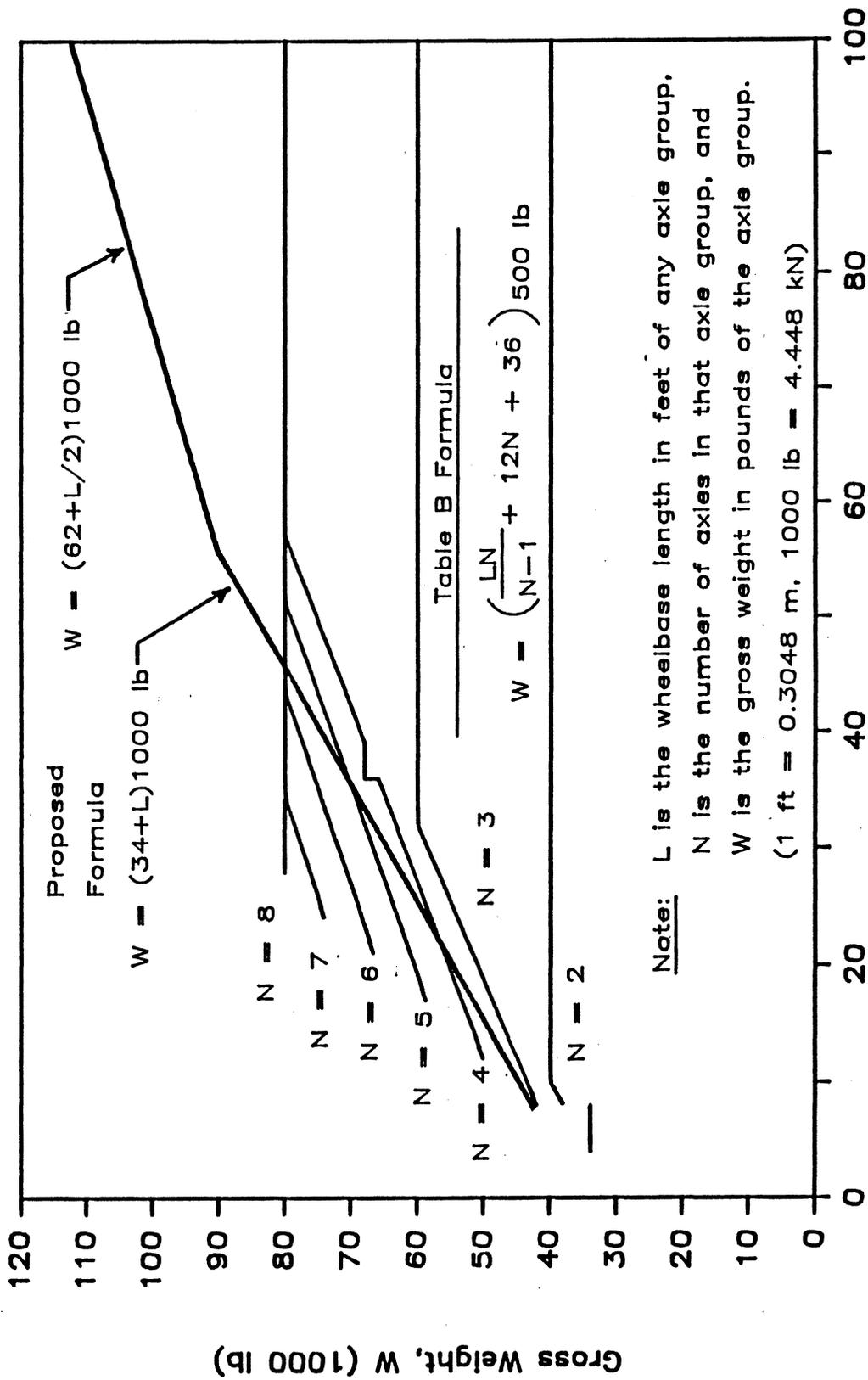
Proposed Formula

$$W = (62 + L/2)1000 \text{ lb}$$

$$W = (34 + L)1000 \text{ lb}$$

Table B Formula

$$W = \left(\frac{LN}{N-1} + 12N + 36\right)500 \text{ lb}$$

Note: L is the wheelbase length in feet of any axle group.
N is the number of axles in that axle group, and
W is the gross weight in pounds of the axle group.
(1 ft = 0.3048 m, 1000 lb = 4.448 kN)

Figure 1. Proposed Formula Shown Superimposed on the Current Table B Formula

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axles, the wheelbase L is the extreme axle spacing in that subset.

Additionally, 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. While a rigorous economic study of the costs of pavement damage compared to 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 to pavements would result.

ASSUMPTIONS

The assumptions used to make the calculations described above 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 concerning the validity of each of these assumptions, but it is doubtful that the resolution of any one of them 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 HS20 bridges and 1.30 for H15 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 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) more than a specified precentage, 30% in the case of H15 bridges and 5% in the case of HS20 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 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 on the fatigue lives of highway bridges, it is ncessary 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. Since 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.

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The calculated stress ranges are compared to 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 which 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

Recognizing 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 of bridges, no change should be made in the bridge formula without considering the consequences of the change to the pavements. The analytical assessment of the impact of such a change on pavement life is not so straightforward as it is for bridges. It is generally accepted that heavy axles, and very short groupings of axles, are more damaging to pavements while gross vehicle weights, or the 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 as 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 1950's where 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 resulting 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 closely spaced tandem axles (groups of two axles) are also tabulated. This makes it possible to calculate the number of equivalent axle loads generated by most of the heavy truck configurations currently in use.

These calculations were made for trucks conforming to the current bridge formula and for trucks conforming to the proposed bridge formula and the results compared. These comparisons for two common truck configurations are shown in figures 2(a) and (b). Figure 2(a) is for the 3S-2, a semi-trailer truck with a steering axle and two tandems (commonly referred to as the eighteen wheeler). Figure 2(b) is for the 2S-1-2, a semitrailer truck with a full trailer on two axles; so it has a steering axle with four widely spaced single axles.

For very short and very long vehicles, figure 2 shows the equivalent axle loads per truck to be about the same. In fact, 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 very common, and the increase in equivalent axle loads would certainly have a detrimental effect on the wearout rate of our pavements.

The calculations and comparisons of the equivalent axle loads per truck, as shown above, 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 shave some weight from the maximum single- and tandem-axle loads to coincide with the adoption of the new formula.
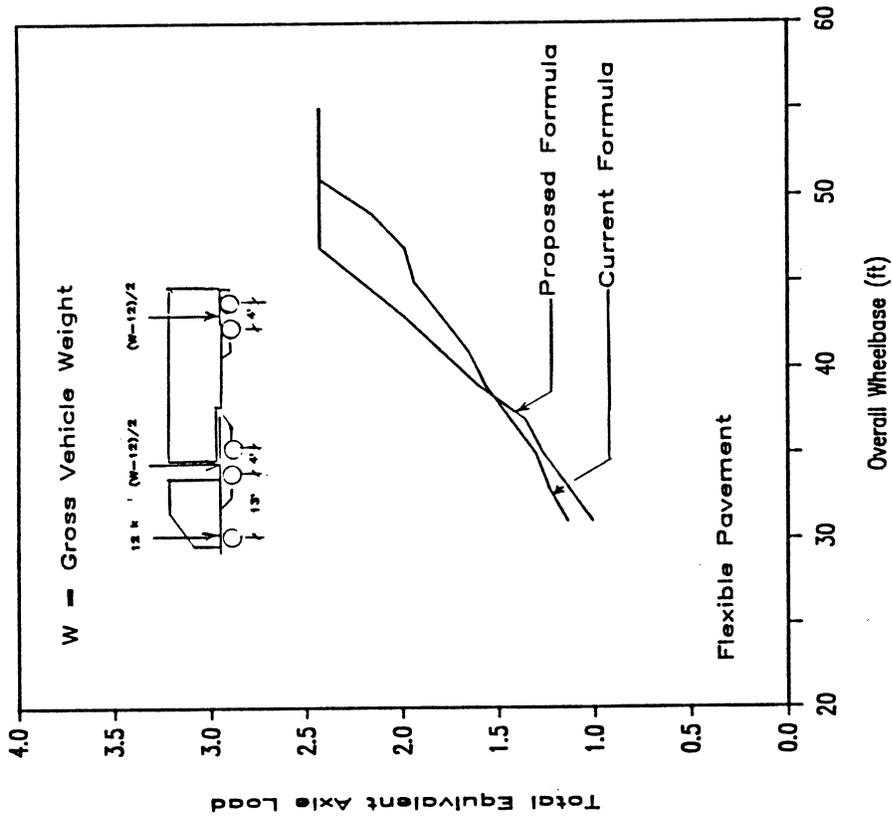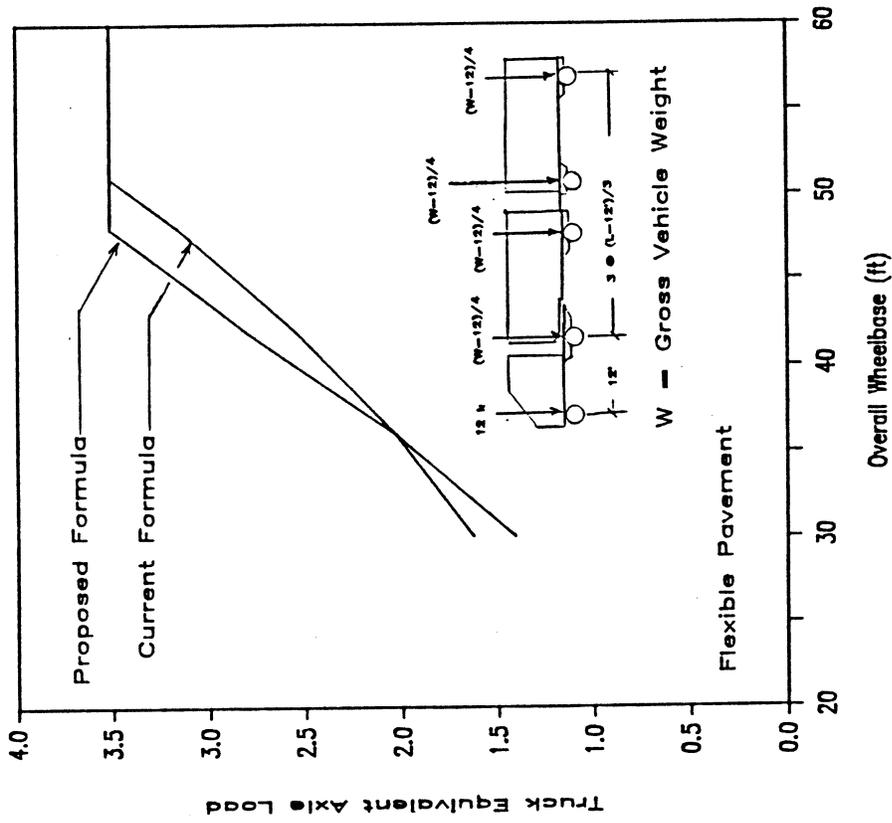
(b) 2S1-2 Vehicle

(a) 3S2 Vehicle

Figure 2. Equivalent Axle Loads per Vehicle for Proposed
Formula and Existing Formula

(1 ft = 0.3048 m)

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CONCLUSIONS

The adoption of the proposed bridge formula would bring some changes to the geometry and distribution of truck loads to 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 the 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 the present formula.

The proposed formula is based on engineering rationale, albeit several controversial assumptions.

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

The indiscriminate issuing of overweight truck permits, especially those on a periodic or annual basis, are 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, while 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.