EVALUATION OF A NEW BRIDGE FORMULA FOR REGULATION OF TRUCK WEIGHTS

A Thesis

by

YATEESH JAYKISHAN CONTRACTOR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Ray James
Committee Members,	Harry Jones
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ABSTRACT

Evaluation of a New Bridge Formula
for Regulation of Truck Weights. (August 2005)
Yateesh Jaykishan Contractor, B.E., University of Mumbai
Chair of Advisory Committee: Dr. Ray James

The current bridge formula, Federal Bridge Formula B (BFB), established in 1974 to protect bridges against excessive overstress, is very restrictive on long combination vehicles due to an 80,000 lb gross vehicle weight limit. Without this limit the formula will not be able to protect bridges in the cases of longer trucks. A formula developed by the Texas Transportation Institute (T.T.I.) called the TTI-HS20 Formula addresses these issues. This formula, developed especially for bridges designed for the HS-20 truck, eliminates the need for the 80,000 lb limit.

A generic formula developed to protect H15 and HS-20 bridges (James et al., 1986) was evaluated in a previous study (James and Zhang, 1991). The approach to evaluating the TTI-HS20 Formula follows the approach outlined in James and Zhang, 1991. Information was collected on two important elements: a set of test bridges representative of the lightest continuous bridges, and a set of test truck configurations representative of real truck traffic with a focus on long combination vehicles.

Critical weights of the selected trucks for the representative bridges are calculated and plotted against the TTI-HS 20 formula and other proposed formulas. A final recommendation as to whether this formula should be adopted nationwide is made.

ACKNOWLEDGEMENTS

I greatly appreciate the financial support by Federal Highway Administration (FHWA) through Battelle. In addition, I would like to thank Dr. Edward Fekpe of Battelle and James Saklas of the FHWA.

My sincerest thanks to Dr. Ray James for his support and guidance throughout the duration of this project and for the time and effort he has put in towards the completion of my thesis.

The results published herein do not constitute standards, specifications, or regulations. The results, findings, and conclusion do not necessarily reflect the views of the FHWA.

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INTRODUCTION

The Federal Highway Administration (FHWA) developed a formula in 1975 to regulate truck size and weight intended to protect bridges from excessive overstress. This formula is called as the Federal Bridge Formula B:

$$W = 500\left(\frac{N}{N-1}L + 12N + 36\right) \leq 80,000\ lb \tag{1}$$

Where:

W - Maximum allowable weight in pounds that can be carried by a group of two or more axles to the nearest 500 pounds.

N - Number of axles being considered

L - Distance in feet between the outer axles of any two or more consecutive axles.

Additionally, Federal single axle weight limit on the Interstate system is 20,000 lb and Federal tandem axle weight limit on the Interstate system is 34,000 lb. As pointed out by James et al. 1986, this formula is inadequate in certain aspects:

1 The relation between the allowable weight and the number of axles is sometimes contrary to dependence of stresses on the number of axles.

2 There exists an arbitrary 80,000 lb gross vehicle weight limit (Western Highway Institute).

3 The current formula allows trucks with many axles more weight therefore overloading some bridges (Kurt 2000). It is overly restrictive for shorter trucks and overly permissive for short six-axle trucks. (Comprehensive Truck Size and Weight Study 1995).

4 Bridges on the interstate highway can carry more weight than allowed by Bridge Formula B without being significantly overstressed. (Comprehensive Truck Size and Weight Study 1995).

This thesis follows the style of *ASCE Journal of Bridge Engineering.*

These inadequacies in the Federal Bridge Formula motivated a study to propose a new bridge formula. A new bridge formula, which has come to be known as the TTI-HS 20 Formula was proposed in a FHWA funded study in 1985. The TTI-HS20 formula offers several advantages; firstly the formula is fairly simple as the allowable weight for an axle group depends only on one variable, the outer axle spacing of that axle group. The new formula is less restrictive on shorter trucks than the current Bridge Formula B but for longer trucks it is more restrictive than Bridge Formula B if the 80,000 lb limit is not considered. The arbitrary 80,000 lb gross vehicle weight limit is removed which allows more economical operation of heavier trucks. The TTI-HS20 Formula is:

$$\begin{aligned} W &= 1000(L+34) & L &\le 8\ ft \\ W &= 1000(2L+26) & 8\ ft &< L \le 24\ ft \\ W &= 1000\left(\frac{L}{2}+62\right) & L &> 24\ ft \end{aligned} \tag{2}$$

Where:

W and L are as defined before.

Single and tandem axle weight limits of 20,000 lb and 34,000 lb, respectively, are retained, but the gross vehicle weight limit of 80,000 lb is removed. Both, the Bridge Formula B and the TTI-HS20 Formula are applicable to any consecutive subset axle group. Also, like the Bridge Formula B the stated basis for the proposed formula is that the actual stresses for HS 20 bridges must not exceed the design stresses by more than 5%.

Other formulas have also been developed to regulate truck weights, Kurt 2000, Ghosn 2000, TRB 1990, but none have attracted as much interest as the TTI-HS20 Formula. The TTI-HS20 Formula is recommended by agencies like the American Road and Transportation Builders Association (ARTBA). It has also been reviewed and recommended in NCHRP Special Report 225 (NCHRP 1990).

In 2003 Texas Transportation Institute (T.T.I.) was subcontracted a work order by a science and technology enterprise, Battelle. The work order, *Development of a New Bridge Protection System* was a sub-part of Battelle Work Order Number BAT 03-026 titled “A new Bridge Formula” funded by the FHWA. This thesis is based largely on the work performed as a part of that project.

Objective

The objective of the study is to evaluate the TTI-HS20 Formula. Sample representative bridges will be loaded under different practical trucks and analyzed. Critical weights causing the specified overstress in the bridge will be calculated. These will be compared with the allowable weights according to TTI-HS20 Formula to check the effectiveness of the formula.

Literature Review

In June 1985 a FHWA funded study conducted by the Texas Transportation Institute resulted in a proposal to replace the existing Bridge Formula B with a new formula designed to protect inventories of bridges consisting of a mix of HS20 and H15 design load bridges (Noel et al. 1985). Subsequently a paper (James et al. 1986) based on an extension of this study proposed a second formula designed to protect inventories of HS20 bridges. The second formula has come to be called the TTI-HS20 formula. Both proposed formulas limit the maximum allowable gross weight on an axle string as a function of the extreme axle spacing, while the existing Bridge Formula B limit depends on the number of axles in the string as well as the extreme axle spacing.

The 1985 study and resulting proposals were motivated by the fact that the existing Bridge Formula B does not allow the economic operation of longer combination vehicles because of an apparently arbitrary 80,000 lb limit imposed which limits the application of the formula to longer vehicles. Both proposed formulas were designed to protect the bridges in the absence of such a limit.

After a continued evaluation of the newly proposed formula (applicable to H15 and HS20 Bridges) in an unfunded study, another paper was published (James and Zhang 1991). As the original formula was developed for simple spans, in the continued study it was checked for its effectiveness on continuous-span bridges. Critical weights of various vehicle configurations are calculated for several representative two-and three-span bridge designs. It was concluded that the proposed formula allows removal or raising the existing arbitrary 80,000 lb gross vehicle weight limit while protecting bridges from excessive level of stress. This study was limited to an analysis of only four continuous bridges and it remained to be determined if the proposed formula would results significantly different loading on longer bridges. Yet, the findings were encouraging for additional study.

In recent years many old H15 bridges have been replaced by HS20 bridges as a result of which HS20 bridges are becoming the most common type of bridges. HS 20 bridges dominate the Interstate system (Luskin and Walton 2001). In the previous study the bridges were checked for fatigue. But fatigue depends on individual and tandem axle weight, and since these limits are not being changed the fatigue costs to the bridge have minor relevance (Luskin and Walton 2001). Bridges designed by the Load Factor Design Method are less conservative and therefore more critical than bridges designed by the Service Load Design Method (Noel et al. 1985). Longer bridges experience higher negative bending moments due to long combination vehicles, these need to be given special attention.

In 1990 a blue-ribbon panel reported an extensive comparison of many proposals for replacement of the Bridge Formula B (TRB 1990). Along with other recommendations, this panel recommended adoption of the TTI-HS20 formula as the basis for a new national truck weight regulation, and estimated the annual savings to the nation in improved transportation efficiency and reduced bridge costs; truck costs would decrease by 2.4 billion dollars a year.

Several other formulas have been suggested to replace the current Bridge Formula B. Some of these are listed next:

1. Using a Reliability Model a formula was proposed to regulate truck weights (Ghosn 2000). This study suggests the following formula in S.I. Units:

$$W = (5.38B + 30)4448 \quad for\ B < 15m$$
$$W = (2.62B + 72)4448 \quad for\ B > 15m \tag{3}$$

Where:

W - Total weight of truck or axle group in newtons (N)

B - Length of the truck or axle group in meters (m)

In English Units this formula can be written as

$$W = 1000(1.64L + 30) \quad for\ L < 50\ ft$$
$$W = 1000(0.8L + 72) \quad for\ L > 50\ ft \tag{4}$$

Where:

W - Total weight of truck or axle group in pounds (lb)

L - Length of the truck or axle group in feet (ft)

2. A proposed modification of the Bridge Gross Weight Formula was suggested in Kurt 2000. This formula like Bridge Formula B depends on the number of axles and length between axles. Uniqueness of this formula is that it contains a constant which is based on the number of bridges for the entire system one decides to overload. Figure 1 shows the graph which helps in the determination of this constant.

$$W = 1000\left(0.5\frac{LN}{N-1} + 3N + C_4\right) \tag{5}$$

Where:

L - Length in feet

N - Number of Axles

C_4 - Constant for Overloading

W - Gross Weight in pounds

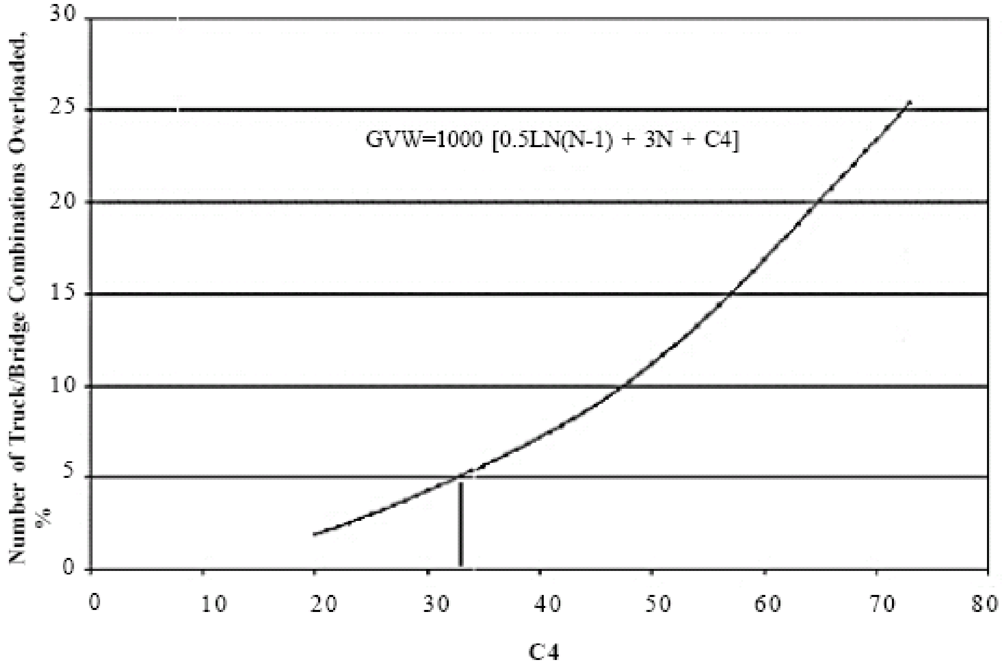

Figure 1. Number of Overloaded Bridges as a Function of C_4 (Kurt 2000)

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3. Combined TTI HS-20/ Formula B - This formula is suggested in TRB Special Report 225 (1990). In this new formula, TTI-HS20 limits would be combined with those of Formula B and the 80,000 lb limit would be eliminated. Single unit trucks and shorter combination vehicles would be allowed to operate under the TTI-HS20 Formula and longer LCVs with seven, eight and nine axles would be allowed to operate at higher weights from Formula B. Federal Axle Limits and grandfather clause exemptions would remain in place.
4. TRB 1990 - A new approach for regulating truck weights was developed by the Transportation Research Board. The maximum weight (in pounds) on a group of two or more consecutive axles should not exceed the following:

$$W = 1000(2L + 26) \qquad for\ L \le 24\ ft$$
$$W = 1000\left(\frac{L}{2} + 62\right) \qquad for\ 24 < L \le 40\ ft \qquad (6)$$
$$W = 1000\left(\frac{9L}{16} + 72\right) \qquad for\ L > 40\ ft$$

(TRB 1990)

- For vehicles with gross weights of 80,000 lb or less, maximum axle weights should be: Single Axle = 20,000 lb and Tandem Axle = 34,000 lb.
- For vehicles with gross weights over 80,000 lb maximum axle weights should be: Single Axle = 15,000 lb and Tandem Axle = 34,000 lb

Assumptions and Simplifications

For the purposes of the present study, the following assumptions are made to simplify and limit the scope of the study

1. Fatigue will not be considered in this study.
2. HS20 bridges and HS20-modified bridges will be tested.
3. Mostly longer bridges designed by load factor design will be analyzed.
4. Because of their smaller dead load effect continuous steel bridges are the most critical bridge type.
5. Only steel beam failure considered; no slab failure.
6. Failure of the beam in flexure governs over shear failure.
7. As the formula was developed considering 5% overstress, this criterion will be used for evaluating the formula. Effectiveness of the formula in case of 10% overstress is also evaluated

METHODOLOGY

The basic methodology is to find the total gross vehicle weight for each truck type which will cause a specified overstress in the interior girder of a bridge. This gross weight will be compared with the limiting value specified by TTI-HS20 Formula for that particular truck type. If the calculated gross weight is greater than or equal to the value specified by the TTI-HS20 formula then the formula is effective in restricting the stresses to within the permissible limits.

For evaluation of the formula, data was collected on two important elements:

1. Bridges - This includes identification of a set of test bridges representative of the lightest (least significant dead load effect) continuous bridges. Battelle has worked with FHWA and several state Department of Transportation agencies to obtain detailed information on bridge inventories and to identify several representative bridges suitable for use. Table 1 highlights the most important bridge properties. Bridge specifications have been listed in detail later in the chapter.

For the first five bridges the design load is the AASHTO HS-20 Truck. This truck is shown in Figure 2. The HS20+Mod Design Truck is the same as HS20 Design Truck modified by a factor 0f 1.25.

Table 1. Selected Bridge Specifications

	Spans	Max. Span (ft)	Design Load	Design Method	Flange Yield Stress (psi)	Girder Profile
Bridge 1	3	280	HS20	SLD	40,000	Parabolic
Bridge 2	2	50	HS20	LFD	50,000	Uniform
Bridge 3	2	75	HS20	LFD	50,000	Uniform
Bridge 4	2	100	HS20	LFD	50,000	Uniform
Bridge 5	4	70	HS20	LFD	36,000	Parabolic
Bridge 6	3	73	HS20+Mod	LFD	36,000	Parabolic
Bridge 7	6	140	HS20+Mod	LFD	46,000*	Uniform
Bridge 8	3	60	HS20+Mod	LFD	36,000	Uniform
Bridge 9	6	135	HS20+Mod	LFD	36,000	Parabolic

* For Section 1 flange yield stress is 36,000 psi.

2. Vehicle configurations: A set of 10 test vehicle configurations wad identified for evaluation. Of these ten vehicle configurations, eight were suggested by Battelle, including two design trucks (a short HS20 and a long HS20) and six truck configurations representing actual configurations found on the nation’s highways. Two additional truck configurations (short three axle and four axle trucks) were added to check the effectiveness of proposed formulas for shorter trucks. Figure 2 shows the ten studied vehicles. Axle loads specified are in kips and tandem axle spacing is 4ft for all trucks in Figure 2.

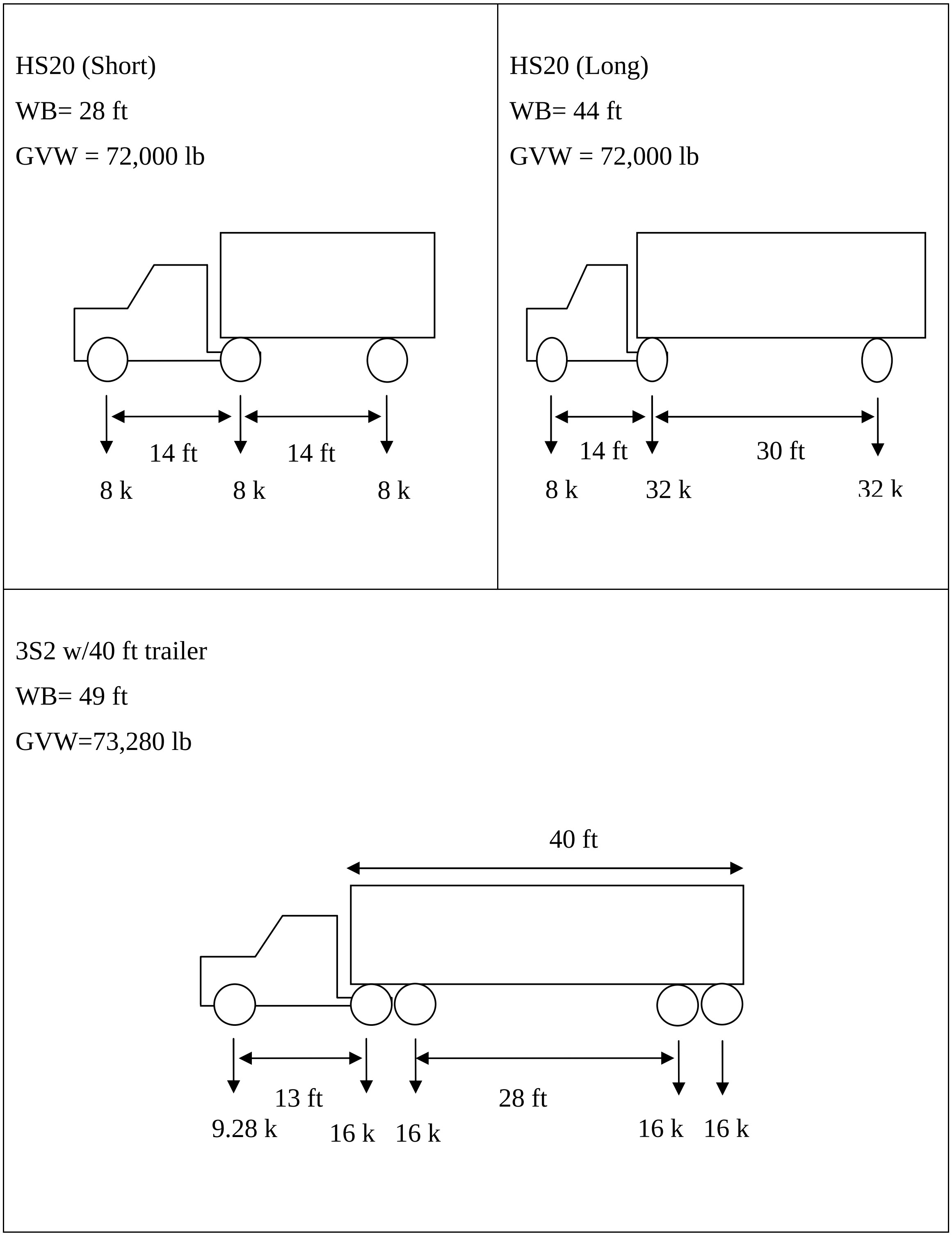


Figure 2. Selected Truck Specifications

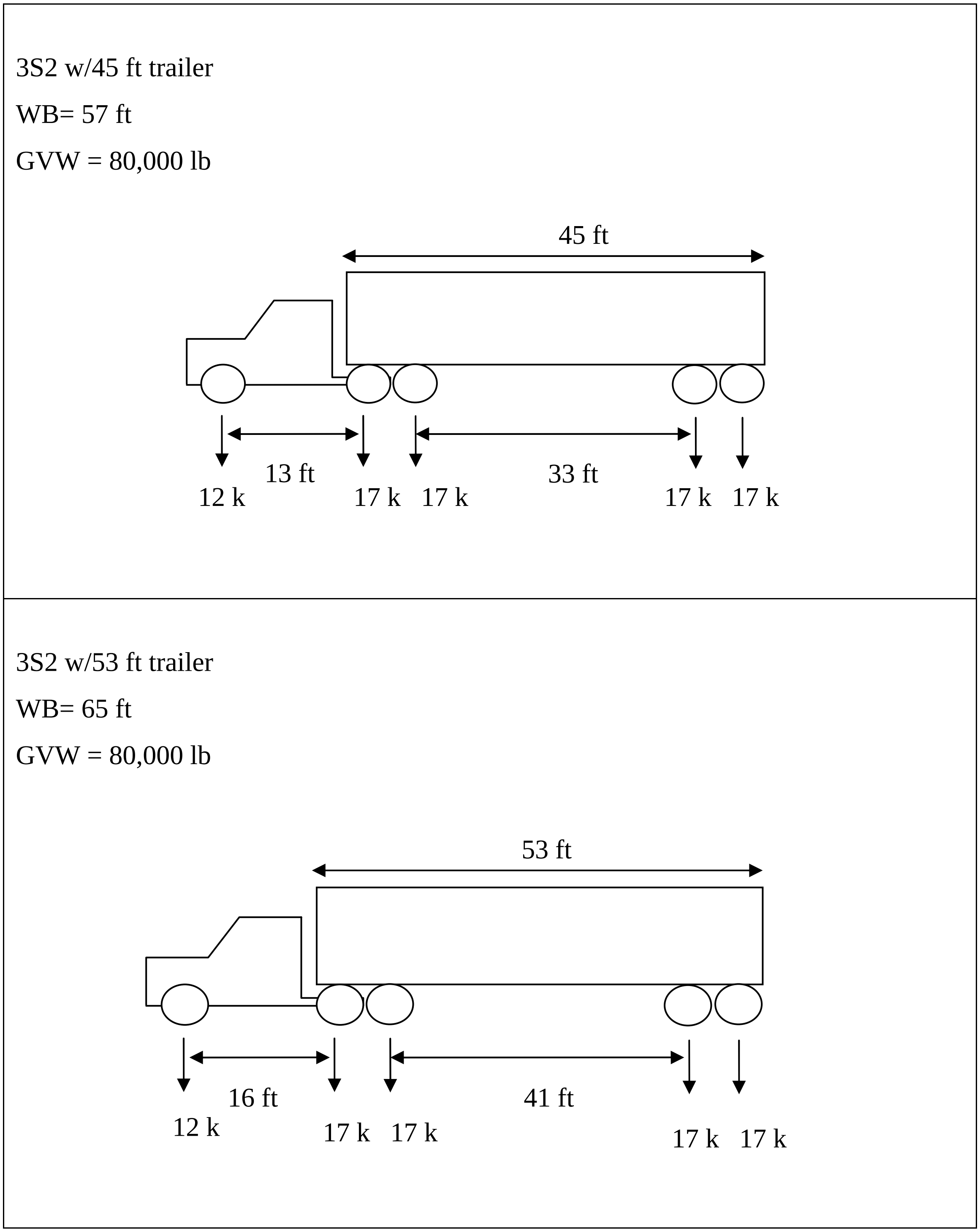
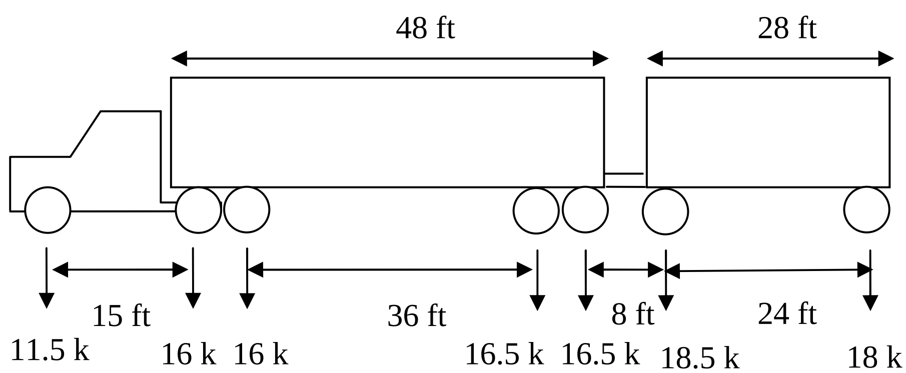


Figure 2. Continued

3S2-2 Rocky Mountain Double

WB = 91 ft

GVW = 113,000 lb



3S2-4 Turnpike Double

WB= 112 ft

GVW = 128,000 lb

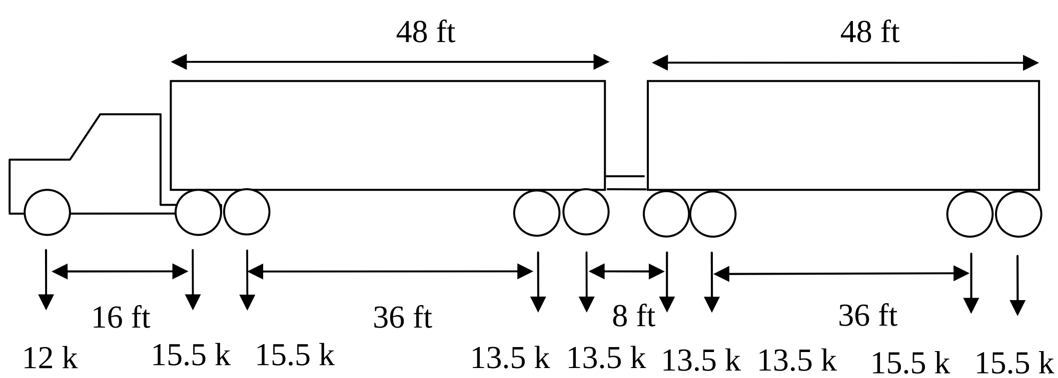


Figure 2. Continued

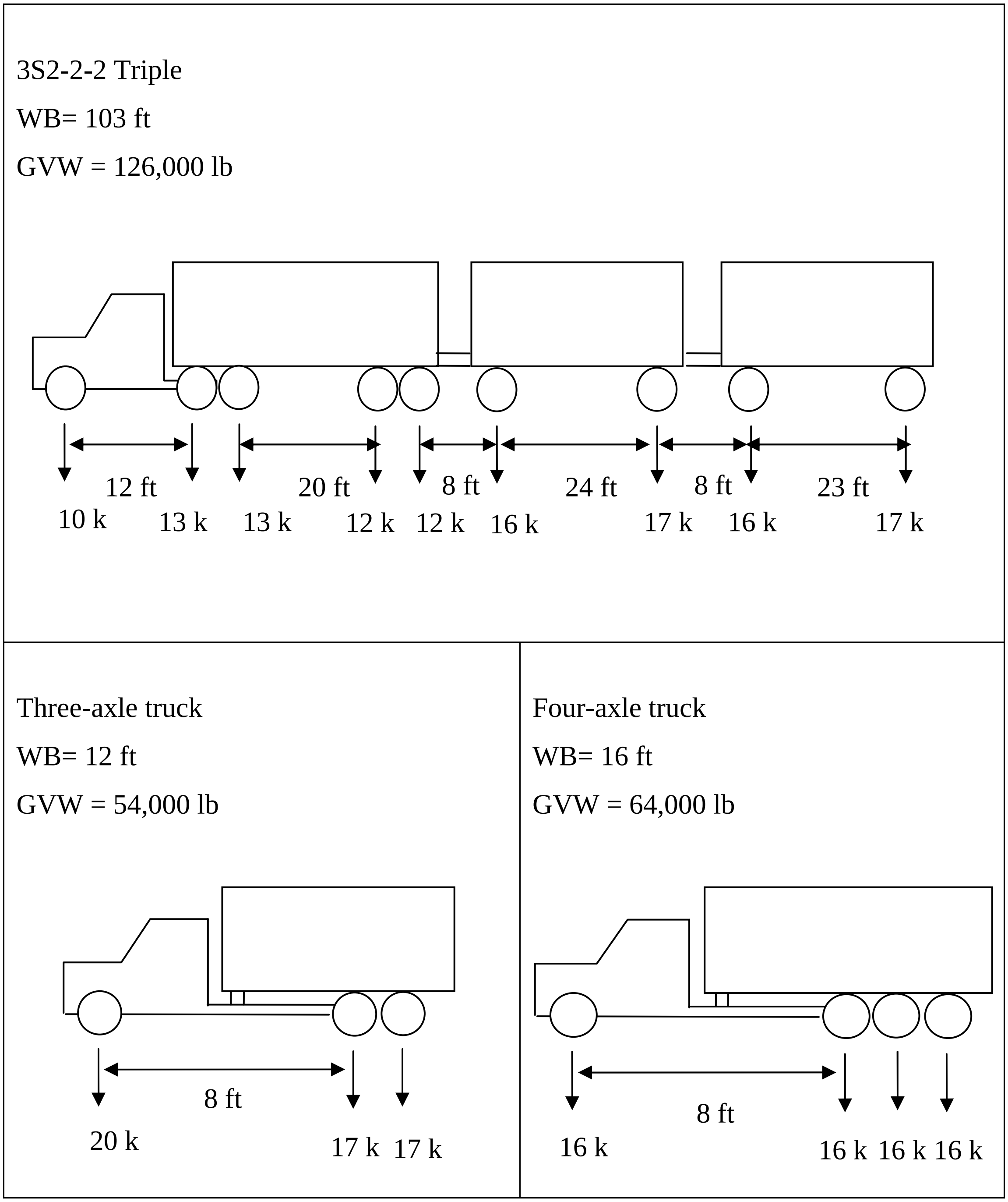


Figure 2. Continued

General Procedure

BMCOL51 version 09.13.89, a Texas Transportation Institute developed software is used in this study. It is a computer program to analyze beam-columns under moving loads. This software is used to calculate the moments for dead loads and envelope for maximum bending moment for live loads.

The data was input into BMCOL51 in three steps:

1. Weight of the steel beam and concrete slab acting only on the steel beam, Dead Load 1 (DL1).
2. Weight of the wearing course and the barrier weight acting on the partially composite section, Dead Load 2 (DL2).
3. Effective live load acting on the composite section, Live Load (LL).

Load Step 1

Number of Increments and Increment Length - The maximum number of increments permissible in BMCOL51 is 500. It is preferable to give the increment length as 12 in. so that the number of increments can be entered as the length of the bridge in feet. Due to the limit on the number of increments as 500 if the bridge length is greater than 500 ft the increment length is increased so that the total number of increments is reduced below or equal to 500.

Support Geometry - In this step location of the supports is entered into the program. The support distance from the extreme left of the bridge is entered. The support location is scaled depending upon the increment length. Also, there is an option of giving the initial deflection and slope at the supports which is in given a default value of zero for all bridges.

Stiffness and Fixed Load Data - In the first load step it is assumed concrete has not hardened and hence the concrete slab does not carry its own weight. The steel girder carries the weight of the tributary area of the concrete slab, which is usually half the center to center distance of girders on each side. If the cross-section of the girder is not constant and changes along the length of the girder the moment of inertia of the steel girder is calculated, at each different cross-section. To get bending stiffness of the cross-section, moment of inertia is multiplied by modulus of elasticity of steel, which is 29,000 ksi for all bridges considered in this study,

$$\begin{aligned} Weight\ of\ \ concrete\ slab\ (lb/\ ft) = Depth\ of\ \ Slab(\ ft) * C/C\ Distance\ between \\ Girders(\ ft) * Density\ of\ \ Concrete(lb/\ ft^3) \end{aligned} \tag{7}$$

The weight of the steel beam alone is calculated by multiplying the area of the steel cross section by the density of steel. This calculation is repeated for each different cross-sectional area. The sum of the weight of the concrete slab and weight of the steel beam gives the total weight acting on the steel girder. The total load needs to be entered in terms of pounds per increment into the Computer Program.

For girders having parabolic depth profile the bending stiffness and the total weight is simplified as varying linearly. This simplification is based on initial tests which showed that the simplification does not cause a significant difference in results.

The values of the bending stiffness and dead load 1 are entered into the Computer Program, BMCOL51 which produces the moments produced by Dead Load 1. These moments are entered into a Microsoft Excel spreadsheet to calculate the critical weight for the particular truck type. The contents of the spreadsheet are discussed later in this chapter.

Load Step 2

In this stage it is assumed that the concrete is cured partially and helps to resist a part of the dead load acting on the girder. The data input in the computer program, BMCOL51 for this load case is:

Number of Increments and Increment Length - The number of increments, increment length and the support geometry remains the same as in the previous case.

Stiffness and Fixed Load Data - To find the area of the slab which helps in resisting the loads acting on the girder, the effective width of the slab needs to be calculated. The Effective width of slab (b_{eff}) is calculated according to AASHTO 10.38.3.1 (1996).

Effective width shall not exceed the following

1. One-fourth of the span length of the girder.
2. The distance center to center of girders.
3. Twelve times the least thickness of the slab.

Next the modular ratio, *n* is calculated. The modular ratio helps transform width of concrete slab to effective steel section width. The modular ratio is the ratio of the modulus of elasticity of steel to the modulus of elasticity of concrete.

$$n = \frac{E_{steel}}{E_{concrete}} \tag{8}$$

To transform the width of the concrete slab to an equivalent steel section, the effective width is divided by three times the modular ratio. This is done to take into account that concrete is not completely cured and has not achieved its entire strength.

$$Transformed\ Width\ of\ slab = \frac{b_{eff}}{3n} \tag{9}$$

Composite action only occurs in the regions where the top flange of the steel girder is in compression. The regions in which there is no composite action the moment of inertia remains the same for all load steps. The moment of inertia for each section along the entire length of the bridges is multiplied by the modulus of elasticity to get the stiffness of the girder for load step 2.

Dead Load 2 includes weight of wearing course and barrier weight. It is a standard practice to assume that the weight of the wearing course and the barrier weight are equally distributed on all the girders. Again, dead load 2 needs to be scaled depending upon the increment length.

These values are input in BMCOL51 which produces the Moments caused by Dead Load 2. These moments are transferred to the previously created Microsoft Excel File where further analysis is performed.

Load Step 3

In this stage concrete has attained its full strength, and in regions where the top flange is in compression the slab helps in resisting the live load. The transformed section is calculated by dividing effective width of the slab by the modular ratio.

$$Transformed\ Width\ of\ slab = \frac{b_{eff}}{n} \tag{10}$$

Data Input for Computer Program, BMCOL51:

1. Number of increments and increment length which pertain to the bridge remain the same as previously specified. But the length of the live load needs to be specified. The length of the truck needs to be entered in terms of the number of increments. Also, number of increments between each position of movable load needs to be entered. A default value of one increment is always entered; the program modifies this value automatically.
2. Stiffness and Fixed Load Data - The moment of inertia of the transformed beam is calculated by taking into account the new transformed width of slab. This modified, larger moment of inertia is again applicable only in the regions where the top flange is in compression, along the rest of the girder the moment of inertia remains the same for all load steps. The value of the fixed load is zero for this load step as in this step only the live load is applied.
3. Movable Load Data – In order to calculate the effective live loads first the Live Load Distribution Factor (DF) and the Impact Factor (I) need to be calculated.

The Distribution Factor is calculated in one of the three ways:

1. Lever Arm Method
2. AASHTO Formula
3. Given in bridge data

To calculate the Impact Factor, (I) Equation (3-1) from 3.8.2.1 AASHTO, Standard Specification for Highway Bridges (1996) is utilized.

$$I = \frac{50\,ft}{L + 125\,ft} \leq 0.3 \tag{11}$$

Where:

L - Length in feet of the loaded portion of influence line. As a conservative simplification, length L for the shortest span in the bridge is used for calculations of the impact factor.

Now, taking into account the live load distribution factor and impact factor the effective live load for each axle load acting on the bridge is calculated:

$$Effective\ Live\ Load = Axle\ Load * DF * (1 + I) \tag{12}$$

The values of the effective live load and the axle spacing are entered into the Computer Program, BMCOL51. The program produces the envelopes for maximum positive and negative moments. These values are transferred to the same Microsoft Excel file for further analysis.

The spreadsheet helps in the calculation of the gross weight which will cause a total stress of allowable stress times specified overstress ratio for a particular truck type. The calculation of critical weight requires the calculation of stress caused by Dead Load 1, Dead Load 2, and Nominal Live Load.

Since service stresses are being checked which are expected to be less than the yield stress of the steel beam - Linear elastic beam behavior is assumed. The bending stresses in the beam are calculated using classical flexural equation

$$\sigma = \frac{M\overline{y}}{I} \tag{13}$$

Where:

σ - Bending stress at top and bottom of steel

M - Bending moment

I - Moment of inertia of the section

$\overline{y}$ - Distance of top and bottom of steel from the neutral axis

For a transformed composite section bending stress can be simplified to,

$$\sigma = \frac{M}{S} \tag{14}$$

Where:

σ - Bending stress at top or bottom of steel

M - Bending moment

S - Section modulus of top or bottom of steel

To calculate these stresses the different section moduli are calculated for the above cases. But before the section moduli can be calculated the centroid of each section is calculated. The centroid for each load step will vary because certain sections along the length of the beam exhibit composite behavior; for these sections the centroid will change for each load step. For the sections which do not exhibit composite behavior the centroid remains the same throughout. Section modulus of the top and bottom of steel is calculated in the following manner:

Dead Load 1

$$S_{top} = \frac{I_{DL1}}{y_{top}} \tag{15}$$

$$S_{bot} = \frac{I_{DL1}}{y_{bot}} \tag{16}$$

Where:

S_{top} - Top section modulus for Dead Load 1

S_{bot} - Bottom section modulus for Dead Load 1

I_{DL1} - Moment of inertia for Dead Load 1

y_{top} - Distance from Centroid (for Dead Load 1) to top of steel

y_{bot} - Distance from Centroid (for Dead Load 1) to bottom of steel

Dead Load 2

$$S_{top} = \frac{I_{DL2}}{y_{top}} \tag{17}$$

$$S_{bot} = \frac{I_{DL2}}{y_{bot}} \tag{18}$$

where:

S_{top} - Top section modulus for Dead Load 2

S_{bot} - Bottom section modulus for Dead Load 2

I_{DL2} - Moment of inertia for Dead Load 2

y_{top} - Distance from centroid (for Dead Load 2) to top of steel

y_{bot} - Distance from centroid (for Dead Load 2) to bottom of steel

Live Load

$$S_{top} = \frac{I_{LL}}{y_{top}} \tag{19}$$

$$S_{bot} = \frac{I_{LL}}{y_{bot}} \tag{20}$$

Where:

S_{top} - Top section modulus Live Load

S_{bot} - Bottom section modulus for Live Load

I_{LL} - Moment of inertia for Live Load

y_{top} - Distance from centroid (for Live Load) to top of steel

y_{bot} - Distance from centroid (for Live Load) to bottom of steel

Two different design methods have been commonly used in the past, Working Stress Design (WSD) or Service Load Design (SLD) and Load Factor Design (LFD). Most bridges, till the recent past were designed by one of the two methods and hence a vast majority of the bridges in the nation are either SLD or LFD Bridges.

The bridges have been checked for AASHTO Load Combination 1 for both design methods, SLD and LFD. AASHTO Load Combination 1 consists of Dead Load + Live Load + Impact.

Service Load Design

For members designed by the service load design the available live load plus impact stress can be calculated on the basis that the total stress does not exceed a certain limit which is defined by the a specific overstress ratio times the allowable stress.

$$\sigma_{DL1} + \sigma_{DL2} + \sigma_{av} = \Omega * \sigma_{all} \tag{21}$$

$$\sigma_{av} = \Omega * \sigma_{all} - \sigma_{DL1} - \sigma_{DL2} \tag{22}$$

Where:

σ_{av} - Available live load plus impact stress

Ω - Overstress ratio

σ_{all} - Allowable stress

The following equations are used to calculate stresses for Dead Load 1, Dead Load 2, and Live Load, respectively. The stresses are calculated at top and bottom of steel section.

$$\sigma_{DL1} = \frac{M_{DL1}}{S_{DL1}} \quad (23)$$

$$\sigma_{DL2} = \frac{M_{DL2}}{S_{DL2}} \quad (24)$$

$$\sigma_{LL+I} = \frac{M_{LL+I}}{S_{LL}} \quad (25)$$

Where:

σ_{DL1} - Stress caused by Dead Load 1

σ_{DL2} - Stress caused by Dead Load 2

σ_{LL+I} - Stress caused by nominal 100,000 lb gross weight vehicle

M_{DL1} - Moment caused due to Dead Load 1

M_{DL2} - Moment caused due to Dead Load 2

M_{LL} - Moment caused due to Live Load

S_{DL1} - Section modulus for Dead Load 1

S_{DL2} - Section modulus for Dead Load 2

S_{LL} - Section modulus for Live Load

Load Factor Design

For load factor design the factored maximum design moment is

$$1.3\left(M_{DL} + \frac{5}{3}M_{LL+I}\right) = \Omega * M \quad (26)$$

$$1.3\left(M_{DL} + \frac{5}{3}M_{LL+I}\right) = \Omega * Fy * S_{LL} \quad (27)$$

Dividing throughout by Section Modulus for Live Load, S_{LL}.

$$1.3\left(\frac{M_{DL}}{S_{LL}} + \frac{5}{3}\frac{M_{LL+I}}{S_{LL}}\right) = \Omega * Fy \quad (28)$$

$$\sigma_{av} = \frac{3}{5}\left(\frac{\Omega * Fy}{1.3} - \frac{M_{DL}}{S_{LL}}\right) \tag{29}$$

Where:

σ_{av} - Available live load plus impact stress

Ω - Allowable overstress ratio

M - Factored maximum design moment

M_{DL} - Moment caused due to Dead Load 1 and Dead Load 2

M_{LL+I} - Design live load + impact moment

S_{LL} - Section modulus for Live Load

Fy - Flange yield stress of steel

M'_{LL+I} -Live load plus impact moment caused by the nominal weight truck

Stress caused by nominal 100,000 lb truck is,

$$\sigma_{LL+I} = \frac{M'_{LL+I}}{S_{LL}} \tag{30}$$

The critical weight is calculated by scaling weight of the nominal truck Wn (100,000 lb) by the ratio of available live load plus impact stress, σ_{av} and stress σ_{LL+I} caused by the nominal vehicle.

$$Wcr = Wn * \frac{\sigma_{av}}{\sigma_{LL+I}} \tag{31}$$

Where:

Wn - Nominal weight of truck (100,000 lb)

Wcr - Critical weight of truck (lb)

Summary

Stress due to dead load 1 is calculated at top and bottom of steel at every increment using the section moduli for load step 1. Similarly the stress due to dead load 2 is calculated using the section modulus for dead load 2. From the above two calculated stresses the available stress is calculated at the top and bottom of steel.

Next the stress due to the nominal truck is calculated at each increment. The weight of the nominal truck times the ratio of the available stress and the stress of the nominal truck gives the critical weight, which is the weight of the truck that causes a specified overstress in the bridge. At each increment at top and bottom of steel, truck weight is calculated which causes the specified overstress. The minimum of all weights is reported as the critical weight of the vehicle for the bridge.

Moment Redistribution

AASHTO 10.48.1.3 (1996) says that in the design of continuous beams of compact section negative moments over supports at Overload and Maximum Load determined by elastic analysis may be reduced by a maximum of 10%, also such reduction shall be accompanied by an increase in moments throughout adjacent spans statically equivalent and opposite in sign to the decrease of the negative moments at the adjacent supports. For example the increase in moment at the center of the span shall equal the average decrease of the moments at the two adjacent supports.

Usually for longer trucks the critical weight is governed by the stresses at the supports. It could be argued that redistribution of live loads should increase critical weights of some of the longer vehicles studied as moment redistribution involves reduction of moments at the supports and correspondingly increasing them at the mid-spans.

Procedure Verification

Before study of new bridges is commenced procedure for their analysis needs to be verified. To achieve this, results from the previous study, James and Zhang (1991) are reproduced. Two bridges are chosen, one to verify the service load design and the other to verify load factor design. Descriptions of the bridges chosen for this exercise are:

1. Two span, 70 - 70 ft, composite section for positive moment only, service load design, HS20 loading (United States Steel 1986).
2. Three span, 273 - 350 - 273 ft, welded plate girder, load factor design, HS20 loading. (*Four Design Examples*)

Example Bridge 1

This bridge is selected from Highway Structures Design Handbook (1986), United States Steel. This bridge has been designed using the Service Load Design Method; hence this bridge has been chosen for this exercise.

Geometry specifications

- Number of Spans - 2
- Span lengths: 70 ft - 70 ft
- Center to center spacing between girders - 8.33 ft
- Thickness of Slab - 7 in.

Material Properties

Steel

- Steel Density (γ_s)= 490 lb/ft^3
- Maximum Allowable Stress for Steel (tension and compression) = 20,000 psi

Allowable Tensile stress, $f_t = 20,000\ psi$. Allowable Compressive Stress, f_c from AASHTO Formula is calculated as 17,700 psi. But due to continuity, AASHTO Specifications permit 20% increase in allowable stress up to 20,000 psi at interior support. An increase of 20% above 17,700 psi gives a value of 21,200 psi, but this is greater than 20,000 psi, so $f_c = 20,000\ psi$ is used.

- Modulus of Elasticity for Steel = 2.9*10^7 psi

Concrete

- Concrete Density (γ_c) = 150 lb/ft^3
- Modular Ratio, n

$$n = \frac{Modulus\ of\ Elasticity\ of\ Steel}{Modulus\ of\ Elasticity\ of\ Concrete} = 8 \tag{32}$$

Load Step 1

Number of Increments and Increment Length

Number of Increments = 140

Increment Length = 12 in.

Support Geometry - Since the span lengths are 70 ft - 70 ft, Support locations are 0, 70, and 140.

Stiffness and Fixed Load Data - The center to center spacing of each beam is 8.33 ft, height of the slab is 7 inches; the density of concrete is 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ concrete\ slab\ (lb/ft) &= \frac{7\ in.}{12} * 8.33\, ft * 150 lb/ft^3 \\ &= 730\ lb/ft \end{aligned} \tag{33}$$

In the design example the weight of steel beam, haunches, diaphragms is assumed to be 170 lb/ft, the same value is adopted here. Summation of the above two weights gives a total weight of 900 lb/ft which is Dead Load 1 for the girder. Since the bridge is symmetrical, values of moment of inertia and bending stiffness of a single girder are shown only for one half of the bridge in Table 2. Note that for each section length girder depth remains uniform.

Table 2. Specifications for Example Bridge 1, Load Step 1

Location (ft)	Moment of Inertia (in^4)	Stiffness ($lb\text{-}in^2$)
0.0 - 13.5	7796	2.261E+11
13.5 - 46.0	8902	2.582E+11
46.0 - 52.5	10218	2.963E+11
52.5 - 64.0	10218	2.963E+11
64.0 - 70.0	14479	4.199E+11

Load Step 2

Stiffness and Fixed Load Data - Effective Width in the bridge data is given as 84 in., which turns out to be 12 times the thickness of the slab.

$$\begin{aligned} Transformed\ Width\ of\ slab &= \frac{84\ in.}{3*8} \\ &= 3.5\ in. \end{aligned} \tag{34}$$

Table 3 shows the moment of inertia and stiffness for the interior girder. Total Dead load 2 due to curbs and railings is 660 lb/ft. Since there are four girders the load per girder is,

$$\begin{aligned} Dead\ Load\ 2\ per\ Girder &= \frac{660\ lb/ft}{4} \\ &= 165\ lb/ft \end{aligned} \tag{35}$$

Load Step 3

Stiffness and Fixed Load Data - Variation of the moment of inertia, stiffness, and behavior, along the length of the bridge for a single girder are shown in Table 4.

$$\begin{aligned} Transformed\ Width\ of\ slab &= \frac{84\ in.}{8} \\ &= 10.5\ in. \end{aligned} \tag{36}$$

Table 3. Specifications for Example Bridge 1, Load Step 2

Location (ft)	Moment of Inertia (in^4)	Stiffness ($lb\text{-}in^2$)	Behavior
0.0 - 13.5	16018	4.645E+11	Composite
13.5 - 46.0	18557	5.382E+11	
46.0 - 52.5	18962	5.499E+11	
52.5 - 64.0	10218	2.963E+11	Non-Composite
64.0 - 70.0	14479	4.199E+11	

Table 4. Specifications for Example Bridge 1, Load Step 3

Location (ft)	Moment of Inertia (in^4)	Stiffness ($lb\text{-}in^2$)	Behavior
0.0 - 13.5	21912	6.354E+11	Composite
13.5 - 46.0	25867	7.501E+11	
46.0 - 52.5	25916	7.516E+11	
52.5 - 64.0	10218	2.963E+11	Non-Composite
64.0 - 70.0	14479	4.199E+11	

Movable Load Data - Live Load Distribution Factor (*DF*) is calculated in the Bridge Data using the AASHTO Formula.

$$DF = \frac{S}{5.5} = \frac{8.33}{5.51} = 1.51\ wheels = 0.755\ axles \quad (37)$$

To calculate the Impact Factor, (*I)* Equation (11) is utilized.

$$I = \frac{50}{70\,ft + 125} \tag{38}$$
$$= 0.256$$

Now the effective live load can be calculated by using Equation (12).

$$Effective\ Live\ Load = Axle\ Load * 0.755 * (1 + 0.256) \tag{39}$$

Four vehicles were tested to check if the critical weights match with the previous study. The chosen vehicles are 2S2 (34 ft), 2S2 (38 ft), 3S2-4 (98 ft), 3S2-4 (104 ft). These four trucks were chosen because the first two trucks, being short are expected to produce critical stresses at midspan and the last two trucks are expected to produce critical stresses at the interior support.

Axle load is scaled to make the total gross vehicle weight to 100,000 lb. The scaled axle load is multiplied by the Impact Factor and Distribution Factor to get the Effective Load for each Axle. Live Load Data for Bridge 1 is tabulated in the Appendix.

Next, the section moduli are calculated for each load step. These results are tabulated in Table 5. Note that the section modulus for ranges which do not exhibit composite behavior does not change.

Table 5. Section Modulus for Bridge 1

Location (ft)	Dead Load 1 (in^3)		Dead Load 2 (in^3)		Live Load (in^3)		Behavior
	Top of Steel	Bottom of Steel	Top of Steel	Bottom of Steel	Top of Steel	Bottom of Steel	
0.0 - 13.5	438.6	439	1790	599	7968	668	Composite
13.5 - 46.0	460	536	1781	727	6789	805	
46.0 - 52.5	536	536	1852	728	6399	804	
52.5 - 64.0	536	536	536	536	536	536	Non-Composite
64.0 - 70.0	771	771	771	771	771	771	

After the stress due to Dead Load 1 and Dead Load 2 have been calculated using equations (23), (24) the available stress is calculated using equation (27). In the calculation for available stress the allowable stress for Bridge 1 is 20,000 psi. The critical weights are calculated just for 5% overstress, as 10% was not considered in the previous study. The critical weight is calculated using equation (25).

Table 6 compares critical weights from previous study and present study. The answers match very well for the first two trucks, in these trucks critical weight is governed by the stresses at midspan. But in the other two trucks where critical weights are governed by stresses at interior support the results do not match.

Table 6. Comparison of Critical Weights for Selected Vehicles

Truck Type	Previous Study (kip)	Current Study (kip)
2S2, 32 ft	93	92
2S2, 38 ft	103	103
3S2-4, 98 ft	171	152
3S2-4, 104 ft	179	159

Investigation into this discrepancy led to the finding that in the previous study the allowable stresses were increased at the interior support by 20%, but without considering the maximum limit of 20,000 psi. The maximum allowable compressive stress from the AASHTO Formula was 17,700 psi. If this stress is increased by 20% it gives a maximum allowable compressive stress of 21200 psi. Using this allowable stress, critical weights for the last two trucks are as tabulated in Table 7.

Table 7. Comparison of Critical Weights

Truck Type	Previous Study (kip)	Current Study (kip)
3S2-4, 98 ft	171	170
3S2-4, 104 ft	179	179

Example Bridge 2

The second bridge of this exercise is an example from Highway Structures Design Handbook (1986), United States Steel. This bridge is studied to verify the procedure for bridges designed by Load Factor Design.

Material Properties

Steel:

- Yield Stress, F_y = 50,000 psi
- Steel Density , γ_s = 490 lb/ft^3
- Modulus of Elasticity for Steel, E_s = 2.9*10^7 psi

Concrete:

- Concrete Strength , $f_c^{'}$ = 4000 psi
- Concrete Density, γ_c = 150 lb/ft^3
- Modular Ratio, n = 8

Geometry specifications

- Number of Spans = 3
- Center to center spacing between girders = 18.5 ft
- Thickness of Slab = 8 in.
- Span Lengths: 273 ft - 350 ft - 273 ft

Load Step 1

Number of Increments and Increment Length - The total bridge length is 896 ft. An increment length of 12 in. cannot be used as this will lead to number of increments greater than 500. An increment length of 2 ft is chosen so that the number of increments is reduced to 448.

Support Geometry - Bridge 2 is made up of 3 spans, 273 ft - 350 ft - 273 ft. The support locations in terms of increments are 0, 137, 312 and 448.

Stiffness and Fixed Load Data -

i. $Estimated\ Weight\ of\ Steel\ Beam = 650\ lb/ft^3$

ii. Center to center spacing of each beam is 18.5 ft, thickness of the slab is 8.0 inches; the density of concrete is 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ concrete\ slab\ (lb/ft) &= \frac{8.0\ in.}{12} * 18.5\ ft * 150\ lb/ft^3 \\ &= 1850\ lb/ft \end{aligned}$$

iii. $Concrete\ Haunches\ on\ girder\ and\ stringer = 106\ lb/ft$

iv. $Stringers,\ cross\text{-}frames,\ lateralbracing = 187\ lb/ft$

$$\begin{aligned} Dead\ Load\ 1 &= 650\ lb/ft + 1850\ lb/ft + 106\ lb/ft + 187\ lb/ft \\ &= 2793\ lb/ft \end{aligned} \quad (40)$$

Dead Load 1 is entered into the computer program in terms of weight per increment. As the increment length is 2 ft dead load is doubled to get the weight per increment, therefore a constant value of dead load 1 = 5586 *lb/increment* is entered. Moment of inertia and stiffness of an interior girder of Example Bridge 2 is tabulated in Table 8.

Table 8. Specifications of Example Bridge 2, Load Step 1

Location (ft)	Moment of Inertia (in^4)	Stiffness ($lb\text{-}in^2$)
0 - 35	411,800	1.194E+13
35 - 63	514,100	1.491E+13
63 - 133	583,600	1.692E+13
133 - 158	559,600	1.623E+13
158 - 192	477,800	1.386E+13
192 - 219	593,200	1.720E+13
219 - 244	960,600	2.786E+13
244 - 303	1,600,800	4.642E+13
303 - 324	902,600	2.618E+13
324 - 360	598,700	1.736E+13
360 - 409	482,600	1.400E+13
409 - 448	560,000	1.624E+13

Load Step 2

Stiffness and Fixed Load Data - Effective Slab Width is given in the bridge data as 90 in.

$$\begin{aligned} Transformed\ Width\ of\ slab &= \frac{90\ in.}{3*8} \\ &= 3.75\ in. \end{aligned} \quad (41)$$

Table 9 shows the moment of inertia and stiffness for the interior beam in Load Step 2. This bridge is composite throughout, not just in regions of positive moment. In the regions of positive moment, concrete and steel reinforcement of the slab participate in resisting the loads. But in the regions of negative moments concrete does not participate; only the steel reinforcement of the slab participates. The values of the moment of inertia are adopted directly from the Highway Structures Design Handbook, in which the steel reinforcement is accounted for.

Dead Load carried by the partially composite section is made up of two parts:

1) $Parapets = 290\ lb/\ ft$

2) $Future\ Wearing\ Surface = 293\ lb/\ ft$

$$\begin{aligned} Dead\ Load\ 2 &= 290\ lb/\ ft + 293\ lb/\ ft \\ &= 583\ lb/\ ft \\ &= 1166\ lb/increment \end{aligned} \tag{42}$$

Table 9. Specifications for Example Bridge 2, Load Step 2

Location (ft)	Moment of Inertia (in^4)	Stiffness ($lb\text{-}in^2$)	Behavior
0 - 35	572,200	1.659E+13	Positive Moment
35 - 63	722,600	2.096E+13	
63 - 133	818,600	2.374E+13	
133 - 158	791,800	2.296E+13	
158 - 192	668,500	1.939E+13	
192 - 219	648,400	1.880E+13	Negative Moment
219 - 244	1,013,600	2.939E+13	
244 - 303	1,652,900	4.793E+13	
303 - 324	953,100	2.764E+13	
324 - 360	657,400	1.906E+13	
360 - 409	684,000	1.984E+13	Positive Moment
409 - 448	792,800	2.299E+13	

Load Step 3

Stiffness and Fixed Load Data - In regions of negative moment steel reinforcement of slab helps in resisting loads; here moment of inertia remains the same as Load Step 2. But in regions of positive moment where concrete helps in resisting loads, moment of inertia increases in Load Step 3. These values have been tabulated in Table 10.

$$\begin{aligned} Transformed\ Width\ of\ slab &= \frac{90\ in.}{8} \\ &= 11.25\ in. \end{aligned} \tag{43}$$

Table 10. Specifications for Example Bridge 2, Load Step 3

Location (ft)	Moment of Inertia (in^4)	Stiffness ($lb\text{-}in^2$)	Behavior
0 - 35	760,300	2.205E+13	Positive Moment
35 - 63	981,400	2.846E+13	
63 - 133	1,120,200	3.249E+13	
133 - 158	1,086,900	3.152E+13	
158 - 192	900,100	2.610E+13	
192 - 219	648,400	1.880E+13	Negative Moment
219 - 244	1,013,600	2.939E+13	
244 - 303	1,652,900	4.793E+13	
303 - 324	953,100	2.764E+13	
324 - 360	657,400	1.906E+13	
360 - 409	929,600	2.696E+13	Positive Moment
409 - 448	1,087,900	3.155E+13	

Movable Load Data - Live Load Distribution Factor is given as 1.484 axles.

To calculate the Impact Factor, (*I)* Equation (5) is utilized.

$$I = \frac{50}{273\,ft + 125} \qquad (44)$$
$$= 0.126$$

Now the effective live load can be calculated, using Equation (6)

$$\textit{Effective Live Load} = \textit{Axle Load} * 1.484 * (1 + 0.126) \qquad (45)$$

Three truck types were tested: 2S2 - 50 ft, 3S22-4 - 98 ft, 3S2-4 - 104 ft. The first truck being a short truck is expected to produce maximum moments at midspan, while the next two trucks are expected to produce maximum moments at interior support.

Since this bridge is designed by Load Factor Design, only section modulus for load step 3 is needed to calculate available stress. These moduli are given in the bridge data and have been reproduced in Table 11.

The available stress is calculated using equation (23). In the previous study only 5% overstress was considered, the same is repeated in this exercise. The critical weight is calculated using equation (25), where nominal weight of truck is 100,000 lb. Critical weights without considering moment redistribution and after considering moment redistribution are tabulated below.

While considering moment redistribution stresses at interior support are reduced by 10% but stresses at midspan are increased by average decrease at adjacent supports. So for mid-spans of the end span, stresses are increased by 5%. While for interior span, stresses are increased by 10% at mid-span.

From the Table 12 it is seen that the results match only for truck type 2S2, 50ft when moment redistribution is not considered. For the other trucks, critical weights of the previous study are considerably higher. It is also observed, that the 3S2-4 trucks produce maximum moments around the midspan of span 2 and not at the interior supports.

Further investigation into the reasons for this difference led to the finding that if dead load and live load stresses are reduced by 10% along entire length of the girder for the two longer trucks, the answers match. Results after this modification are tabulated in Table 13.

Table 11. Section Modulus for Load Case 3 of Interior Beam

Location (ft)	Top of Steel (in^3)	Bottom of Steel (in^3)	Behavior
0 - 35	17932	6584	Positive Moment
35 - 63	18956	9173	
63 - 133	19601	10965	
133 - 158	19336	10560	
158 - 192	18624	8179	
192 - 219	8010	8374	Negative Moment
219 - 244	12563	12748	
244 - 303	20293	20457	
303 - 324	12138	11715	
324 - 360	7855	7242	
360 - 409	18600	8571	Positive Moment
409 - 448	19354	10570	

Table 12. Critical Weights for Example Bridge 2

Truck Type	Previous Study (kip)	Current Study: No Moment Redistribution (kip)	Current Study: Moment Redistribution (kip)
2S2, 50 ft	151	151	130
3S2-4, 98 ft	190	165	142
3S2-4, 104 ft	196	167	144

Table 13. Critical Weights for the Longer Trucks

Truck Type	Previous Study (kip)	Current Study (kip)
3S2-4, 98 ft	190	193
3S2-4, 104 ft	196	196

Bridge 1

The first bridge is a Variable Depth Plate Girder Unit Design Example from TEXAS SDHPT Bridge Division (1988). C-S-J: Bridge Design Guide, Date: 8-88.

Geometry specifications

- Number of Spans - 3
- Span lengths: 200 ft - 280 ft - 200 ft
- Number of Girders - 3
- Center to center spacing between girders - 16 ft
- Thickness of Slab - 9 in.

Material Properties

Steel

- Steel Density (γ_s)= 490 lb/ft^3
- Maximum Allowable Stress for Steel (tension and compression) = 27000 psi

For High Strength Steel $f_t = 27,000\ psi$. f_c is calculated using Table 10.32.1A, which gives a value of 25,560 *psi*. But AASHTO, Standard Specifications for Highway Bridges (14th Edition) 10.32.1A footnote [a] says that continuous girders may be proportioned for negative moment at interior supports for an allowable unit stress 20% higher than permitted by the formula in Table 10.32.1a. But this should not exceed allowable unit stress for compression flange supported its full length, which for High Strength Steel is 27,000 psi. So, $f_c = 27,000\ psi$ is used.

- Modulus of Elasticity for Steel = $2.9*10^7$ psi

Concrete

- Concrete Density (γ_c) = 150 lb/ft^3
- Concrete Strength ($f_c^{'}$) = 4000 psi
- Calculation of Modulus of Elasticity for Concrete, E_c

$$E_c = (\gamma_c)^{1.5} * 33\sqrt{f_c^{'}} \\ = 3.834*106 \tag{46}$$

Modular Ratio, n

$$n = \frac{Modulus\ of\ Elasticity\ of\ Steel}{Modulus\ of\ Elasticity\ of\ Concrete} = 8 \tag{47}$$

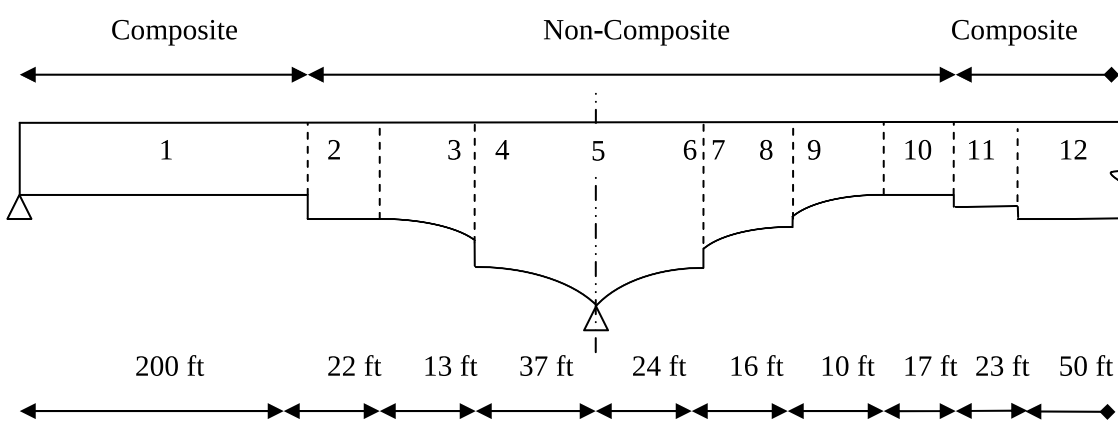


Figure 3. Longitudinal Profile of Bridge 1

Load Step 1

Number of Increments and Increment Length - The total bridge length is 680 ft. If an increment length of 12 in. is input in BMCOL51 the number of increments will be 680, which is not permitted as it is greater than 500. So the increment length is increased to 16.8 in. consequently the total number of increments is reduced to 486.

Support Geometry - Bridge 2 is made up of 3 spans having lengths of 200 ft. 280 ft. and 200 ft. Due to an increment length of 16.8 in. instead of 12 in. support locations are entered as 0, 143, 343, and 486.

Stiffness and Fixed Load Data - The center to center spacing of each beam is 16 ft, so a tributary width of 16 ft of the slab is acting on the interior beam. The height of the slab is 9 inches; the density of concrete is 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ concrete\ slab\ (lb/ft) &= 0.75\,ft*16\,ft*150lb/ft^3 \\ &= 1800\ lb/ft \end{aligned} \tag{48}$$

Figure 3 points out that the plate girder has a parabolic profile from a longitudinal location of 150 ft. to 250 ft and 430 ft. to 530 ft. taking this into account the moment of inertia, bending stiffness and total weight acting on the interior girder is calculated and is shown in Table 14. Since the bridge is symmetrical, values are only shown for one half of the bridge. Table 14 also shows the girder profile along half the length of the bridge.

Load Step 2

Stiffness and Fixed Load Data:

b_{eff} = minimum of

1. $\frac{200\,ft*12}{4}$ = 600 in.
2. $16\,ft*12$ = 192 in. (49)
3. $12*9in$ = 108 in.

b_{eff} = 108 in.

$$Transformed\ Width\ of\ slab = \frac{108in}{3*8} \tag{50}$$

= 4.5 in.

In Bridge 2 the top flange is in tension from a location of 128 ft. to 267 ft. on one half of the bridge and symmetrically on the other half of the bridge. The moment of inertia is calculated by taking into account the transformed width of slab for the regions in which the top flange is in compression.

Dead load 2 of 220 lb/ft is given in the Bridge Data. This load is scaled to take into account increment length of 16.8 in. instead of 12 in. this yields a value of 3080 lb/increment. Table 15 shows the moment of inertia and stiffness for the interior girder. The value of Bending stiffness and load/increment are entered into the computer program to produce the bending moment due to Dead Load 2.

Load Step 3

The increment length - For each different truck that is entered into the computer program its length is input in terms of the number of increments. The distance in terms of the number of increments is calculated from the extreme left axle. The total length of each truck in terms of the number of increments is entered into the computer program in this stage.

Stiffness and Fixed Load Data - Table 16 shows moment of inertia and stiffness of an interior girder of Bridge 1 for Load Step 3. This table also shows variation of girder profile and behavior along the length of the bridge.

$$\begin{aligned} Transformed\ Width\ of\ slab &= \frac{108\ in}{8} \\ &= 13.5\ in \end{aligned} \tag{51}$$

Table 14. Specifications for Bridge 1, Load Step 1

Location (ft)	Dead Load 1 (lb/ft)	Dead Load 1 (lb/increment)	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)	Girder Profile
0	2229	3120	1.234E+05	3.579E+12	Straight
128	2423	3392	1.938E+05	5.620E+12	
150	2423	3392	1.938E+05	5.620E+12	
163	2430	3402	2.071E+05	6.006E+12	Parabolic
	2596	3634	2.883E+05	8.361E+12	
200	2729	3821	7.615E+05	2.208E+13	
224	2664	3730	4.984E+05	1.445E+13	
	2498	3497	3.726E+05	1.081E+13	
240	2480	3472	3.188E+05	9.245E+12	
	2336	3270	2.219E+05	6.435E+12	
250	2333	3266	2.164E+05	6.276E+12	
267	2257	3160	2.011E+05	5.832E+12	Straight
290	2318	3245	2.333E+05	6.766E+12	
340	2318	3245	2.333E+05	6.766E+12	

Table 15. Specifications for Bridge 1, Load Step 2

Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Girder Profile	Behavior
0	1.973E+05	5.721E+12	Straight	Composite
128	1.938E+05	5.620E+12	Straight	Composite
150	1.938E+05	5.620E+12	Straight	Non-Composite
163	2.071E+05	6.006E+12	Parabolic	Non-Composite
	2.883E+05	8.361E+12	Parabolic	Non-Composite
200	7.615E+05	2.208E+13	Parabolic	Non-Composite
224	4.984E+05	1.445E+13	Parabolic	Non-Composite
	3.726E+05	1.081E+13	Parabolic	Non-Composite
240	3.188E+05	9.245E+12	Parabolic	Non-Composite
	2.219E+05	6.435E+12	Parabolic	Non-Composite
250	2.164E+05	6.276E+12	Parabolic	Non-Composite
267	2.891E+05	8.384E+12	Straight	Non-Composite
290	3.428E+05	9.940E+12	Straight	Composite
340	3.428E+05	9.940E+12	Straight	Composite

Table 16. Specifications for Bridge 1, Load Step 3

Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Girder Profile	Behavior
0	2.710E+05	7.858E+12	Straight	Composite
128	1.938E+05	5.620E+12		
150	1.938E+05	5.620E+12		Non-Composite
163	2.071E+05	6.006E+12	Parabolic	
	2.883E+05	8.361E+12		
200	7.615E+05	2.208E+13		
224	4.984E+05	1.445E+13		
	3.726E+05	1.081E+13		
240	3.188E+05	9.245E+12		
	2.219E+05	6.435E+12		
250	2.164E+05	6.276E+12		
267	3.817E+05	1.107E+13	Straight	
290	4.647E+05	1.348E+13		Composite
340	4.647E+05	1.348E+13		

Movable Load Data - In the case of Bridge 1 the Live Load Distribution Factor is calculated using the Lever Arm Method. This method is adopted from the Bridge Design

Example. The calculation for the distribution factor is shown in equation (52) with the help of Figure 4.

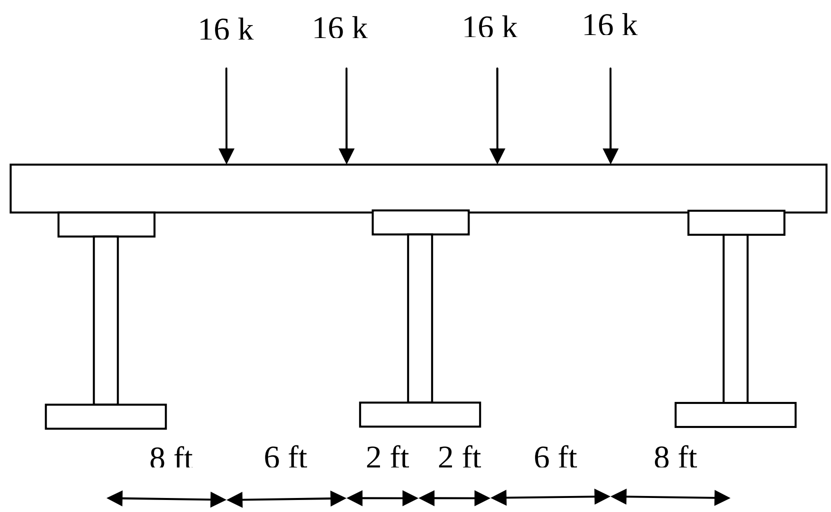


Figure 4. Live Load Distribution Factor by Lever Arm Method

$$Distribution\ Factor\ (DF) = 2*\left\{\frac{16k\left(\frac{8'+14'}{16'}\right)}{32k}\right\} \tag{52}$$

$$= 1.375$$

To calculate the Impact Factor, (*I*) Equation (11) is utilized.

$$I = \frac{50}{200\,ft + 125} \tag{53}$$

$$= 0.154$$

Now the effective live load can be calculated by using Equation (12).

$$Effective\ Live\ Load = Axle\ Load * 1.375 * (1 + 0.154) \tag{54}$$

The given axle spacing for each truck type is proportioned for 16.8 in. increment length. Axle load is also scaled to get the total gross vehicle weight to 100,000 lb. The scaled axle load is multiplied by the Impact Factor and Distribution Factor to get the Effective Load for each Axle. The values of the effective live load and the scaled axle spacing are entered into the Computer Program, BMCOL51. The program produces the envelopes for maximum positive and negative input. These values are transferred to the same Microsoft Excel file for further analysis.

Centroid of the top and bottom of steel for each load step is calculated and tabulated in Table 17; it can be observed that the location of the centroid does not change for non-composite sections.

Next, the section moduli are calculated for each load step and tabulated in Table 18. Note that the section modulus for sections which do not exhibit composite behavior does not change.

After the stress due to Dead Load 1 and Dead Load 2 have been calculated using equations (23), (24) the available stress is calculated using equation (22). In the calculation for available stress the allowable stress for Bridge 1 is 27,000 psi. The overstress ratio is first calculated for 5% overstress by substituting Ω as 1.05 and later calculated for 10% overstress by substituting Ω as 1.10. The critical weight is calculated using equation (31). The critical weight is calculated using the spreadsheet created for each bridge.

Table 17. Location of Centroid for Bridge 1

Location (ft)	Dead Load 1 (in)		Dead Load 2 (in)		Live Load (in)		Girder Profile	Behavior
	Top	Bottom	Top	Bottom	Top	Bottom		
0	44.80	30.70	32.36	43.14	20.00	55.50	Straight	Composite
128	38.50	38.50	38.50	38.50	38.50	38.50	Straight	Composite
150	38.50	38.50	38.50	38.50	38.50	38.50	Straight	Non-Composite
163	39.11	39.11	39.11	39.11	39.11	39.11	Parabolic	Non-Composite
	40.62	40.62	40.62	40.62	40.62	40.62	Parabolic	Non-Composite
200	63.00	63.00	63.00	63.00	63.00	63.00	Parabolic	Non-Composite
224	52.06	52.06	52.06	52.06	52.06	52.06	Parabolic	Non-Composite
	51.56	51.56	51.56	51.56	51.56	51.56	Parabolic	Non-Composite
240	48.11	48.11	48.11	48.11	48.11	48.11	Parabolic	Non-Composite
	48.68	45.36	48.68	45.36	48.68	45.36	Parabolic	Non-Composite
250	48.28	44.96	48.28	44.96	48.28	44.96	Parabolic	Non-Composite
267	48.57	44.66	36.28	56.97	23.37	69.88	Straight	Non-Composite
290	53.90	40.08	41.64	52.36	27.98	66.02	Straight	Composite
340	53.90	40.08	41.64	52.36	27.98	66.02	Straight	Composite

Table 18. Section Moduli for Interior Plate Girder of Bridge 1

<table>
<tr><th rowspan="2">Location (ft)</th><th colspan="2">Dead Load 1 (in^3)</th><th colspan="2">Dead Load 2 (in^3)</th><th colspan="2">Live Load (in^3)</th><th rowspan="2">Girder Profile</th><th rowspan="2">Behavior</th></tr>
<tr><th>Top</th><th>Bottom</th><th>Top</th><th>Bottom</th><th>Top</th><th>Bottom</th></tr>
<tr><td>0</td><td>2755</td><td>4020</td><td>6096</td><td>4573</td><td>13550</td><td>4882</td><td rowspan="2">Straight</td><td rowspan="2">Composite</td></tr>
<tr><td>128</td><td>5033</td><td>5033</td><td>5033</td><td>5033</td><td>5033</td><td>5033</td></tr>
<tr><td>150</td><td>5033</td><td>5033</td><td>5033</td><td>5033</td><td>5033</td><td>5033</td><td></td><td rowspan="10">Non - Composite</td></tr>
<tr><td rowspan="2">163</td><td>5295</td><td>5295</td><td>5295</td><td>5295</td><td>5295</td><td>5295</td><td rowspan="7">Parabolic</td></tr>
<tr><td>7098</td><td>7098</td><td>7098</td><td>7098</td><td>7098</td><td>7098</td></tr>
<tr><td>200</td><td>12088</td><td>12088</td><td>12088</td><td>12088</td><td>12088</td><td>12088</td></tr>
<tr><td rowspan="2">224</td><td>9574</td><td>9574</td><td>9574</td><td>9574</td><td>9574</td><td>9574</td></tr>
<tr><td>7227</td><td>7227</td><td>7227</td><td>7227</td><td>7227</td><td>7227</td></tr>
<tr><td rowspan="2">240</td><td>6627</td><td>6627</td><td>6627</td><td>6627</td><td>6627</td><td>6627</td></tr>
<tr><td>4558</td><td>4893</td><td>4558</td><td>4893</td><td>4558</td><td>4893</td></tr>
<tr><td>250</td><td>4482</td><td>4813</td><td>4482</td><td>4813</td><td>4482</td><td>4813</td><td></td></tr>
<tr><td>267</td><td>4140</td><td>4503</td><td>7968</td><td>5075</td><td>16336</td><td>5462</td><td rowspan="3">Straight</td></tr>
<tr><td>290</td><td>4328</td><td>5820</td><td>8232</td><td>6546</td><td>16605</td><td>7039</td><td rowspan="2">Composite</td></tr>
<tr><td>340</td><td>4328</td><td>5820</td><td>8232</td><td>6546</td><td>16605</td><td>7039</td></tr>
</table>

Bridge 2

The second, third and fourth bridges of this study are examples from Highway Structures Design Handbook (1986), United States Steel. These bridge examples share few characteristics which are listed below.

- Design Method: Load Factor Design

Material Properties

Steel:

- ASTM A588, Grade A Steel Yield Stress, F_y = 50000 psi
- Steel Density (γ_s)= 490 lb/ft^3
- Modulus of Elasticity for Steel, E_s = 2.9*10^7 psi

Concrete:

- Concrete Strength ($f_c^{'}$) = 4000 psi
- Concrete Density (γ_c) = 150 lb/ft^3
- Calculation of Modulus of Elasticity for Concrete, E_c

$$E_c = (\gamma_c)^{1.5} * 33\sqrt{f_c^{'}} \quad (55)$$

$$= 3.834*10^6$$

- Modular Ratio, n

$$n = \frac{Modulus\ of\ Elasticity\ of\ Steel}{Modulus\ of\ Elasticity\ of\ Concrete} = 8 \quad (56)$$

Geometry specifications common to Bridges 2, 3, 4:

- Number of Spans - 2
- Number of Girders - 5
- Center to center spacing between girders - 9.25 ft
- Thickness of Slab - 7.5 in.

Geometry Specifications unique to Bridge 2:

- Span Lengths: 50 ft – 50 ft
- Beam Size: W_{27*102}

Section Properties: Height - 27.1 in.

Area - 30 in^2

Moment of Inertia - 3620 in^4

(AISC LRFD Steel Manual, 2nd Edition)

Load Step 1

Number of Increments and Increment Length - The total bridge length is 100 ft. If an increment length of 12 in. is used in BMCOL51 the number of increments will be 100, which is permitted as it is less than 500.

Support Geometry - Bridge 2 is made up of 2 spans, each having a length of 50 ft. The support locations are entered as 0, 50, and 100.

Stiffness and Fixed Load Data

$$Weight\ of\ Steel\ Beam = \frac{30 in.^2}{144} * 490 lb/ft^3 \quad (57)$$

$$= 102.1 lb/ft$$

The center to center spacing of each beam is 9.25 ft, so a tributary width of 9.25 ft of the slab is acting on the interior beam. The height of the slab is 7.5 inches; the density of concrete is 150 lb/ft^3.

$$Weight\ of\ concrete\ slab\ (lb/ft) = \frac{7.5 in.}{12} * 9.25 ft * 150 lb/ft^3 = 867.2\ lb/ft \quad (58)$$

$$Dead\ Load\ 1 = 102.1\ lb/ft + 867.2\ lb/ft = 969.3\ lb/ft \quad (59)$$

$$Stiffness\ of\ Beam = 29*10^6\ lb/in^2 * 3620\ in^4 = 1.05*10^{11}\ lb\text{-}in^2 \quad (60)$$

Table 19 shows the value of Dead Load 1, which is the sum of the weights of the steel beam and the weight of the concrete slab it supports. The table also contains the moment of inertia of the steel beam itself, in this case W_{27*102} and its bending stiffness.

Table 19. Specifications for Bridge 2, Load Step 1

Location (ft)	Dead Load 1 (lb/ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)
0 - 100	9.639E+02	3.620E+03	1.050E+11

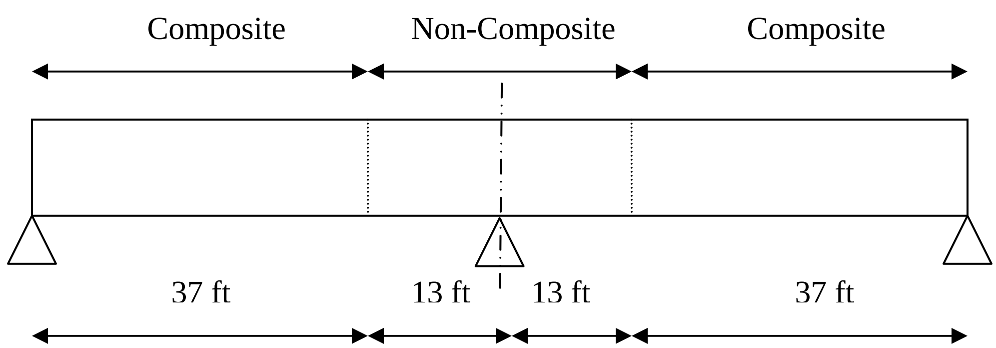


Figure 5. Longitudinal Profile of Bridge 2

Load Step 2

Stiffness and Fixed Load Data:

b_{eff} = minimum of

1. $\frac{50\,ft*12}{4} = 150$ in.

2. $9.25\,ft*12 = 111$ in. (61)

3. $12*7.5\,in. = 90$ in.

b_{eff} = 90 in.

Equation (9) is utilized to calculate the transformed width of slab in load step 2. Here it shows partially composite behavior.

$$Transformed\ Width\ of\ slab = \frac{90\ in.}{3*8} = 3.75\ in. \tag{62}$$

As is evident from Figure 5, in Bridge 2 the top flange is in tension from a location of 37 ft. to 63 ft. and along the rest of the bridge it shows Composite Behavior. The Handbook assumes load of the parapet and guardrail is equally distributed to all beams. Dead Load 2 of 320 lb/ft is given in the Bridge Data. Table 20 shows the moment of inertia and stiffness for the interior beam in Load Step 2.

Table 20. Specifications for Bridge 2, Load Step 2

Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
0 - 37	8.096E+03	2.348E+11	Composite
37 - 63	3.620E+03	1.050E+11	Non-Composite
63 - 100	8.096E+03	2.348E+11	Composite

Load Step 3

The increment length – Live Load length in terms of the number of increments is calculated from the extreme left axle.

\Stiffness and Fixed Load Data – Fixed Load is zero as only live load will be applied in this load step. Table 21 helps to illustrate specifications of a single interior beam of Bridge 2 for Load Step 3. The beam behaves as a complete composite section in regions of positive bending moment.

$$\textit{Transformed Width of slab} = \frac{90\ in.}{8} = 11.25\ in. \tag{63}$$

Table 21. Specifications for Bridge 2, Load Step 3

Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
0 - 37	1.064E+04	3.085E+11	Composite
37 - 63	3.620E+03	1.050E+11	Non-Composite
63 - 100	1.064E+04	3.085E+11	Composite

Movable Load Data - In the case of Bridge 2 the formula used in the Design Handbook for Live Load Distribution Factor is the same as that specified in AASHTO Standard Specifications for Highway Bridges (1996) for span with concrete floor supported by 4 or more steel stringers.

$$= \frac{S}{5.5} \text{ (for Interior Beams)}$$

$$= \frac{9.25}{5.5} = 1.682 \text{ (for wheel load)} \tag{64}$$

$$= \frac{1.682}{2} = 0.841 \text{ (for axle load)}$$

Where:

S - Spacing between adjacent girders

To calculate the Impact Factor, (*I*) Equation (11) is utilized.

$$I = \frac{50}{50\,ft + 125} = 0.259 \tag{65}$$

Now the effective live load can be calculated, using Equation (12)

$$Effective\ Live\ Load = Axle\ Load * 0.841 * (1 + 0.259) \quad (66)$$

In the case of bridge 2 axle loads are also not scaled to make the total gross vehicle weight to 100,000 lb. The axle load is multiplied by the Impact Factor and Distribution Factor to get the Effective Load for each Axle.

Bridge 2 is designed using the Load Factor Design Method. Hence from equation (29) section modulus for only load step 3 (S_{LL}) is required to calculate the available live load plus impact stress. The centroid location for Load Step 3 is calculated and shown in Table 22. Section Modulus of the top and bottom of steel for load step 3 is tabulated in Table 23.

Table 22. Location of Centroid for Load Case 3

Location (ft)	Top (in.)	Bottom (in.)	Behavior
0 - 37	0.79	26.31	Composite
37 - 63	13.55	13.55	Non-Composite
63 - 100	0.79	26.31	Composite

The available stress is calculated using equation (23). The overstress ratio is first calculated for 5% overstress by substituting Ω as 1.05 and later calculated for 10% overstress by substituting Ω as 1.10. The critical weight is calculated using equation (25), but instead of substituting a nominal weight of 100,000 lb for each vehicle, the total weight for each vehicle is substituted. For example while calculating the critical weight for 3S2 w/ 45' trailer Wn is substituted as 80,000 lb. The critical weight is calculated using the spreadsheet created for each bridge.

Table 23. Section Modulus of Interior Beam for Load Case 3

Location (ft)	Top (in^3)	Bottom (in^3)	Behavior
0 - 37	13507	404.34	Composite
37 - 63	267.16	267.16	Non-Composite
63 - 100	13507	404.34	Composite

Verification

Dead Load moments obtained are compared at two locations with the moments specified in the Design Handbook. The locations are (1) Mid-span (2) Interior Support. The moments are also compared at theses two locations for HS-20 (short) Truck.

The moments specified in the design handbook are the design moments before the sectional properties are calculated, so a uniform stiffness is assumed, the moments are calculated and tabulated in Table 24. To reproduce these results for verification of the method, while producing the moments through the compute program it is assumed that stiffness is uniform throughout. Though, when actual calculations are made for critical weights, exact stiffness values are substituted.

Since the other bridges studied from the design handbook are similar to the above bridge, the verification process is performed only for this bridge.

Table 24. Comparison of Moments for Bridge 2

Maximum Moment		Design Handbook (kip-ft)	BMCOL51 (kip-ft)
Dead Load 1	Midspan	174	175
	Interior Support	311	312
Dead Load 2	Midspan	57	57
	Interior Support	101	101
HS20(short) (*LL+I*)	Midspan	542	553
	Interior Support	403	412

Moment Redistribution

The Design Handbook says that when it is advantageous negative moments over supports of continuous beams are reduced up to ten percent and positive moments are proportionally increased in accordance with the Specifications.

The dead load moments in the region of negative moments at the supports were reduced by 10% by multiplying by 0.9. The available stress is calculated by modifying Equation (29). The modified equation is shown below.

$$\sigma_{av} = \frac{3}{5}\left(\frac{\Omega * Fy}{1.3} - \frac{0.9 * M_{DL}}{S_{LL}}\right) \tag{67}$$

Live load moments are also reduced by 10%. As live load stress varies linearly with the moment the stress is directly reduced by 10% in equation (30). Equation (31) is used to calculate the critical weight is modified to take in to account the reduction in live load moment.

$$\sigma_{LL+I} = \frac{0.9 * M_{LL+I}}{S_{LL}} \tag{68}$$

$$Wcr = Wn * \frac{\sigma_{av}}{0.9 * \sigma_{LL+I}} \tag{69}$$

All the bridges looked at in this study from the Design Handbook are two span bridges. The moments at the midspan are increased by average of the decrease in moments at the supports. Though the moments need to be increased or decreased proportionately along the length of the bridge, a simplification is made by reducing moments by 10% in negative moment region and increasing by 5% in the positive moment region. Equation (29), to calculate the available stresses, and equation (31), to calculate critical weights are modified and listed below.

$$\sigma_{av} = \frac{3}{5}\left(\frac{\Omega * Fy}{1.3} - \frac{1.05 * M_{DL}}{S_{LL}}\right) \tag{70}$$

$$Wcr = Wn * \frac{\sigma_{av}}{1.05 * \sigma_{LL+I}} \tag{71}$$

The critical weights are calculated for each truck type and are tabulated in the next chapter. If for a particular truck type the critical weight after moment redistribution is lesser than before, then the higher value is used because the Design Handbook says the moment redistribution is to be used where it is advantageous.

Bridge 3

This bridge example is from Highway Structures Design Handbook (1986), United States Steel. As previously mentioned this bridge shares a few characteristics with the previous bridge:

- Design Method: Load Factor Design

Material Properties

Steel:

- ASTM A588, Grade A Steel Yield Stress, F_y = 50000 psi
- Steel Density (γ_s)= 490 lb/ft^3
- Modulus of Elasticity for Steel, E_s = 2.9*10^7 psi

Concrete:

- Concrete Strength ($f_c^{'}$) = 4000 psi

- Concrete Density (γ_c) = 150 lb/ft^3
- Calculation of Modulus of Elasticity for Concrete, E_c

$$E_c = (\gamma_c)^{1.5} * 33\sqrt{f_c^{'}} \quad (72)$$
$$= 3.834*106$$

- Modular Ratio, n

$$n = \frac{Modulus\ of\ Elasticity\ of\ Steel}{Modulus\ of\ Elasticity\ of\ Concrete} = 8 \quad (73)$$

Geometry specifications common to Bridges 2, 3, 4:

- Number of Spans = 2
- Number of Girders = 5
- Center to center spacing between girders = 9.25 ft
- Thickness of Slab = 7.5 in.

Geometry Specifications unique to Bridge 2:

- Span Lengths: 75 ft - 75 ft
- Beam Size: W_{36*160}

Section Properties: Height = 36 in.

Area = 47 in^2

Moment of Inertia = 9760 in^4

(From AISC LRFD Steel Manual, 2nd Edition)

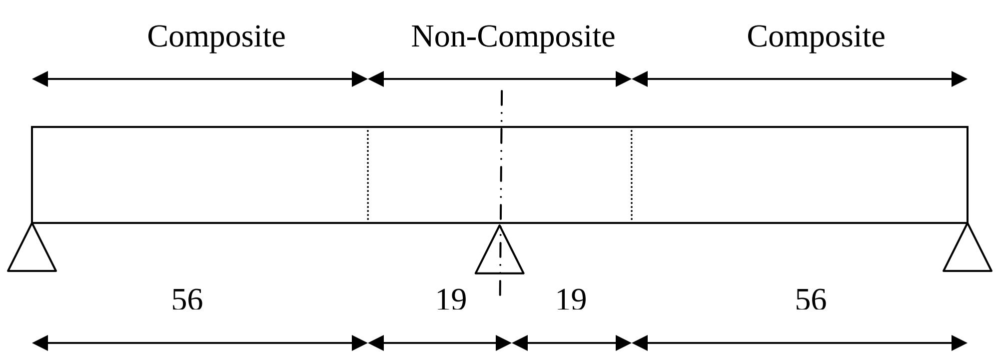


Figure 6. Longitudinal Profile of Bridge 3

Load Step 1

Number of Increments and Increment Length – Figure 6 shows the longitudinal profile of Bridge This figure shows that the total bridge length is 150 ft. If an increment length of 12 in. is used in BMCOL51 the number of increments will be 150, which is permitted as it is less than 500.

Support Geometry - As can be seen from Figure 6, Bridge 2 is made up of 2 spans, each having a length of 75 ft. The support locations are entered as 0, 75 and 150.

Stiffness and Fixed Load Data -

$$\begin{aligned} Weight\ of\ \ Steel\ Beam &= \frac{47}{144}\ ft^2 * 490lb/ft^3 \\ &= 159.9\ lb/ft \end{aligned} \tag{74}$$

The center to center spacing of each beam is 9.25 ft, so a tributary width of 9.25 ft of the slab is acting on the interior beam. The height of the slab is 7.5 inches; the density of concrete is 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ \ concrete\ slab\ (lb/ft) &= \frac{7.5}{12}\ ft * 9.25\,ft * 150lb/ft^3 \\ &= 867.2\ lb/ft \end{aligned} \tag{75}$$

$$\begin{aligned} Dead\ \ Load\ 1 &= 159.9\ lb/ft + 867.2\ lb/ft \\ &= 1027\ lb/ft \end{aligned} \tag{76}$$

$$\begin{aligned} Stiffness\ of\ \ Beam &= 29*10^6\ \ lb/in^2 * 9760\ in^4 \\ &= 2.83*10^{11}\ \ lb\text{-}in^2 \end{aligned} \tag{77}$$

Table 25 shows the value of Dead Load 1, which is the sum of the weights of the steel beam and the weight of the concrete slab it supports. The table also contains the moment of inertia of the steel beam itself, in this case W_{36*160} and its bending stiffness.

Table 25. Specifications of Steel Beam for Load Step 1 of Bridge 3

Location (ft)	Dead Load 1 (lb/ft)	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)
0 - 150	1.027E+03	9.760E+03	2.830E+11

Load Step 2

Stiffness and Fixed Load Data

b_{eff} = minimum of

1. $\frac{75\,ft*12}{4}$ = 225 in.
2. $9.25\,ft*12$ = 111 in. (78)
3. $12*7.5\ in.$ = 90 in.

b_{eff} = 90 in.

Equation (9) is utilized to calculate the transformed width of slab in load step 2. Here it shows partially composite behavior.

$$Transformed\ Width\ of\ slab = \frac{90\ in.}{3*8} = 3.75\ in. \quad (79)$$

In Bridge 3 the top flange is in tension from a location of 56 ft. to 94 ft. and along the rest of the bridge it shows Composite Behavior. Dead Load 2 of 320 lb/ft is given in the Bridge Data. Table 26 shows the moment of inertia and stiffness for the interior beam in Load Step 2.

Table 26. Beam Specifications for Bridge 3, Load Step 2

Location (ft)	Moment of Inertia (I) (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
0 - 56	1.822E+04	5.283E+11	Composite
56 - 94	9.760E+03	2.830E+11	Non-Composite
94 - 150	1.822E+04	5.283E+11	Composite

Load Step 3

Increment length - Live Load length in terms of the number of increments is calculated from the extreme left axle.

Stiffness and Fixed Load Data – Fixed Load is zero as only live load will be applied in this load step. The beam behaves as a complete composite section in regions of positive bending moment. Specifications for Bridge 3 are shown in Table 27.

$$\textit{Transformed Width of slab} = \frac{90\ in}{8} \tag{80}$$

= 11.25 in.

Table 27. Specifications for Bridge 3, Load Step 3

Location (ft)	Moment of Inertia (I) (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
0 - 56	2.444E+04	7.086E+11	Composite
56 - 94	9.760E+03	2.830E+11	Non-Composite
94 - 150	2.444E+04	7.086E+11	Composite

Movable Load Data - In the case of Bridge 2 the formula used in the Design Handbook for Live Load Distribution Factor is the same as that specified in AASHTO (1996) for span with concrete floor supported by 4 or more steel stringers,

$$= \frac{S}{5.5} \text{ (for Interior Beams)}$$

$$= \frac{9.25}{5.5} = 1.682 \text{ (for wheel load)} \tag{81}$$

$$= \frac{1.682}{2} = 0.841 \text{ (for axle load)}$$

Where:

S - Spacing between adjacent girders

To calculate the Impact Factor, (*I)* Equation (11) is utilized.

$$I = \frac{50}{75\,ft + 125} \tag{82}$$

$$= 0.250$$

Now the effective live load can be calculated, using Equation (12).

$$Effective\ Live\ Load = Axle\ Load * 0.841 * (1 + 0.250) \tag{83}$$

In the case of Bridge 3 axle load is scaled to get the total gross vehicle weight to 100,000 lb. The scaled axle load is multiplied by the Impact Factor and Distribution Factor to get the Effective Load for each Axle.

The centroid location for Load Step 3 is shown in Table 28. Section Modulus of the top and bottom of steel for load step 3 is tabulated in Table 29.

Table 28. Location of Centroid for Bridge 3, Load Step 3

Location (ft)	Top (in)	Bottom (in)	Behavior
0 - 56	4.03	31.97	Composite
56 - 94	18.0	18.0	Non-Composite
94 - 150	4.03	31.97	Composite

The available stress is calculated using equation (29). The overstress ratio is first calculated for 5% overstress by substituting Ω as 1.05 and later calculated for 10% overstress by substituting Ω as 1.10. The critical weight is calculated using equation

(31) where Wn is 100,000 lb. The critical weight is calculated using the spreadsheet created for each bridge. The critical weight for 5%, 10% overstress is tabulated in the next chapter.

Bridge 3 has similar specifications as Bridge 2; therefore moment redistribution for Bridge 3 is carried out in a similar way as Bridge 2.

Table 29. Section Modulus for Load Case 3

Location (ft)	Top (in^3)	Bottom (in^3)	Behavior
0	6061.6	764.34	Composite
37	542.22	542.22	
			Non-Composite
63	542.22	542.22	
			Composite
100	6061.6	764.34	

Bridge 4

Bridge 4 like previous two bridges is an example from Highway Structures Design Handbook (1986), United States Steel. The common characteristics shared with previous two bridges are:

Design Method: Load Factor Design

Material Properties

Steel:

- ASTM A588, Grade A Steel Yield Stress, F_y = 50000 psi
- Steel Density (γ_s)= 490 lb/ft^3
- Modulus of Elasticity for Steel, E_s = $2.9*10^7$ psi

Concrete:

- Concrete Strength ($f_c^{'}$) = 4000 psi
- Concrete Density (γ_c) = 150 lb/ft^3
- Calculation of Modulus of Elasticity for Concrete, E_c

$$E_c = (\gamma_c)^{1.5} * 33\sqrt{f_c^{'}} \quad (84)$$
$$= 3.834*10^6$$

- Modular Ratio, n

$$n = \frac{Modulus\ of\ Elasticity\ of\ Steel}{Modulus\ of\ Elasticity\ of\ Concrete} = 8$$

Bridge specifications common to Bridges 2, 3, 4:

- Number of Spans = 2
- Number of Girders = 5
- Center to center spacing between girders = 9.25 ft
- Thickness of Slab = 7.5 in.

Bridge Specifications unique to Bridge 4:

- Span Lengths: 100 ft – 100 ft
- Beam Size: W_{36*280}

  Section Properties: Height = 36.5 in.

  Area = 82.4 in^2

  Moment of Inertia = 18900 in^4

  (From AISC LRFD Steel Manual, 2nd Edition)

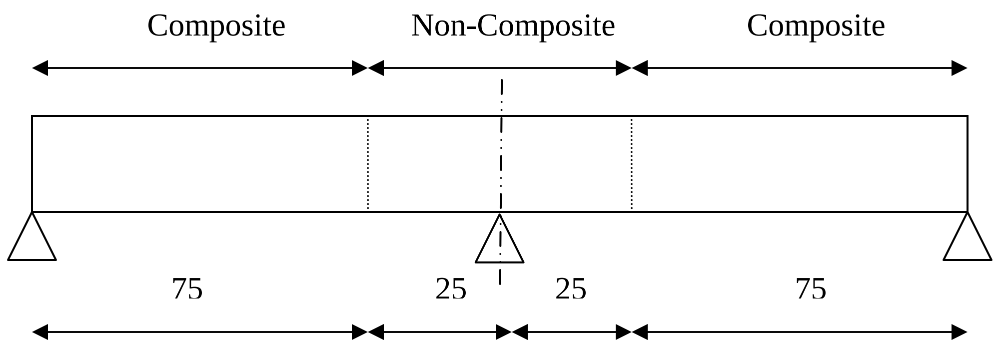


Figure 7. Longitudinal Profile of Bridge 4

Load Step 1

Number of Increments and Increment Length – Figure 7 shows that the total bridge length is 200 ft. If an increment length of 12 in. is used in BMCOL51 the number of increments will be 200, which is permitted as it is less than 500.

Support Geometry - Bridge 2 is made up of 2 spans, each having a length of 100 ft. The support locations are entered as 0, 100 and 200.

Stiffness and Fixed Load Data -

$$\begin{aligned} Weight\ of\ Steel\ Beam &= \frac{82.4}{144} ft^2 * 490 lb/ft^3 \\ &= 280.4\ lb/ft \end{aligned} \tag{85}$$

The center to center spacing of each beam is 9.25 ft, so a tributary width of 9.25 ft of the slab is acting on the interior beam. The height of the slab is 7.5 inches; the density of concrete is 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ concrete\ slab\ (lb/ft) &= \frac{7.5}{12} ft * 9.25 ft * 150 lb/ft^3 \\ &= 867.2\ lb/ft \end{aligned} \tag{86}$$

$$\begin{aligned} Dead\ Load\ 1 &= 280.4\ lb/ft + 867.2\ lb/ft \\ &= 1147.6\ lb/ft \end{aligned} \tag{87}$$

Table 30 shows the value of Dead Load 1, which is the sum of the weights of the steel beam and the weight of the concrete slab it supports. The table also contains the moment of inertia of the steel beam itself, in this case W_{36*280} and its bending stiffness.

Table 30. Specifications for Bridge 4, Load Step 1

Location (ft)	Dead Load 1 (lb/ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)
0 - 200	1.148E+03	1.890E+04	5.481E+11

Load Step 2

- Stiffness and Fixed Load Data:

b_{eff} = minimum of

1. $\frac{100\,ft*12}{4} = 225$ in.
2. $9.25\,ft*12 = 111$ in. (88)
3. $12*7.5\ in. = 90$ in.

b_{eff} = 90 in.

Equation (9) is utilized to calculate the transformed width of slab in load step 2. Here it shows partially composite behavior.

$$Transformed\ Width\ of\ slab = \frac{90\ in.}{3*8} \tag{89}$$

$$= 3.75 \text{ in.}$$

In Bridge 4 the top flange is in tension from a location of 75 ft. to 125 ft. and along the rest of the bridge it shows Composite Behavior. Dead Load 2 of 320 lb/ft is given in the Bridge Data. Table 31 shows the moment of inertia and stiffness for the interior beam in Load Step 2.

Table 31. Specifications for Bridge 4, Load Step 2

Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
0 - 75	2.918E+04	8.462E+11	Composite
75 - 125	1.890E+04	5.481E+11	Non-Composite
125 - 200	2.918E+04	8.462E+11	Composite

Load Step 3

Increment length - Live Load length in terms of the number of increments is calculated from the extreme left axle. As the increment length is 12 in. the length of the live load in terms of the number of increments is the length of the live load in ft.

Stiffness and Fixed Load Data -To calculate the moment of inertia for the composite section the transformed slab width is calculated and tabulated in Table 32.

$$Transformed\ Width\ of\ slab = \frac{90\ in}{8} = 11.25\ in. \quad (90)$$

Table 32. Specifications for Bridge 4, Load Step 3

Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
0 - 75	3.947E+04	1.145E+12	Composite
75 - 125	1.890E+04	5.481E+11	Non-Composite
125 - 200	3.947E+04	1.145E+12	Composite

Movable Load Data - In the case of Bridge 2 the formula used in the Design Handbook for Live Load Distribution Factor is the same as that specified in AASHTO (1996) for span with concrete floor supported by 4 or more steel stringers,

$$= \frac{S}{5.5} \text{ (for Interior Beams)}$$

$$= \frac{9.25}{5.5} = 1.682 \text{ (for wheel load)} \qquad (91)$$

$$= \frac{1.682}{2} = 0.841 \text{ (for axle load)}$$

Where

S - Spacing between adjacent girders

To calculate the Impact Factor, (*I)* Equation (11) is utilized.

$$I = \frac{50}{100\,ft + 125} \qquad (92)$$

$$= 0.222$$

Now the effective live load can be calculated using Equation (12)

$$Effective\ Live\ Load = Axle\ Load * 0.841 * (1 + 0.222) \qquad (93)$$

In the case of bridge 2 axle loads are also not scaled to get the total gross vehicle weight to 100,000 lb. The axle load is multiplied by the Impact Factor and Distribution Factor to get the Effective Load for each Axle. Live Load for Bridge 2 is shown in the Appendix.

The centroid location for Load Step 3 is shown in Table 33. Section Modulus of the top and bottom of steel for load step 3 is tabulated in Table 34.

The available stress is calculated using equation (29). The overstress ratio is first calculated for 5% overstress by substituting Ω as 1.05 and later calculated for 10% overstress by substituting Ω as 1.10. The critical weight is calculated using equation (31), but instead of substituting a nominal weight of 100,000 lb for each vehicle, the actual weight for each vehicle is substituted. For example while calculating the critical weight for 3S2 w/ 45’ trailer Wn is substituted as 80,000 lb. The critical weight is calculated using the spreadsheet created for each bridge.

Moment redistribution for Bridge 4 is carried out in a similar way as Bridges 2 and 3, as three bridges share similar characteristics.

Table 33. Location of Centroid for Load Step 3

Location (ft)	Top (in)	Bottom (in)	Behavior
0 - 75	7.12	29.38	Composite
75 - 125	18.25	18.25	Non-Composite
125 - 200	7.12	29.38	Composite

Table 34. Section Modulus for Load Step 3

Location (ft)	Top (in^3)	Bottom (in^3)	Behavior
0 - 75	5544.09	1343.50	Composite
75 - 125	1035.6	1035.6	Non-Composite
125 - 200	5544.09	1343.50	Composite

Bridge 5

Bridge 5 is an example received from the South Dakota Department of Transportation through a survey conducted by Battelle, the research institute which sponsored this study. The data is given in the form of a BARS (Bridge Analysis and Rating System) File.

Bridge Specifications are:

- Design Method - Load Factor Design
- Design Load - HS20
- Number of Spans - 4 Span Continuous Composite Girder
- Total Length - 254 ft
- Span lengths: 55 ft - 70 ft - 70 ft - 55 ft
- Live Load Distribution Factor - 1.606 (wheel load)
- Dead Load 2 - 130 lb/ft
- Thickness of Slab - 6.75 in.

Material Properties:

- Material - Composite Steel and Concrete (CSC)
- Modulus of Elasticity for Steel - $2.9*10^7$ psi
- Yield Stress for Steel - 36000 psi
- Concrete Density (γ_c) - 150 lb/ft^3
- Modular Ratio, n = 8

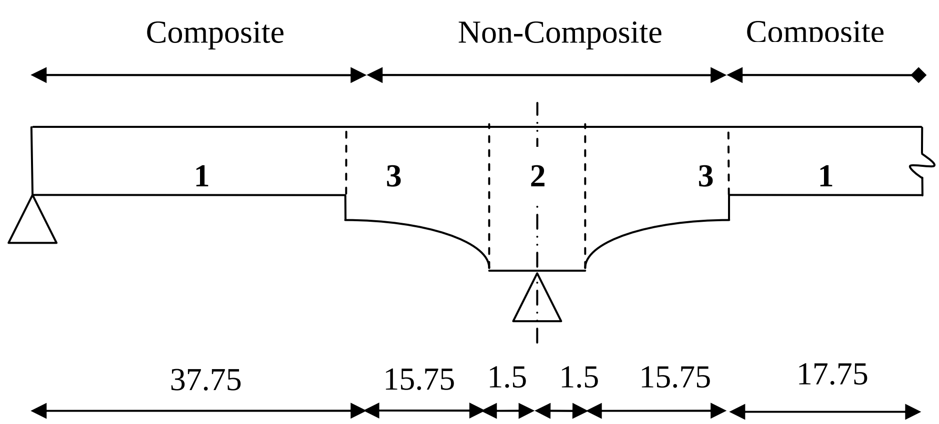


Figure 8. Longitudinal Profile of Bridge 5

Load Step 1

Number of Increments and Increment Length

Number of Increments = 250

Increment Length = 12 in.

Support Geometry - Bridge 5 is made up of 4 spans having lengths of 55 ft, 70 ft, 70 ft. and 50 ft. The Location of the supports from extreme left of the bridge is 0, 55, 125, 195, and 250.

Stiffness and Fixed Load Data - Width of slab is given as 106 in. and thickness is 6.75 in. Density of concrete is assumed to be 150 lb/ft^3.

$$\begin{aligned} \textit{Weight of concrete slab } (lb/ft) &= \frac{6.75}{12} ft * \frac{106}{12} ft * 150 lb/ft^3 \\ &= 745.3\ lb/ft \end{aligned} \tag{94}$$

Longitudinal Profile of the plate girder is shown in Figure 8. Since the bridge is symmetrical only one fourth of the entire bridge is shown in the figure. The numbers in the boxes indicate section number at that location.

Table 35 shows the section numbers along the length of the bridge, it also shows the variation in the plate girder depth along the bridge. Weight of the plate girder itself, total weight, which includes the girder weight and the concrete slab weight are also tabulated. Besides this, moment of inertia and bending stiffness of the girder is calculated and is shown in Table 35. Since the bridge is symmetrical, values are only shown for one half of the bridge.

Load Step 2

Stiffness and Fixed Load Data - Besides the section variation and plate depth variation along the length of the bridge Table 36 shows the regions of composite and non-composite behavior. The bridge has been designed such that section 1 lies in the composite region while all the other sections are in the non-composite region.

The value of effective slab width is given as 81 in. This in fact is 12 times the thickness of the slab, which usually governs the effective width.

$$Transformed\ Width\ of\ slab = \frac{81\ in}{3*8} \tag{95}$$

$$= 3.375 \text{ in.}$$

Dead load 2 of 130 lb/ft is given in the Bridge Data and as the increment length is 12 in. the load per increment is also 130 lb. Table 36 also shows the moment of inertia and stiffness for the interior girder for Load Step 2 by taking into account contribution of the slab in regions of positive bending moment. Value of moment of inertia is adopted from the BARS file.

Table 35. Specifications for Bridge 5, Load Step 1

Location (ft)	Section Number	Member Weight (lb/ft)	Total Weight (lb/increment)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Girder Profile
0	1	88.9	8.342E+02	5.953E+03	1.726E+11	Uniform
38	1	89.9	8.342E+02	5.953E+03	1.726E+11	Uniform
38	3	103.8	8.491E+02	7.733E+03	2.243E+11	Parabolic
54	2 / 2	116.5	8.618E+02	1.429E+04	4.144E+11	Parabolic / Uniform
56	2 / 2	116.5	8.618E+02	1.429E+04	4.144E+11	Uniform / Parabolic
72	3	103.8	8.491E+02	7.733E+03	2.243E+11	Parabolic
72	1	88.9	8.342E+02	5.953E+03	1.726E+11	Uniform
108	1	88.9	8.342E+02	5.953E+03	1.726E+11	Uniform
108	3	103.8	8.491E+02	7.733E+03	2.243E+11	Parabolic
124	2 / 2	116.5	8.618E+02	1.429E+04	4.144E+11	Parabolic / Uniform
125	2	116.5	8.618E+02	1.429E+04	4.144E+11	Uniform

Load Step 3

Increment length - For each different truck that is entered into the computer program its length is input in terms of the number of increments. The distance in terms of the number of increments is calculated from the extreme left axle.

Stiffness and Fixed Load Data

$$Transformed\ Width\ of\ slab = \frac{81\ in}{8} \tag{96}$$
$$= 10.125\ in.$$

Moment of Inertia for Load Step 3 is adopted from the BARS file. The bending stiffness along the length of the girder, which needs to be input the computer program, is tabulated in Table 37.

Table 36. Specifications for Bridge 5, Load Step 2

Location (ft)	Section Number	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)	Girder Profile	Behavior
0	1	14087.60	4.085E+11	Uniform	Composite
38	1	14087.60	4.085E+11		
	3	7732.78	2.243E+11	Parabolic	Non - Composite
54	2	14288.50	4.144E+11		
	2			Uniform	
56	2	14288.50	4.144E+11		
	2			Parabolic	
72	3	7732.78	2.243E+11		
	1	14087.60	4.085E+11	Uniform	Composite
108	1	14087.60	4.085E+11		
	3	7732.78	2.243E+11	Parabolic	Non - Composite
124	2	14288.50	4.144E+11		
	2			Uniform	
125	2	14288.50	4.144E+11		

Table 37. Specifications for Bridge 5, Load Step 3

Location (ft)	Section Number	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)	Girder Profile	Behavior
0	1	18711.6	5.426E+11	Uniform	Composite
38	1	18711.6	5.426E+11		
	3	7732.78	2.243E+11	Parabolic	Non - Composite
54	2	14288.5	4.144E+11		
	2			Uniform	
56	2	14288.5	4.144E+11		
	2			Parabolic	
72	3	7732.78	2.243E+11		
	1	18711.6	5.426E+11	Uniform	Composite
108	1	18711.6	5.426E+11		
	3	7732.78	2.243E+11	Parabolic	Non - Composite
124	2	14288.5	4.144E+11		
	2			Uniform	
125	2	14288.5	4.144E+11		

Movable Load Data - In the case of Bridge 5 the Live Load Distribution Factor is given in the bridge data as 1.606 for a wheel load. This factor is halved to get the distribution factor for an axle load.

To calculate the Impact Factor, (*I*) Equation (5) is utilized. This value matches the value specified in the Bridge Data.

$$I = \frac{50}{55\,ft + 125} \tag{97}$$

$$= 0.278$$

Now the effective live load can be calculated by using Equation (6).

$$\mathit{Effective\ Live\ Load} = \mathit{Axle\ Load} * 0.803 * (1 + 0.278) \tag{98}$$

Now that all the required moments have been calculated the next task is to calculate the required stresses. Section Modulus of the top and bottom of steel for load step 3 is given in the Bridge Data and the values tabulated in Table 38 are adopted from there.

Table 38. Section Modulus for Bridge 5, Load Step 3

<table>
<tr><th rowspan="2">Location (ft)</th><th rowspan="2">Section Number</th><th colspan="2">Section Modulus (in^3)</th><th rowspan="2">Girder Profile</th><th rowspan="2">Behavior</th></tr>
<tr><th>Top of Steel</th><th>Bottom of Steel</th></tr>
<tr><td>0</td><td>1</td><td>6265.1</td><td>547.1</td><td rowspan="2">Uniform</td><td rowspan="2">Composite</td></tr>
<tr><td rowspan="2">38</td><td>1</td><td>6265.1</td><td>547.1</td></tr>
<tr><td>3</td><td>414.1</td><td>413.7</td><td rowspan="2">Parabolic</td><td rowspan="6">Non - Composite</td></tr>
<tr><td rowspan="2">54</td><td>2</td><td rowspan="2">578.8</td><td rowspan="2">578.8</td></tr>
<tr><td>2</td><td rowspan="2">Uniform</td></tr>
<tr><td rowspan="2">56</td><td>2</td><td rowspan="2">578.8</td><td rowspan="2">578.8</td></tr>
<tr><td>2</td><td rowspan="2">Parabolic</td></tr>
<tr><td rowspan="2">72</td><td>3</td><td>414.1</td><td>413.7</td></tr>
<tr><td>1</td><td>6265.1</td><td>547.1</td><td rowspan="2">Uniform</td><td rowspan="2">Composite</td></tr>
<tr><td rowspan="2">108</td><td>1</td><td>6265.1</td><td>547.1</td></tr>
<tr><td>3</td><td>414.1</td><td>413.7</td><td rowspan="2">Parabolic</td><td rowspan="4">Non - Composite</td></tr>
<tr><td rowspan="2">124</td><td>2</td><td rowspan="2">578.8</td><td rowspan="2">578.8</td></tr>
<tr><td>2</td><td rowspan="2">Uniform</td></tr>
<tr><td>125</td><td>2</td><td>578.8</td><td>578.8</td></tr>
</table>

The available stress is calculated using Equation (23). The yield stress is substituted as 36,000 psi. Available stresses are calculated for two cases, 5% overstress by substituting Ω as 1.05 and 10% overstress by substituting Ω as 1.10. The critical weight is calculated using equation (25) where Wn is substituted as 100,000 lb. The critical weight is calculated using the spreadsheet created for each bridge.

Verification

The total dead load moment produced by the computer program, BMCOL51 was compared with the moment given in the BARS File. Also, moments produced by a vehicle from the BARS file were compared with the moments produced by the computer program, BMCOL51. The vehicle analyzed was a 3S2 vehicle which is not the same as any of the 3S2 vehicles analyzed in this study. The 3S2 vehicle is shown in Figure 9 and the results are tabulated in Table 39.

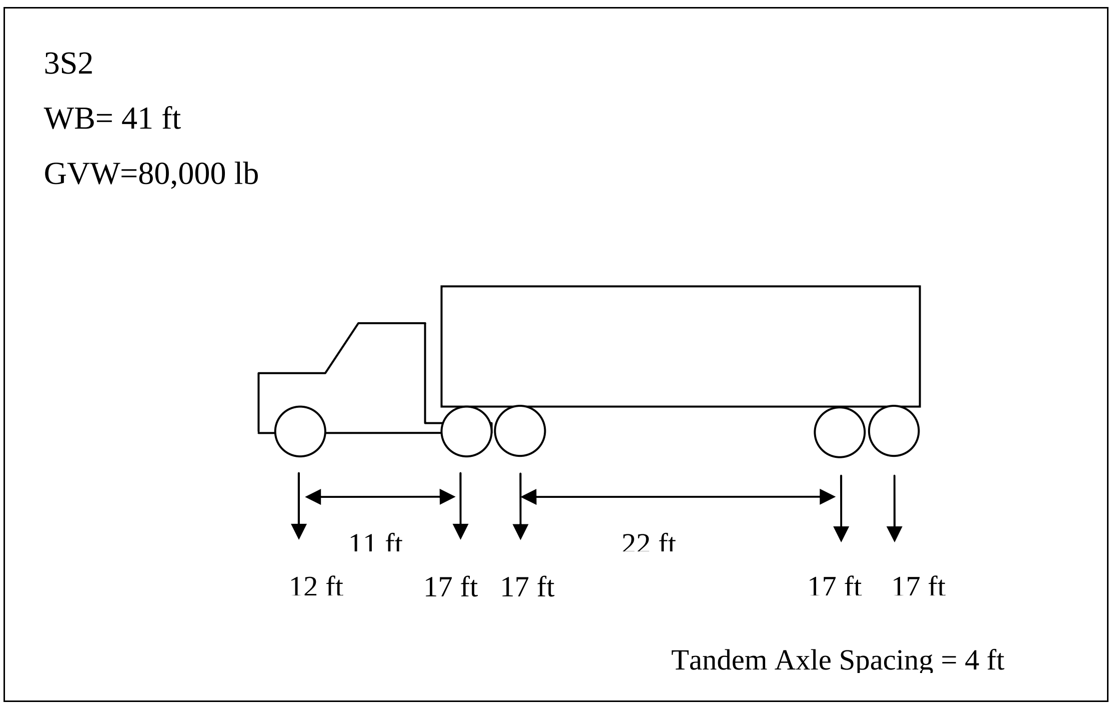


Figure 9. 3S2 Vehicle used for Bridge 5

Table 39. Moments from BARS and BMCOL51

	BARS (kip-ft)	BMCOL51 (kip-ft)
Maximum Positive Dead Load Moment	164	174
Max 3S2 Moment (*LL+I)*	570	570

Moment Redistribution

The dead load moments in the region of negative moments at the supports were reduced by 10% by multiplying by 0.9. The available stress is calculated using equation (67). Live load moments are also reduced by 10%. This is directly taken into account while calculating the critical weight by directly reducing the live load stress by 10%. Equation (69) is used to calculate the critical weight.

Bridge 5 is a four span bridge. The increase in positive moments at midspan is the average of the decrease in moments at the adjacent supports. The positive moments in spans 1 and 4 are increased by 5%, as one of the adjacent supports is an end support, so there is no moment reduction at this support and at the other support there is a reduction of 10%. The moments in span 2 and 3 are increased by 10%, as at both the adjacent supports the moments are reduced by 10%.

Available stresses are calculated for midspan region of spans 1 and 4 with the help of Equation (70). The critical weight is calculated in the midspan region by using equation (71). Available stresses are calculated for midspan region of spans 2 and 3 with the help of Equation (99). The critical weight is calculated in the midspan region by using equation (100).

$$\sigma_{av} = \frac{3}{5}\left(\frac{\Omega * Fy}{1.3} - \frac{1.10 * M_{DL}}{S_{LL}}\right) \tag{99}$$

$$Wcr = Wn * \frac{\sigma_{av}}{1.10 * \sigma_{LL+I}} \tag{100}$$

The critical weights are calculated for each truck type and are tabulated in the Results Section. If for a particular truck type the critical weight after moment redistribution is lesser than before, then the higher value is used.

Bridge 6

Bridge 6 is an example received from the South Dakota Department of Transportation through a survey conducted by Battelle, the research institute which sponsored this study. The data is given in the form of a BARS (Bridge Analysis and Rating System) File.

Bridge Specifications are:

- Design Method - Load Factor Design
- Design Load - HS20
- Number of Spans - 3 Span Continuous Composite Girder
- Total Length - 192 ft
- Span lengths: 57.02 ft – 72.5 ft – 57.02 ft
- Live Load Distribution Factor - 1.545 (wheel load)
- Dead Load 2 - 130 lb/ft
- Thickness of Slab - 6.75 in.
- Slab Width (per girder) – 102 in.
- Effective Slab Width – 81 in.

Material Properties:

- Material - Composite Steel and Concrete (CSC)
- Modulus of Elasticity for Steel - $2.9*10^7$psi
- Yield Stress for Steel - 36000 psi
- Concrete Density (γ_c) - 150 lb/ft^3
- Modular Ratio, $n = 8$

Load Step 1

Number of Increments and Increment Length

Number of Increments = 187

Increment Length = 12 in.

Support Geometry – The span length is rounded of, as decimal points cannot be input in the Computer Program. The approximated span lengths are of 57 ft, 73 ft and 57 ft. The Location of the supports from extreme left of the bridge is 0, 57, 130, 187.

Stiffness and Fixed Load Data - Width of slab is given as 102 in. and thickness is 6.75 in. Density of concrete is assumed to be 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ \ concrete\ slab\ (lb/\ ft)\ &=\ \frac{6.75}{12}\ ft*\frac{102}{12}\ ft*150\ lb/\ ft^3 \\ &=\ 717.2\ lb/\ ft \end{aligned} \tag{101}$$

Longitudinal Profile of the plate girder is shown in Figure 10. Since the bridge is symmetrical only one half of the entire bridge is shown in the figure. The numbers in boxes indicate section number at that location.

Table 40 shows the section numbers along the length of the bridge, it also shows the variation in the plate girder depth along the bridge. Weight of the plate girder itself, total weight, which includes the girder weight and the concrete slab weight are also tabulated. Besides this, moment of inertia and bending stiffness of the girder is calculated and is shown in Table 40. Since the bridge is symmetrical, values are only shown for one half of the bridge. The total weight per increment and bending stiffness are shown in Scientific Number format with three decimal places because they are entered in this format in the computer program.

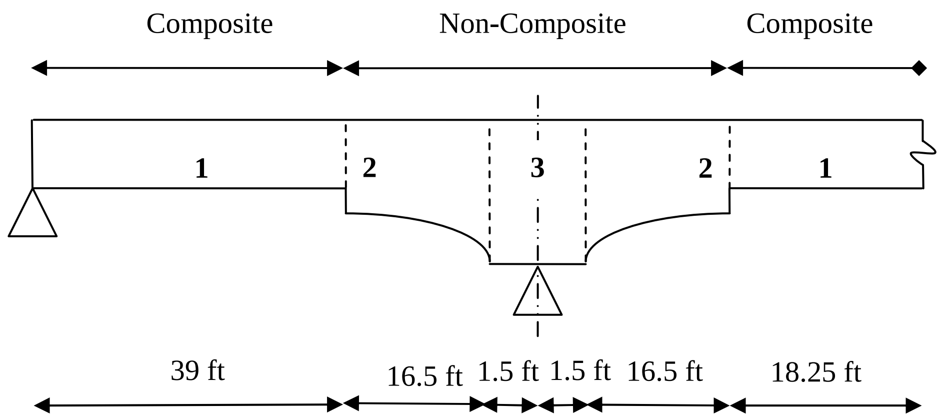


Figure 10. Longitudinal Profile of Bridge 6

Table 40. Specifications for Bridge 6, Load Step 1

Location (ft)	Section Number	Member Weight (lb/ft)	Total Weight (lb/increment)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Girder Profile
0	1	102.5	8.197E+02	7424	2.153E+11	Uniform
39	1	102.5	8.197E+02	7424	2.153E+11	
	2	121.6	8.388E+02	9785	2.838E+11	Parabolic
56	3	134.4	8.516E+02	17512	5.079E+11	
	3	134.4	8.516E+02	17512	5.079E+11	Uniform
58	3	134.4	8.516E+02	17512	5.079E+11	
	3	134.4	8.516E+02	17512	5.079E+11	Parabolic
75	2	121.6	8.388E+02	9785	2.838E+11	
	1	102.5	8.197E+02	7424	2.153E+11	Uniform
93.5	1	102.5	8.197E+02	7424	2.153E+11	

Load Step 2

Stiffness and Fixed Load Data - Besides the section variation and plate depth variation along the length of the bridge Table 41 shows the regions of composite and non-composite behavior. In the bridge data the composite ranges are slightly different from those used in this study. A conservative simplification is made; composite action occurs only in the region of section 1 and non-composite action occurs in the region of section 2.

The value of effective slab width is given as 81 in. This in fact is 12 times the thickness of the slab, which usually governs the effective width.

$$Transformed\ Width\ of\ slab = \frac{81\ in}{3*8} \tag{102}$$

$$= 3.375 \text{ in.}$$

Dead load 2 of 130 lb/ft is given in the Bridge Data and as the increment length is 12 in. the load per increment is also 130 lb. Table 41 also shows the moment of inertia and stiffness for the interior girder for Load Step 2 by taking into account contribution of the slab in regions of positive bending moment. Value of moment of inertia is adopted from the BARS file.

Load Step 3

Increment length - For each different truck that is entered into the computer program its length is input in terms of the number of increments. The distance in terms of the number of increments is calculated from the extreme left axle.

Stiffness and Fixed Load Data -

$$Transformed\ Width\ of\ slab = \frac{81\ in}{8} \tag{103}$$

$$= 10.125\ in.$$

Moment of Inertia for Load Step 3 is adopted from the BARS file. The bending stiffness along the length of the girder, which needs to be input the computer program, is tabulated in Table 42.

Table 41. Specifications for Bridge 6, Load Step 2

Location (ft)	Section Number	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)	Girder Profile	Behavior
0	1	15636	4.534E+11	Uniform	Composite
39	1	15636	4.534E+11		
	2	9785	2.838E+11	Parabolic	Non - Composite
56	3	17512	5.079E+11		
	3	17512	5.079E+11	Uniform	
58	3	17512	5.079E+11		
	3	17512	5.079E+11	Parabolic	
75	2	9785	2.838E+11		
	1	15636	4.534E+11	Uniform	Composite
93.5	1	15636	4.534E+11		

Table 42. Specifications for Bridge 6, Load Step 3

Location (ft)	Section Number	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)	Girder Profile	Behavior
0	1	20781	6.026E+11	Uniform	Composite
39	1	20781	6.026E+11		
	2	9785	2.838E+11	Parabolic	Non - Composite
56	3	17512	5.079E+11		
	3	17512	5.079E+11	Uniform	
58	3	17512	5.079E+11		
	3	17512	5.079E+11	Parabolic	
75	2	9785	2.838E+11		
	1	20781	6.026E+11	Uniform	Composite
93.5	1	20781	6.026E+11		

Movable Load Data - In the case of Bridge 6 the Live Load Distribution Factor is given in the bridge data as 1.545 for a wheel load. This factor is halved to get the distribution factor for an axle load.

To calculate the Impact Factor, (*I*) Equation (11) is utilized. This value matches the value specified in the Bridge Data.

$$\begin{aligned} I &= \frac{50}{57\,ft + 125} \\ &= 0.275 \end{aligned} \tag{104}$$

Now the effective live load can be calculated by using Equation (12).

$$Effective\ Live\ Load = Axle\ Load * 0.7725 * (1 + 0.275) \tag{105}$$

Now that all the required moments have been calculated the next task is to calculate the required stresses. Section Modulus of the top and bottom of steel for load step 3 is given in the Bridge Data and the values tabulated in Table 43 are adopted from there.

Table 43. Section Modulus for Load Step 3 of Bridge 6

<table>
<tr><th>Location (ft)</th><th>Section Number</th><th>Top of Steel</th><th>Bottom of Steel</th><th>Girder Profile</th><th>Behavior</th></tr>
<tr><td>0</td><td>1</td><td>5682.5</td><td>614</td><td rowspan="2">Uniform</td><td rowspan="2">Composite</td></tr>
<tr><td rowspan="2">39</td><td>1</td><td>5682.5</td><td>614</td></tr>
<tr><td>2</td><td>518.4</td><td>518.4</td><td rowspan="2">Parabolic</td><td rowspan="6">Non - Composite</td></tr>
<tr><td rowspan="2">56</td><td>3</td><td>704.0</td><td>704.0</td></tr>
<tr><td>3</td><td>704.0</td><td>704.0</td><td rowspan="2">Uniform</td></tr>
<tr><td rowspan="2">58</td><td>3</td><td>704.0</td><td>704.0</td></tr>
<tr><td>3</td><td>704.0</td><td>704.0</td><td rowspan="2">Parabolic</td></tr>
<tr><td rowspan="2">75</td><td>2</td><td>518.4</td><td>518.4</td></tr>
<tr><td>1</td><td>5682.5</td><td>614</td><td rowspan="2">Uniform</td><td rowspan="2">Composite</td></tr>
<tr><td>93.5</td><td>1</td><td>5682.5</td><td>614</td></tr>
</table>

The available stress is calculated using Equation (29). The yield stress is substituted as 36,000 psi. Available stresses are calculated for two cases, 5% overstress by substituting Ω as 1.05 and 10% overstress by substituting Ω as 1.10. The critical weight is calculated using equation (31) where *Wn* is substituted as 100,000 lb.

Verification

From Table 44 it is evident that the results match well for dead load moments. The live load moments are tabulated in Table 45; for Live Loads the moments are compared for two vehicles: HS-20 (short) and 3S2. Moments are compared for two cases: when stiffness is considered to be uniform and when actual stiffness is used. The results show that when stiffness is uniform the moments are similar but when the actual stiffness is used the results differ to a certain extent.

Table 44. Dead Load Moments

	BARS (kip-ft)	BMCOL51 (kip-ft)
Maximum Positive Dead Load Moment	192	188

Table 45. Live Load Moments

	BARS (kip-ft)	BMCOL51 UNIFORM EI (kip-ft)	BMCOL51 ACTUAL EI (kip-ft)
Max HS-20 (short) Moment (*LL+I)*	621	629	661
Max 3S2 Moment (*LL+I)*	540	545	571

Moment Redistribution

Dead load moments in the region of negative moments at supports were reduced by 10% by multiplying by 0.9. The available stress is calculated using equation (67). Live load moments are also reduced by 10%. This is directly taken into account while calculating the critical weight by directly reducing the live load stress by 10% using Equation (69).

Bridge 6 is a three span bridge. The increase in positive moments at midspan is the average of the decrease in moments at the adjacent supports. The positive moments in spans 1 and 3 are increased by 5%, as one of the adjacent supports is an end support, so there is no moment reduction at this support and at the other support there is a reduction of 10%. The moments in span 2 are increased by 10%, as at both the adjacent supports the moments are reduced by 10%.

Available stresses are calculated for midspan region of spans 1 and 3 with the help of Equation (70). The critical weight is calculated in the midspan region by using equation (71). Available stresses for midspan region of span 2 are calculated with the help of Equation (99). The critical weight is calculated in the midspan region by using equation (100).

Bridge 7

Bridge 7 is an example received from the South Dakota Department of Transportation through a survey conducted by Battelle, the research institute which sponsored this study. The data is given in the form of a BARS (Bridge Analysis and Rating System) File.

Bridge Specifications are:

- Design Method - Load Factor Design
- Design Load - HS20
- Number of Spans - 6 Span Continuous Composite Girder
- Total Length - 780 ft
- Span lengths: 110 ft - 140 ft – 140 ft -140 ft – 140 ft – 110 ft
- Live Load Distribution Factor - 1.5 (wheel load)
- Dead Load 2 - 325 lb/ft
- Thickness of Slab - 8.5 in.
- Slab Width (per girder) - 99 in.
- Effective Slab Width - 81 in.

Material Properties:

- Material - Composite Steel and Concrete (CSC)
- Modulus of Elasticity for Steel - $2.9*10^7$ psi
- Flange Yield Stress for Steel

  Section 1 - 36,000 psi

  Section 2 - 46,000 psi

  Section 3 - 46,000 psi

  Section 4 - 46,000 psi

  Section 5 - 46,000 psi
- Concrete Density (γ_c) - 150 lb/ft^3
- Modular Ratio, n = 8

Load Step 1

Number of Increments and Increment Length - The total length of the bridge is 780 ft. As this value is greater than 500 an increment length greater than 12 in. needs to be entered.

Number of Increments = 468

Increment Length = 20 in.

Support Geometry - As the increment length is not 12 in. the support location cannot be directly entered in terms of its location if ft. For an increment length of 20 in. the support locations are 0, 66, 150, 234, 318, 402, and 468.

Stiffness and Fixed Load Data - Width of slab is given as 99 in. and thickness is 8.5 in. Density of concrete is assumed to be 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ concrete\ slab\ (lb/ft) &= \frac{8.5}{12}\,ft * \frac{99}{12}\,ft * 150\ lb/ft^3 \\ &= 876.6\ lb/ft \end{aligned} \tag{106}$$

Longitudinal Profile of the plate girder is shown in Figure 11. Section numbers are shown on the girder. Table 46 shows the section numbers along the length of the bridge. As the bridge does not have any parabolic ranges the variation of plate girder depth along the length of the bridge is not shown. Weight of the plate girder itself, total weight, which includes the girder weight and the concrete slab weight, $876.6\ lb/ft$, are also tabulated. Besides this, moment of inertia and bending stiffness of the girder is calculated and is shown in Table 46. As the increment length is 20 in. and not 12 in., total weight per foot is not equal to the total weight per increment.

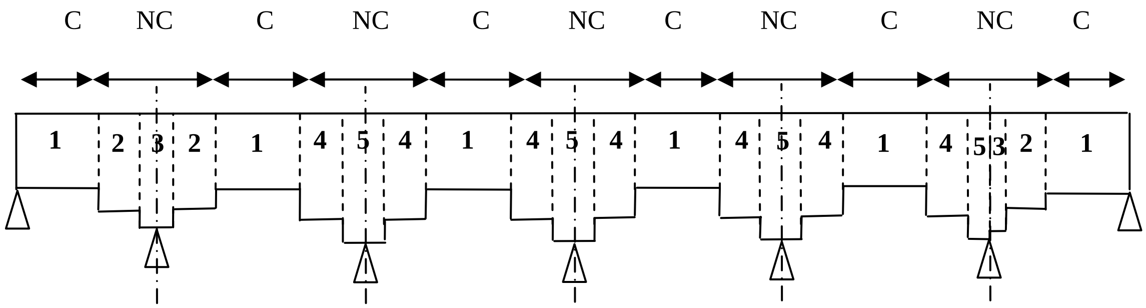


Figure 11. Longitudinal Profile of Bridge 7

Load Step 2

Stiffness and Fixed Load Data - Table 47 shows the regions of composite behavior and non-composite section. The bridge has been designed such that section 1 is the only section where the composite action takes place, the rest of the sections are in regions of negative moment and therefore do not exhibit composite behavior.

The effective width and transformed need not be calculated as the values of the moment of inertia for load step 2 are already given. Dead load 2 of 325 lb/ft is given in the Bridge Data. The load per increment (20 in.) is calculated and entered in the computer program. Table 47 shows the moment of inertia and stiffness for the interior girder for Load Step 2 by taking into account contribution of the slab in regions of positive bending moment. Value of moment of inertia is adopted from the BARS file.

Load Step 3

Increment length - For each different truck that is entered into the computer program its length is input in terms of the number of increments. The distance in terms of the number of increments is calculated from the extreme left axle.

Stiffness and Fixed Load Data - Moment of Inertia for Load Step 3 is adopted from the BARS file. The bending stiffness along the length of the girder, which needs to be input the computer program, is tabulated in Table 48.

Table 46. Specifications for Bridge 7, Load Step 1

Section Number	Section Length (ft)	Location (ft)	Member Weight (lb/ft)	Total Weight (lb/ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)
1	78	0 - 78	149.7	1.026E+03	36968	1.072E+12
2	20	78 - 98	177.6	1.054E+03	48706	1.412E+12
3	12	98 - 110	195.7	1.072E+03	56673	1.644E+12
3	12	110 - 122	195.7	1.072E+03	56673	1.644E+12
2	20	122 - 142	177.6	1.054E+03	48706	1.412E+12
1	76	142 - 218	149.7	1.026E+03	36968	1.072E+12
4	20	218 - 238	189.7	1.066E+03	53618	1.555E+12
5	12	238 - 250	207.6	1.084E+03	61545	1.785E+12
5	12	250 - 262	207.6	1.084E+03	61545	1.785E+12
4	20	262 - 282	189.7	1.066E+03	53618	1.555E+12
1	76	282 - 358	149.7	1.026E+03	36968	1.072E+12
4	20	358 - 378	189.7	1.066E+03	53618	1.555E+12
5	12	378 - 390	207.6	1.084E+03	61545	1.785E+12
5	12	390 - 402	207.6	1.084E+03	61545	1.785E+12
4	20	402 - 422	189.7	1.066E+03	53618	1.555E+12
1	76	422 - 498	149.7	1.026E+03	36968	1.072E+12
4	20	498 - 518	189.7	1.066E+03	53618	1.555E+12
5	12	518 - 530	207.6	1.084E+03	61545	1.785E+12
5	12	530 - 542	207.6	1.084E+03	61545	1.785E+12
4	20	542 - 562	189.7	1.066E+03	53618	1.555E+12
1	76	562 - 638	149.7	1.026E+03	36968	1.072E+12
4	20	638 - 658	189.7	1.066E+03	53618	1.555E+12
5	12	658 - 670	207.6	1.084E+03	61545	1.785E+12
3	12	670 - 682	195.7	1.072E+03	56673	1.644E+12
2	20	682 - 702	177.6	1.054E+03	48706	1.412E+12
1	78	702 - 780	149.7	1.026E+03	36968	1.072E+12

Table 47. Specifications for Bridge 7, Load Step 2

Section Number	Section Length (ft)	Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
1	78	0 - 78	77650	2.252E+12	Composite
2	20	78 - 98	48706	1.412E+12	Non-Composite
3	12	98 - 110	56673	1.644E+12	
3	12	110 - 122	56673	1.644E+12	
2	20	122 - 142	48706	1.412E+12	
1	76	142 - 218	77650	2.252E+12	Composite
4	20	218 - 238	53618	1.555E+12	Non-Composite
5	12	238 - 250	61545	1.785E+12	
5	12	250 - 262	61545	1.785E+12	
4	20	262 - 282	53618	1.555E+12	
1	76	282 - 358	77650	2.252E+12	Composite
4	20	358 - 378	53618	1.555E+12	Non-Composite
5	12	378 - 390	61545	1.785E+12	
5	12	390 - 402	61545	1.785E+12	
4	20	402 - 422	53618	1.555E+12	
1	76	422 - 498	77650	2.252E+12	Composite
4	20	498 - 518	53618	1.555E+12	Non-Composite
5	12	518 - 530	61545	1.785E+12	
5	12	530 - 542	61545	1.785E+12	
4	20	542 - 562	53618	1.555E+12	
1	76	562 - 638	77650	2.252E+12	Composite
4	20	638 - 658	53618	1.555E+12	Non-Composite
5	12	658 - 670	61545	1.785E+12	
3	12	670 - 682	56673	1.644E+12	
2	20	682 - 702	48706	1.412E+12	
1	78	702 - 780	77650	2.252E+12	Composite

Table 48. Specifications for Bridge 7, Load Step 3

Section Number	Section Length (ft)	Location (ft)	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)	Behavior
1	78	0 - 78	105405	3.057E+12	Composite
2	20	78 - 98	48706	1.412E+12	Non-Composite
3	12	98 - 110	56673	1.644E+12	
3	12	110 - 122	56673	1.644E+12	
2	20	122 - 142	48706	1.412E+12	
1	76	142 - 218	105405	3.057E+12	Composite
4	20	218 - 238	53618	1.555E+12	Non-Composite
5	12	238 - 250	61545	1.785E+12	
5	12	250 - 262	61545	1.785E+12	
4	20	262 - 282	53618	1.555E+12	
1	76	282 - 358	105405	3.057E+12	Composite
4	20	358 - 378	53618	1.555E+12	Non-Composite
5	12	378 - 390	61545	1.785E+12	
5	12	390 - 402	61545	1.785E+12	
4	20	402 - 422	53618	1.555E+12	
1	76	422 - 498	105405	3.057E+12	Composite
4	20	498 - 518	53618	1.555E+12	Non-Composite
5	12	518 - 530	61545	1.785E+12	
5	12	530 - 542	61545	1.785E+12	
4	20	542 - 562	53618	1.555E+12	
1	76	562 - 638	105405	3.057E+12	Composite
4	20	638 - 658	53618	1.555E+12	Non-Composite
5	12	658 - 670	61545	1.785E+12	
3	12	670 - 682	56673	1.644E+12	
2	20	682 - 702	48706	1.412E+12	
1	78	702 - 780	105405	3.057E+12	Composite

Movable Load Data - In the case of Bridge 7 the Live Load Distribution Factor is given in the bridge data as 1.5 for a wheel load. This factor is halved to get the distribution factor for an axle load.

To calculate the Impact Factor, (*I*) Equation (11) is utilized. This value matches the value specified in the Bridge Data.

$$I = \frac{50}{110\,ft + 125} = 0.213 \tag{107}$$

Now the effective live load can be calculated by using Equation (12).

$$Effective\ Live\ Load = Axle\ Load * 0.75 * (1 + 0.2) \tag{108}$$

The available stress is calculated using Equation (29). Section Modulus for Load Step 3, S_{LL} required for calculation of available stress is tabulated in Table 49 for top and bottom of the steel section.

Since the stresses are being calculated at the top and bottom of steel, flange yield stresses of the respective sections need to be substituted to find available stress. Yield stress value of 36,000 psi is substituted for section 1 and 46000 psi for the remaining sections. Available stresses are calculated for two cases, 5% overstress by substituting Ω as 1.05 and 10% overstress by substituting Ω as 1.10.

The critical weight is calculated using equation (31) where Wn is substituted as 100,000 lb. The critical weights are calculated using a Microsoft Excel Spreadsheet.

Table 49. Section Modulus for Load Step 3 of Bridge 7

Section Length (ft)	Location (ft)	Top of Steel (in^3)	Bottom of Steel (in^3)	Behavior
78	0 - 78	10446.90	1659.00	Composite
20	78 - 98	1198.77	1453.91	Non-Composite
12	98 - 110	1521.40	1521.40	
12	110 - 122	1521.40	1521.40	
20	122 - 142	1198.77	1453.91	
76	142 - 218	10446.90	1659.00	Composite
20	218 - 238	1324.36	1581.93	Non-Composite
12	238 - 250	1646.70	1646.70	
12	250 - 262	1646.70	1646.70	
20	262 - 282	1324.36	1581.93	
76	282 - 358	10446.90	1659.00	Composite
20	358 - 378	1324.36	1581.93	Non-Composite
12	378 - 390	1646.70	1646.70	
12	390 - 402	1646.70	1646.70	
20	402 - 422	1324.36	1581.93	
76	422 - 498	10446.90	1659.00	Composite
20	498 - 518	1324.36	1581.93	Non-Composite
12	518 - 530	1646.70	1646.70	
12	530 - 542	1646.70	1646.70	
20	542 - 562	1324.36	1581.93	
76	562 - 638	10446.90	1659.00	Composite
20	638 - 658	1324.36	1581.93	Non-Composite
12	658 - 670	1646.70	1646.70	
12	670 - 682	1521.40	1521.40	
20	682 - 702	1198.77	1453.91	
78	702 - 780	10446.90	1659.00	Composite

Verification

Maximum dead load moments and moments due to HS20 (short) obtained from the BARS file and the computer program, BMCOL51 are compared in Table 50. Here the axle loads for HS20 truck are not scaled to make the weight of the truck equal to 100,000 lb; instead the original axle loads of 8 kip, 32 kip, 32 kip are used.

Table 50. Comparison of Moments

	BARS (kip-ft)	BMCOL51 (kip-ft)
Maximum Positive Dead Load Moment	1083	1084
Max HS20(short) Moment(*LL+I*)	1419	1427

Moment Redistribution

Dead load moments in the region of negative moments at supports were reduced by 10% by multiplying by 0.9. The available stress is calculated using equation (67). Live load moments are also reduced by 10%. This is directly taken into account while calculating the critical weight by directly reducing the live load stress by 10% using Equation (69).

Bridge 7 is a six span bridge. The increase in positive moments at midspan is the average of the decrease in moments at the adjacent supports. The positive moments in spans 1 and 6 are increased by 5%, as one of the adjacent supports is an end support, so there is no moment reduction at this support and at the other support there is a reduction of 10%. The moments in span 2, 3, 4 and 5 are increased by 10%, as at both the adjacent supports the moments are reduced by 10%.

Available stresses are calculated for midspan region of spans 1 and 6 with the help of Equation (70). The critical weight is calculated in the midspan region by using equation (71). Available stresses for midspan region of span 2, 3, 4, and 5 are calculated with the help of Equation (99). The critical weight is calculated in the midspan region by using equation (100).

Bridge 8

Bridge 8 is one of the examples received from the South Dakota Department of Transportation through a survey conducted by Battelle, the research institute that sponsored this study. The data is given in the form of a BARS (Bridge Analysis and Rating System) File.

Bridge Specifications are:

- Design Method - Load Factor Design
- Design Load - HS20
- Number of Spans - 3 Span Continuous Composite Girder
- Total Length - 158 ft
- Span lengths: 48 ft - 60 ft – 48 ft
- Live Load Distribution Factor - 1.545 (wheel load)
- Dead Load 2 - 335 lb/ft
- Thickness of Slab - 7 in.
- Slab Width (per girder) - 102 in.

Material Properties:

- Material - Composite Steel and Concrete (CSC)
- Modulus of Elasticity for Steel - $2.9*10^7$ psi
- Yield Stress for Steel
- Concrete Density (γ_c) - 150 lb/ft^3

Load Step 1

Number of Increments and Increment Length - The total length of the bridge is 780 ft. As this value is greater than 500 an increment length greater than 12 in. needs to be entered.

Number of Increments = 156

Increment Length = 12 in.

Support Geometry - Span lengths are 48 ft, 60 ft, 48 ft.; the increment length is 12 in. therefore the support location can directly be entered as 0, 48, 108, and 156.

Stiffness and Fixed Load Data - Width of slab is given as 102 in. and thickness is 7.0 in. Density of concrete is assumed to be 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ concrete\ slab\ (lb/ft) &= \frac{7.0}{12}\, ft * \frac{102}{12}\, ft * 150\ lb/ft^3 \\ &= 743.8\ lb/ft \end{aligned} \tag{109}$$

Longitudinal Profile of the plate girder is shown in Figure 12. Since the bridge is symmetrical only half the bridge is shown. The numbers on the girder represent the section number.

Table 51 shows the section numbers along the length of the bridge. As the bridge does not have a parabolic or varying plate girder depth in any range, the variation of plate girder depth along the length of the bridge is not shown. Weight of the plate girder itself, total weight, which includes the girder weight and the concrete slab weight are also tabulated. Besides this, moment of inertia and bending stiffness of the girder is calculated and is shown in Table 51. Since the bridge is symmetrical the specifications for only half the bridge are tabulated.

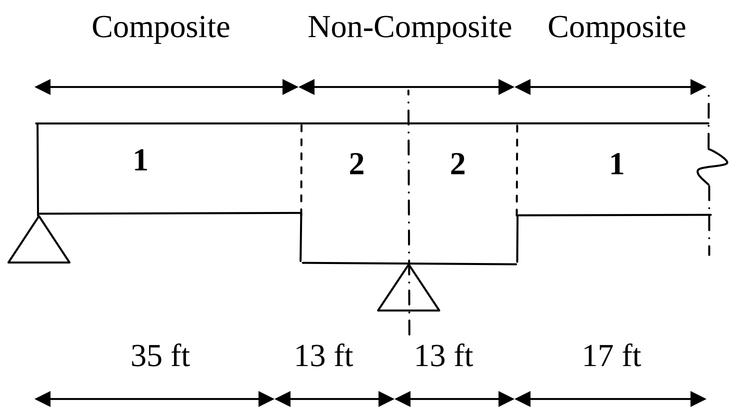


Figure 12. Longitudinal Profile of Bridge 8

Table 51. Specifications for Bridge 8, Load Step 1

Section Number	Section Length (ft)	Location (ft)	Member Weight (lb/ft)	Total Weight (lb/ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)
1	35	0 - 35	80.8	8.246E+02	5323	1.544E+11
2	13	35 - 48	97.8	8.416E+02	7165	2.078E+11
2	13	48 - 61	97.8	8.416E+02	7165	2.078E+11
1	17	61 - 78	80.8	8.246E+02	5323	1.544E+11

Load Step 2

Stiffness and Fixed Load Data - Table 52 shows the regions of composite behavior and non-composite section. In the bridge data the composite ranges are slightly different from those used in this study. In the bridge data the composite range is specified a few feet beyond section 1, so that a few feet of section 2 also undergoes composite behavior.

A conservative simplification is made; composite action occurs only in the region of section 1 and non-composite action occurs in the region of section 2.

The effective width and transformed need not be calculated as the values of the moment of inertia for load case 2 is already given. Dead load 2 of 335 lb/ft is given in the Bridge Data. Table 52 shows the moment of inertia and stiffness for the interior girder for Load Step 2 by taking into account contribution of the slab in regions of positive bending moment. Value of moment of inertia is adopted from the BARS file. Since the bridge is symmetrical, values are shown only for one half of the bridge.

Table 52. Specifications for Bridge 8, Load Step 2

Section Number	Section Length (ft)	Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
1	35	0 - 35	13510	3.918E+11	Composite
2	13	35 - 48	7165	2.078E+11	Non-
2	13	48 - 61	7165	2.078E+11	Composite
1	17	61 - 78	13510	3.918E+11	Composite

Load Step 3

Increment length - For each different truck that is entered into the computer program its length is input in terms of the number of increments. In Table 53 distance of individual axles from the extreme left axle in terms of the number of increments is calculated. The axle spacing of the extreme outer axles is entered here.

Stiffness and Fixed Load Data - Moment of Inertia for Load Step 3 is adopted from the BARS file. The bending stiffness along the length of the girder, which needs to be input the computer program, is tabulated in Table 53.

Table 53. Specifications for Bridge 8, Load Step 3

Section Number	Section Length (ft)	Location (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Behavior
1	35	0 - 35	17143	4.971E+11	Composite
2	13	35 - 48	7165	2.078E+11	Non-
2	13	48 - 61	7165	2.078E+11	Composite
1	17	61 - 78	17143	4.971E+11	Composite

Movable Load Data - In the case of Bridge 7 the Live Load Distribution Factor is given in the bridge data as 1.545 for a wheel load. This factor is halved to get the distribution factor for an axle load.

To calculate the Impact Factor, (*I*) Equation (11) is utilized. This value matches the value specified in the Bridge Data.

$$I = \frac{50}{48\,ft + 125} \\ = 0.289 \tag{110}$$

Now the effective live load can be calculated by using Equation (12).

$$Effective\ Live\ Load = Axle\ Load * 0.7725 * (1 + 0.289) \tag{111}$$

The available stress is calculated using Equation (29). Section Modulus for Load Step 3, S_{LL} required for calculation of available stress is tabulated in Table 54 for top and bottom of the steel section. These values are adopted from the BARS file of this particular bridge.

Yield stress is substituted as 36,000 psi. Available stresses are calculated for two cases, 5% overstress by substituting Ω as 1.05 and 10% overstress by substituting Ω as 1.10. Critical weight is calculated using equation (31) where Wn is substituted as 100,000 lb. Critical weight is calculated using the spreadsheet created for each bridge.

Table 54. Section Modulus for Load Step 3 of Bridge 8

Section Number	Section Length (ft)	Location (ft)	Top of Steel	Bottom of Steel	Behavior
1	35	0 - 35	18161.40	472.50	Composite
2	13	35 - 48	375.70	383.60	Non-
2	13	48 - 61	375.70	383.60	Composite
1	17	61 - 78	18161.40	472.50	Composite

Verification

To verify the procedure and results the total maximum dead load moments obtained from the study is compared with the value in the BARS File. Also the moment due to HS20 (short) is compared. Here the actual axle loads are used without scaling them to get a maximum gross weight of 100,000 lb. Values of moments for the above two cases are tabulated in Table 55.

Table 55. Comparison of Moments for Bridge 8

	BARS (kip-ft)	BMCOL51 (kip-ft)
Maximum Positive Dead Load Moment	184	184
Max HS20(short) Moment(*LL+I)*	563	556

Moment Redistribution

Dead load moments in the region of negative moments at supports were reduced by 10% by multiplying by 0.9. The available stress is calculated using equation (67). Live load moments are also reduced by 10%. This is directly taken into account while calculating the critical weight by directly reducing the live load stress by 10% using Equation (69).

Bridge 8 is a three span bridge. The increase in positive moments at midspan is the average of the decrease in moments at the adjacent supports. The positive moments in spans 1 and 3 are increased by 5%, as one of the adjacent supports is an end support, so there is no moment reduction at this support and at the other support there is a reduction of 10%. The moments in span 2 are increased by 10%, as at both the adjacent supports the moments are reduced by 10%.

Available stresses are calculated for midspan region of spans 1 and 3 with the help of Equation (70). The critical weight is calculated in the midspan region by using equation (71).

Available stresses for midspan region of span 2 are calculated with the help of Equation (99). The critical weight is calculated in the midspan region by using equation (100).

Bridge 9

Bridge 9 is one of the examples received from the South Dakota Department of Transportation through a survey conducted by Battelle, the funding research institute for this study. The data is given in the form of a BARS (Bridge Analysis and Rating System) File.

Bridge Specifications are:

- Design Method - Load Factor Design
- Design Load - HS20
- Number of Spans - 6 Span Continuous Composite Girder
- Total Length - 748 ft

- Span lengths: 104 ft - 135 ft - 135 ft - 135 ft - 135 ft - 104 ft
- Live Load Distribution Factor - 1.606 (wheel load)
- Dead Load 2 - 205 lb/ft
- Thickness of Slab - 8 in.
- Slab Width (per girder) - 106 in.

Material Properties:

- Material - Composite Steel and Concrete (CSC)
- Modulus of Elasticity for Steel - $2.9*10^7$ psi
- Yield Stress for Steel - 36000 psi
- Concrete Density (γ_c) - 150 lb/ft^3

Load Step 1

Number of Increments and Increment Length - The total length of the bridge is 748 ft. As this value is greater than 500 an increment length greater than 12 in. needs to be entered.

Number of Increments = 499

Increment Length = 18 in.

Support Geometry - The support locations are entered in terms of the number of increments hence will not be the same as they would be in feet. Support location in feet and in increments is shown in Table 56.

Table 56. Support Location for Bridge 9

Location (ft)	Location (increment)
0	0
104	69
239	159
374	249

509	339
644	429
748	499

Stiffness and Fixed Load Data - Width of slab is given as 106 in. and thickness is 8.0 in. Density of concrete is assumed to be 150 lb/ft^3.

$$\begin{aligned} Weight\ of\ \ concrete\ slab\ (lb/\ ft)\ &=\ \frac{8.0}{12}\,ft*\frac{106}{12}\,ft*150\ lb/\ ft^3 \\ &=\ 883.3\ lb/\ ft \end{aligned} \tag{112}$$

Longitudinal Profile of the plate girder is shown in Figure 13. Since the bridge is symmetrical only half the bridge is shown. The numbers on the girder represent the section number and the length of each range is shown in feet.

Table 57 shows the section numbers, location of change of range, length of range and variation of plate girder depth along the length of the bridge. Weight of the plate girder itself, total weight, which includes the girder weight and the concrete slab weight are also tabulated. Besides this, moment of inertia and bending stiffness of the girder is calculated in Table 57. Since the bridge is symmetrical, specifications for only half the bridge are tabulated.

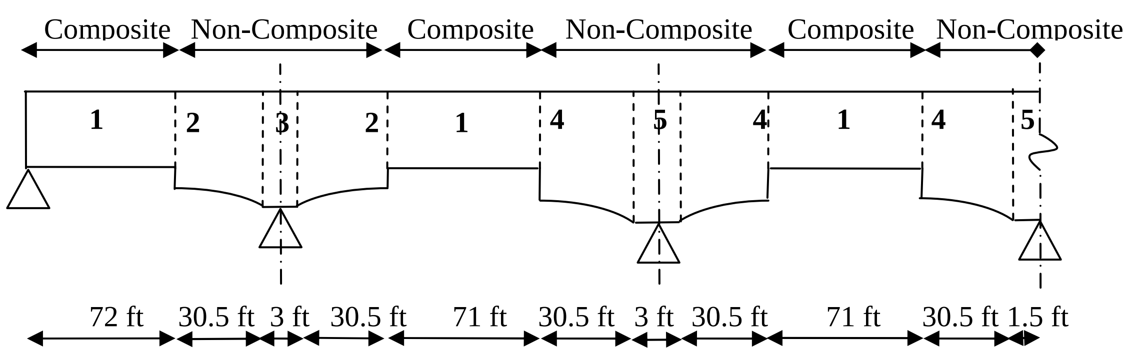


Figure 13. Longitudinal Profile of Bridge 9

Load Step 2

Stiffness and Fixed Load Data - Table 58 shows the regions of composite behavior and non-composite section. The bridge has been designed such that section 1 lies in the composite region while all the other sections are in the non-composite region.

The effective and transformed width need not be calculated as the values of the moment of inertia for load case 2 is already given. Table 58 also shows the moment of inertia and stiffness for the interior girder for Load Step 2 by taking into account contribution of the slab in regions of positive bending moment. Value of moment of inertia is adopted from the BARS file. Since the bridge is symmetrical, values are shown only for one half of the bridge.

Load Step 3

Increment length - For each different truck that is entered into the computer program its length is input in terms of the number of increments. Distance of individual axles from the extreme left axle in terms of the number of increments is calculated. The axle spacing of the extreme outer axles is entered here.

Stiffness and Fixed Load Data - Moment of Inertia for Load Step 3 is adopted from the BARS file. The bending stiffness along the length of the girder, which needs to be input the computer program, is tabulated in Table 59.

Table 57. Specifications for Bridge 9, Load Step 1

Section Number	Location (ft)	Length of Range (ft)	Member Weight (lb/ft)	Total Weight (lb/increment)	Moment of Inertia (in^4)	Bending Stiffness (lb-in^2)	Girder Profile
1	0	72	146.7	1.030E+03	17410	5.049E+11	Uniform
1	72		146.7	1.030E+03	17410	5.049E+11	
2		30.5	200.8	1.084E+03	30196	8.757E+11	Parabolic
3	102.5		239.0	1.122E+03	95619	2.773E+12	
3		3	239.0	1.122E+03	95619	2.773E+12	Uniform
3	105.5		239.0	1.122E+03	95619	2.773E+12	
3		30.5	239.0	1.122E+03	95619	2.773E+12	Parabolic
2	136		200.8	1.084E+03	30196	8.757E+11	
1		71	146.7	1.030E+03	17410	5.049E+11	Uniform
1	207		146.7	1.030E+03	17410	5.049E+11	
4		30.5	207.6	1.091E+03	31076	9.012E+11	Parabolic
5	237.5		245.9	1.129E+03	99387	2.882E+12	
5		3	245.9	1.129E+03	99387	2.882E+12	Uniform
5	240.5		245.9	1.129E+03	99387	2.882E+12	
5		30.5	245.9	1.129E+03	99387	2.882E+12	Parabolic
4	306.5		207.6	1.091E+03	31076	9.012E+11	
1		71	146.7	1.030E+03	17410	5.049E+11	Uniform
1	342		146.7	1.030E+03	17410	5.049E+11	
4		30.5	207.6	1.091E+03	31076	9.012E+11	Parabolic
5	372.5		245.9	1.129E+03	99387	2.882E+12	
5		1.5	245.9	1.129E+03	99387	2.882E+12	Uniform
5	374		245.9	1.129E+03	99387	2.882E+12	

Table 58. Specifications for Bridge 9, Load Step 2

Section Number	Location (ft)	Length of Range (ft)	Moment of Inertia (in^4)	Bending Stiffness ($lb\text{-}in^2$)	Girder Profile	Behavior
1	0	72	42666	1.237E+12	Uniform	Composite
1	72		42666	1.237E+12		
2		30.5	30196	8.757E+11	Parabolic	Non-Composite
3	102.5		95619	2.773E+12		
3		3	95619	2.773E+12	Uniform	
3	105.5		95619	2.773E+12		
3		30.5	95619	2.773E+12	Parabolic	
2	136		30196	8.757E+11		
1		71	42666	1.237E+12	Uniform	Composite
1	207		42666	1.237E+12		
4		30.5	31076	9.012E+11	Parabolic	Non-Composite
5	237.5		99387	2.882E+12		
5		3	99387	2.882E+12	Uniform	
5	240.5		99387	2.882E+12		
5		30.5	99387	2.882E+12	Parabolic	
4	306.5		31076	9.012E+11		
1		71	42666	1.237E+12	Uniform	Composite
1	342		42666	1.237E+12		
4		30.5	31076	9.012E+11	Parabolic	Non-Composite
5	372.5		99387	2.882E+12		
5		1.5	99387	2.882E+12	Uniform	
5	374		99387	2.882E+12		

Table 59. Specifications for Bridge 9, Load Step 3

<table>
<tr><th>Section Number</th><th>Location (ft)</th><th>Length of Range (ft)</th><th>Moment of Inertia (in^4)</th><th>Bending Stiffness (lb-in^2)</th><th>Girder Profile</th><th>Behavior</th></tr>
<tr><td>1</td><td>0</td><td rowspan="2">72</td><td>58558</td><td>1.698E+12</td><td rowspan="2">Uniform</td><td rowspan="2">Composite</td></tr>
<tr><td>1</td><td rowspan="2">72</td><td>58558</td><td>1.698E+12</td></tr>
<tr><td>2</td><td rowspan="2">30.5</td><td>30196</td><td>8.757E+11</td><td rowspan="2">Parabolic</td><td rowspan="6">Non-Composite</td></tr>
<tr><td>3</td><td rowspan="2">102.5</td><td>95619</td><td>2.773E+12</td></tr>
<tr><td>3</td><td rowspan="2">3</td><td>95619</td><td>2.773E+12</td><td rowspan="2">Uniform</td></tr>
<tr><td>3</td><td rowspan="2">105.5</td><td>95619</td><td>2.773E+12</td></tr>
<tr><td>3</td><td rowspan="2">30.5</td><td>95619</td><td>2.773E+12</td><td rowspan="2">Parabolic</td></tr>
<tr><td>2</td><td rowspan="2">136</td><td>30196</td><td>8.757E+11</td></tr>
<tr><td>1</td><td rowspan="2">71</td><td>58558</td><td>1.698E+12</td><td rowspan="2">Uniform</td><td rowspan="2">Composite</td></tr>
<tr><td>1</td><td rowspan="2">207</td><td>58558</td><td>1.698E+12</td></tr>
<tr><td>4</td><td rowspan="2">30.5</td><td>31076</td><td>9.012E+11</td><td rowspan="2">Parabolic</td><td rowspan="6">Non-Composite</td></tr>
<tr><td>5</td><td rowspan="2">237.5</td><td>99387</td><td>2.882E+12</td></tr>
<tr><td>5</td><td rowspan="2">3</td><td>99387</td><td>2.882E+12</td><td rowspan="2">Uniform</td></tr>
<tr><td>5</td><td rowspan="2">240.5</td><td>99387</td><td>2.882E+12</td></tr>
<tr><td>5</td><td rowspan="2">30.5</td><td>99387</td><td>2.882E+12</td><td rowspan="2">Parabolic</td></tr>
<tr><td>4</td><td rowspan="2">306.5</td><td>31076</td><td>9.012E+11</td></tr>
<tr><td>1</td><td rowspan="2">71</td><td>58558</td><td>1.698E+12</td><td rowspan="2">Uniform</td><td rowspan="2">Composite</td></tr>
<tr><td>1</td><td rowspan="2">342</td><td>58558</td><td>1.698E+12</td></tr>
<tr><td>4</td><td rowspan="2">30.5</td><td>31076</td><td>9.012E+11</td><td rowspan="2">Parabolic</td><td rowspan="4">Non-Composite</td></tr>
<tr><td>5</td><td rowspan="2">372.5</td><td>99387</td><td>2.882E+12</td></tr>
<tr><td>5</td><td rowspan="2">1.5</td><td>99387</td><td>2.882E+12</td><td rowspan="2">Uniform</td></tr>
<tr><td>5</td><td>374</td><td>99387</td><td>2.882E+12</td></tr>
</table>

Movable Load Data - Axle spacing in terms of the number of number of increments is calculated and shown in Appendix. In the case of Bridge 9 the Live Load Distribution Factor is given in the bridge data as 1.606 for a wheel load. This factor is halved to get the distribution factor for an axle load.

To calculate the Impact Factor, (*I)* equation (11) is utilized. This value matches the value specified in the Bridge Data.

$$I = \frac{50}{104\,ft + 125} \qquad (113)$$
$$= 0.218$$

Now the effective live load can be calculated by using equation (12).

$$Effective\ Live\ Load = Axle\ Load * 0.803 * (1 + 0.218) \qquad (114)$$

The available stress is calculated using Equation (29). Section Modulus for Load Step 3, S_{LL} required for calculation of available stress is tabulated in Table 60 for top and bottom of the steel section. These values are adopted from the BARS file of this particular bridge.

Yield stress is substituted as 36,000 psi. Available stresses are calculated for two cases, 5% overstress by substituting Ω as 1.05 and 10% overstress by substituting Ω as 1.10. Critical weight is calculated using equation (31) where Wn is substituted as 100,000 lb. Critical weight is calculated using the spreadsheet created for each bridge.

Table 60. Section Modulus for Load Step 3 of Bridge 9

Section Number	Location (ft)	Length of Range (ft)	Top of Steel (in^3)	Bottom of Steel (in^3)	Girder Profile	Behavior
1	0	72	8733.90	1352.50	Uniform	Composite
1	72		8733.90	1352.50		
2		30.5	1188.83	1188.83	Parabolic	Non-Composite
3	102.5		2204.50	2204.50		
3		3	2204.50	2204.50	Uniform	
3	105.5		2204.50	2204.50		
3		30.5	2204.50	2204.50	Parabolic	
2	136		1188.83	1188.83		
1		71	8733.90	1352.50	Uniform	Composite
1	207		8733.90	1352.50		
4		30.5	1221.55	1221.55	Parabolic	Non-Composite
5	237.5		2288.10	2288.10		
5		3	2288.10	2288.10	Uniform	
5	240.5		2288.10	2288.10		
5		30.5	2288.10	2288.10	Parabolic	
4	306.5		1221.55	1221.55		
1		71	8733.90	1352.50	Uniform	Composite
1	342		8733.90	1352.50		
4		30.5	1221.55	1221.55	Parabolic	Non-Composite
5	372.5		2288.10	2288.10		
5		1.5	2288.10	2288.10	Uniform	
5	374		2288.10	2288.10		

Verification

Moments obtained from the BARS file and from the computer program, BMCOL51 are compared below for maximum dead load moments and moment due to HS20 (short) truck in Table 61.

Table 61. Comparison of Moments for Bridge 9

	BARS (kip-ft)	BMCOL51 (kip-ft)
Maximum Positive Dead Load Moment	734	738
Max HS20(short) Moment(*LL+I)*	1271	1274

Moment Redistribution

Dead load moments in the region of negative moments at supports were reduced by 10% by multiplying by 0.9. The available stress is calculated using equation (67). Live load moments are also reduced by 10%. This is directly taken into account while calculating the critical weight by directly reducing the live load stress by 10% using Equation (69).

Bridge 9 is a six span bridge. The increase in positive moments at midspan is the average of the decrease in moments at the adjacent supports. The positive moments in spans 1 and 6 are increased by 5%, as one of the adjacent supports is an end support, so there is no moment reduction at this support and at the other support there is a reduction of 10%. The moments in span 2, 3, 4, 5 are increased by 10%, as at both the adjacent supports the moments are reduced by 10%.

Available stresses are calculated for midspan region of spans 1 and 6 with the help of Equation (70). The critical weight is calculated in the midspan region by using equation (71).

Available stresses for midspan region of span 2, 3, 4, and 5 are calculated with the help of Equation (99). The critical weight is calculated in the midspan region by using equation (100).

RESULTS

Critical weights of each truck type are plotted for three cases:

1. Considering 5% Overstress, without moment redistribution
2. Considering 5% Overstress, with moment redistribution

   Moment Redistribution is to be applied only in cases where it is advantageous. In Tables 63 to 71 and in Figures 12 to 20 moment redistribution values for 5% overstress are tabulated as calculated, even if they are lesser than if moment redistribution is not considered. However, in values after moment redistribution are reported only if they are greater than critical weight without moment redistribution.

3. Considering 10% Overstress, without moment redistribution - Critical weights considering 10% overstress will always will be greater than critical weights calculated by considering 5% overstress (without moment redistribution).

Figures 12 to 20 show the critical weight for each truck type for the three above mentioned cases. Along with critical weights, TTI HS20 Formula and Bridge Formula B are plotted. Each bridge is represented individually in the following figures and later in the chapter they are clubbed together for each of the above cases.

TTI-HS20 equation is shown as a line in the following figures. The formula is the minimum of the axle weight limits and the formula itself. Plotted as discrete points are the critical weights when it is limited by a 20 kip single or 34 kip tandem rather than the TTI-HS20 formula. The axle weight limits govern for the design trucks HS20 (short) and the HS20 (long) and the actual trucks 3S2 w/45' trailer 80,000 lbs and 3S2 w/53' trailer 80,000 lbs. For these trucks the graph shows a point below the plot of the formula corresponding to the axle weight limits.

Bridge Formula ‘B’ is the plot of the minimum of the axle weight limits and the formula itself. The formula is not plotted as a line; instead, discrete points representing the allowable weight for each truck type are plotted. Table 62 shows the allowable weights for the selected vehicles according to TTI-HS20 Formula and Bridge Formula B.

Table 62. Allowable Gross Weight for Each Truck Type by the TTI HS-20 Formula and Formula B

Truck Type	TTI HS-20 (kip)	Formula B (kip)
HS-20(Short)	60*	57
HS-20(Long)	60*	60*
3S2 w/40' trailer	86.5	78.6
3S2 w/45' trailer	88*	80
3S2 w/53' trailer	88*	80
3S2-2 Rocky Mtn Dbl	107.5	80
3S2-4 Turnpike Dbl	118	80
3S2-2-2 Triple	113.5	80
Three Axle Truck	50	45
Four Axle Truck	58	52.7

***** denotes Gross Weight governed by Axle Weight Limits

Bridge 1

Critical weights for Bridge 1 are tabulated in Table 63 and plotted in Figure 14. In Bridge 1 there is no separate case for moment redistribution, for 5% overstress.

Bridge 2

From Table 64 and Figure 15 it is evident that critical weights for 3S2 with 40 ft trailer and 3S2 with 45 ft trailer are lesser than values specified by TTI HS20 Formula. In these cases TTI-HS20 is not effective if moment redistribution is not considered. However after moment redistribution critical weights are higher than the values from the formula.

Table 63. Critical Weights for Bridge 1

Truck Type	5% Overstress (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	97	107	60
HS 20(long)	105	116	60
3S2 w/40' trailer	108	119	86.5
3S2 w/45' trailer	112	123	88
3S2 w/53' trailer	117	128	88
3S2-2(Rocky Mtn Dbl)	124	136	107.5
3S2-4(Turnpike Dbl)	136	149	118
3S2-2-2(Triple)	129	142	113.5
3 Axle Truck	94	103	50
4 Axle Truck	94	103	58

Table 64. Critical Weights for Bridge 2

Truck Type	5% Overstress (kip)	Mom. Red. (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	82	77	86	60
HS 20(long)	83	100	90	60
3S2 w/40' trailer	**84**	101	91	86.5
3S2 w/45' trailer	**87**	104	94	88
3S2 w/53' trailer	92	110	100	88
3S2-2(Rocky Mtn Dbl)	114	136	123	107.5
3S2-4(Turnpike Dbl)	125	150	136	118
3S2-2-2(Triple)	127	152	137	113.5
3 Axle Truck	68	64	72	50
4 Axle Truck	70	66	74	58

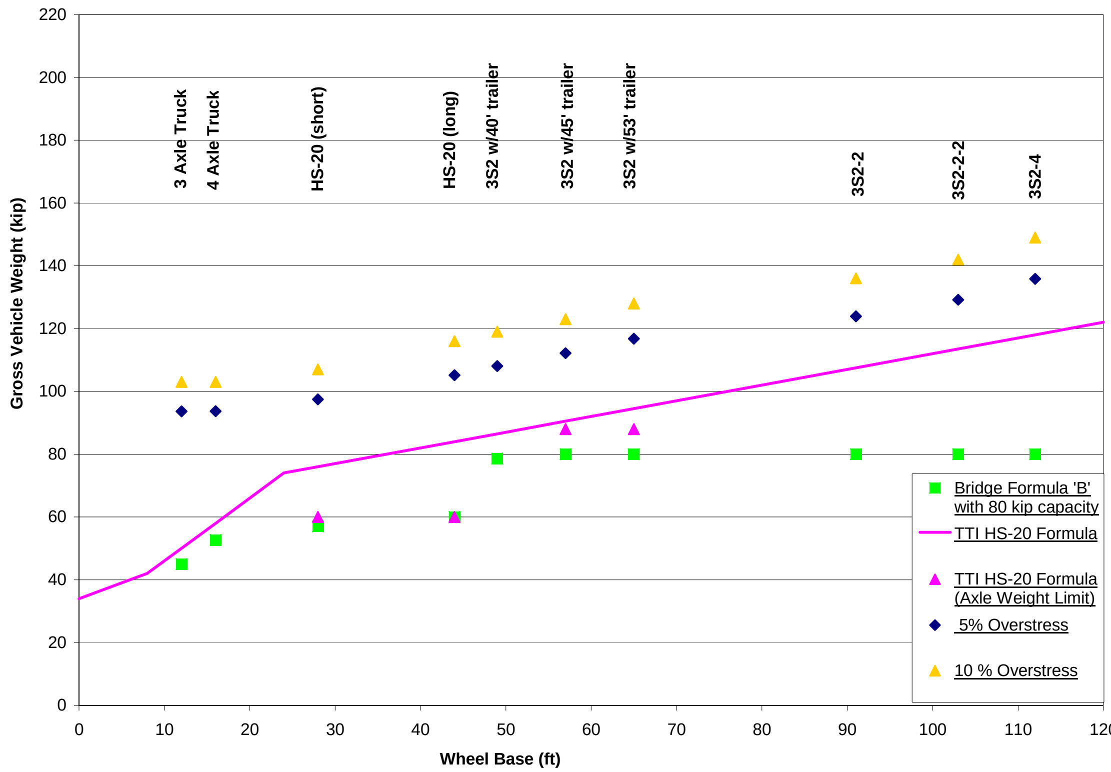


Figure 14. Formula B, TTI-HS20 and Critical Weights for Bridge 1

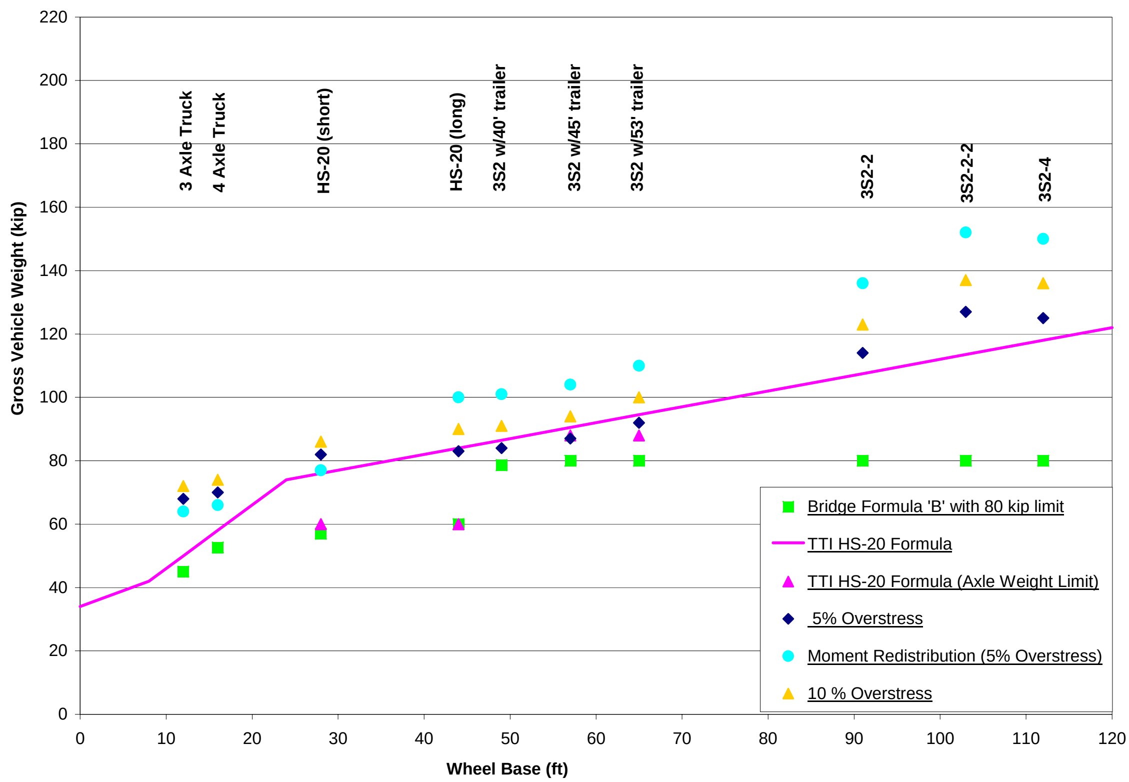


Figure 15. Formula B, TTI-HS20 and Critical Weights for Bridge 2

Bridge 3

If moment redistribution is not considered TTI HS-20 is not effective in restricting stresses within the 5% overstress limit for three truck types: 3S2-2 (Rocky Mountain Double), 3S2-4 (Turnpike Double) and 3S2-2-2 (Triple). However, the design handbook permits moment redistribution as beams satisfy compactness requirements. Critical weights are tabulated in Table 65 and plotted in Figure 16.

Table 65. Critical Weights for Bridge 3

Truck Type	5% Overstress (kip)	Mom. Red. (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	86	81	91	60
HS 20(long)	103	103	113	60
3S2 w/40' trailer	102	111	111	86.5
3S2 w/45' trailer	98	120	107	88
3S2 w/53' trailer	95	117	104	88
3S2-2(Rocky Mtn Dbl)	**102**	125	112	107.5
3S2-4(Turnpike Dbl)	**117**	144	129	118
3S2-2-2(Triple)	**111**	136	122	113.5
3 Axle Truck	77	72	81	50
4 Axle Truck	78	74	83	58

Table 66. Critical Weights for Bridge 4

Truck Type	5% Overstress (kip)	Mom. Red. (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	107	100	114	60
HS 20(long)	127	119	135	60
3S2 w/40' trailer	134	125	142	86.5
3S2 w/45' trailer	145	136	154	88
3S2 w/53' trailer	155	149	168	88
3S2-2(Rocky Mtn Dbl)	140	170	154	107.5
3S2-4(Turnpike Dbl)	147	181	162	118
3S2-2-2(Triple)	148	182	163	113.5
3 Axle Truck	98	92	105	50
4 Axle Truck	100	94	106	58

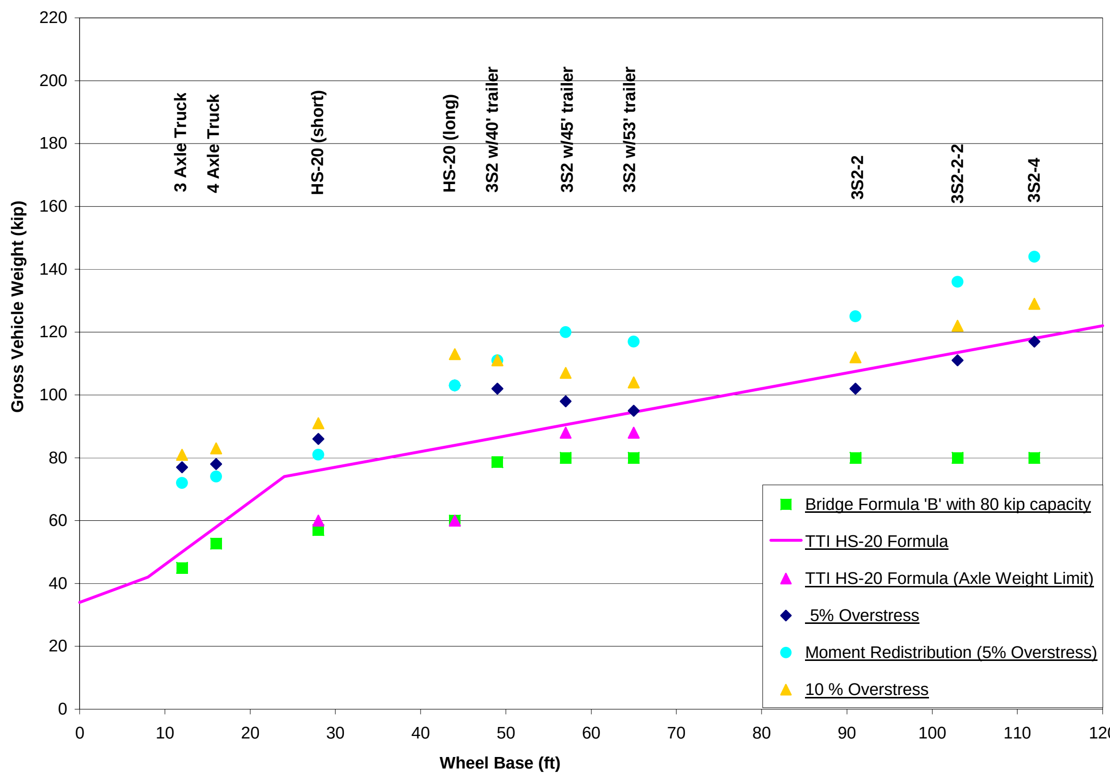


Figure 16. Formula B, TTI-HS20 and Critical Weights for Bridge 3

Bridge 4

Critical weights for all cases including 5% overstress without moment redistribution are greater than values specified by TTI-HS20 Formula. Hence, for this bridge TTI-HS20 formula holds true. Critical weights for the three cases and allowable weights according to TTI-HS20 Formula are shown in Table 66 and Figure 17.

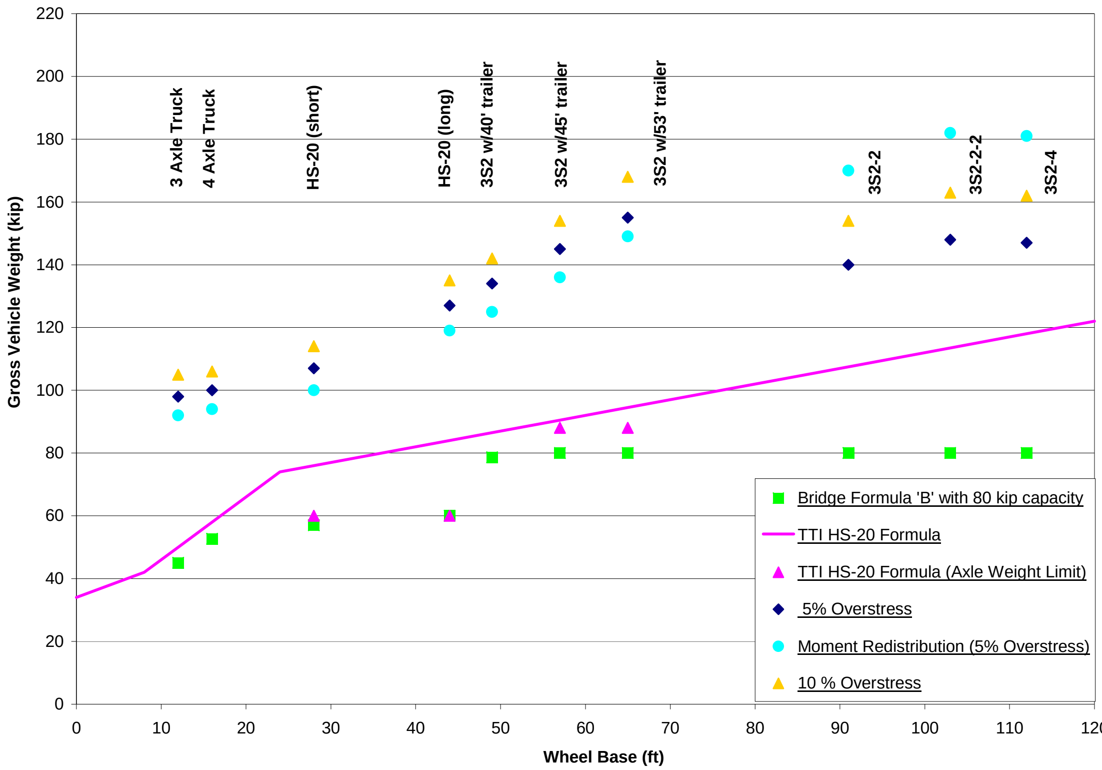


Figure 17. Formula B, TTI-HS20 and Critical Weights for Bridge 4

Bridge 5

Bridges 5 to 9 are examples from the South Dakota, and are actual bridge. These are plate girder bridges; most of the time plate girder bridges do not satisfy compactness requirements. Hence, they are not designed considering moment redistribution. It can be seen that even without the consideration of moment redistribution TTI-HS20 is able to protect these bridges against excessive overstress. Critical weights for Bridge 5 are tabulated in Table 67 and plotted in Figure 18.

Table 67. Critical Weights for Bridge 5

Truck Type	5% Overstress (kip)	Mom. Red. (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	76	68	80	60
HS 20(long)	101	91	107	60
3S2 w/40' trailer	111	100	117	86.5
3S2 w/45' trailer	110	111	118	88
3S2 w/53' trailer	109	120	116	88
3S2-2(Rocky Mtn Dbl)	120	140	129	107.5
3S2-4(Turnpike Dbl)	142	165	152	118
3S2-2-2(Triple)	133	155	143	113.5
3 Axle Truck	65	59	69	50
4 Axle Truck	68	61	71	58

Table 68. Critical Weights for Bridge 6

Truck Type	5% Overstress (kip)	Mom Red. (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	86	78	91	60
HS 20(long)	114	102	120	60
3S2 w/40' trailer	124	112	131	86.5
3S2 w/45' trailer	138	124	146	88
3S2 w/53' trailer	141	135	150	88
3S2-2(Rocky Mtn Dbl)	156	163	166	107.5
3S2-4(Turnpike Dbl)	185	197	198	118
3S2-2-2(Triple)	175	198	187	113.5
3 Axle Truck	75	67	79	50
4 Axle Truck	77	69	81	58

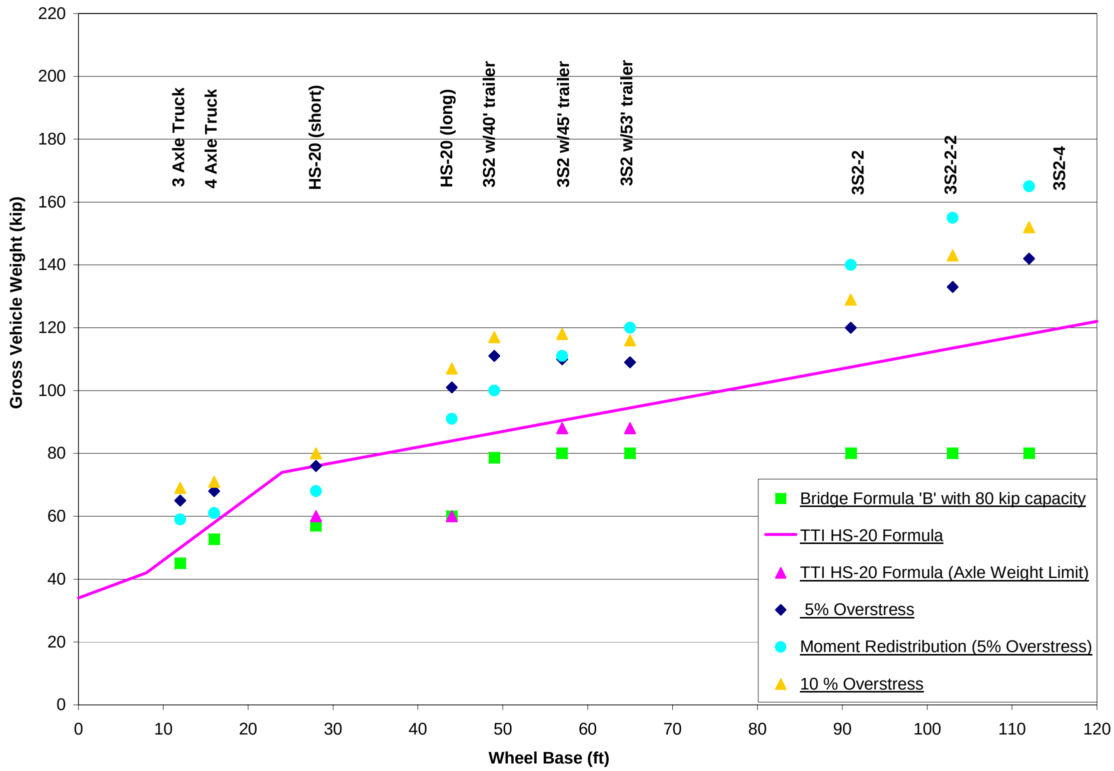


Figure 18. Formula B, TTI-HS20 and Critical Weights for Bridge 5

Bridge 6

Critical weights for Bridge 6 are tabulated in Table 68 and plotted in Figure 19.

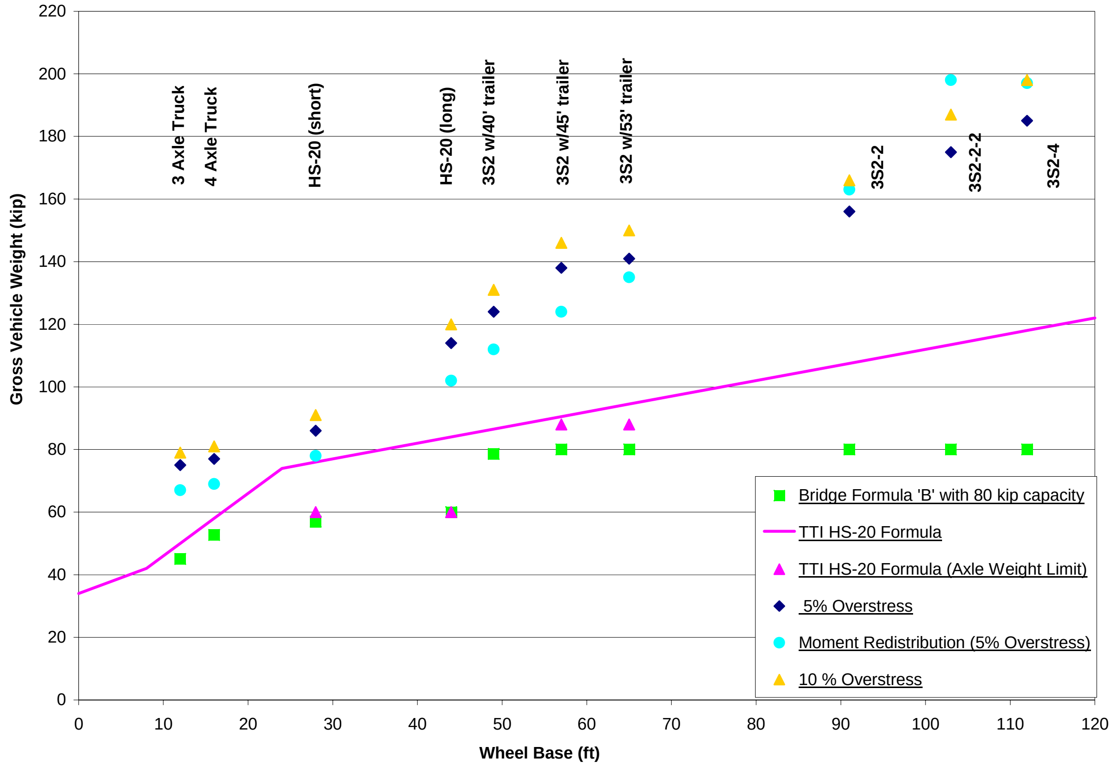


Figure 19. Formula B, TTI-HS20 and Critical Weights for Bridge 6

Bridge 7

Critical weights for Bridge 7 are tabulated in Table 69 and plotted in Figure 20.

Table 69. Critical Weights for Bridge 7

Truck Type	5% Overstress (kip)	Mom. Red. (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	91	85	97	60
HS 20(long)	104	97	111	60
3S2 w/40' trailer	107	100	114	86.5
3S2 w/45' trailer	114	106	121	88
3S2 w/53' trailer	123	115	131	88
3S2-2(Rocky Mtn Dbl)	135	126	143	107.5
3S2-4(Turnpike Dbl)	151	141	161	118
3S2-2-2(Triple)	144	134	153	113.5
3 Axle Truck	84	78	89	50
4 Axle Truck	85	80	91	58

Table 70. Critical Weights for Bridge 8

Truck Type	5% Overstress (kip)	Mom. Red. (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	74	66	78	60
HS 20(long)	94	92	101	60
3S2 w/40' trailer	94	103	101	86.5
3S2 w/45' trailer	95	113	103	88
3S2 w/53' trailer	99	116	106	88
3S2-2(Rocky Mtn Dbl)	115	135	124	107.5
3S2-4(Turnpike Dbl)	136	160	146	118
3S2-2-2(Triple)	132	156	143	113.5
3 Axle Truck	62	56	66	50
4 Axle Truck	65	58	68	58

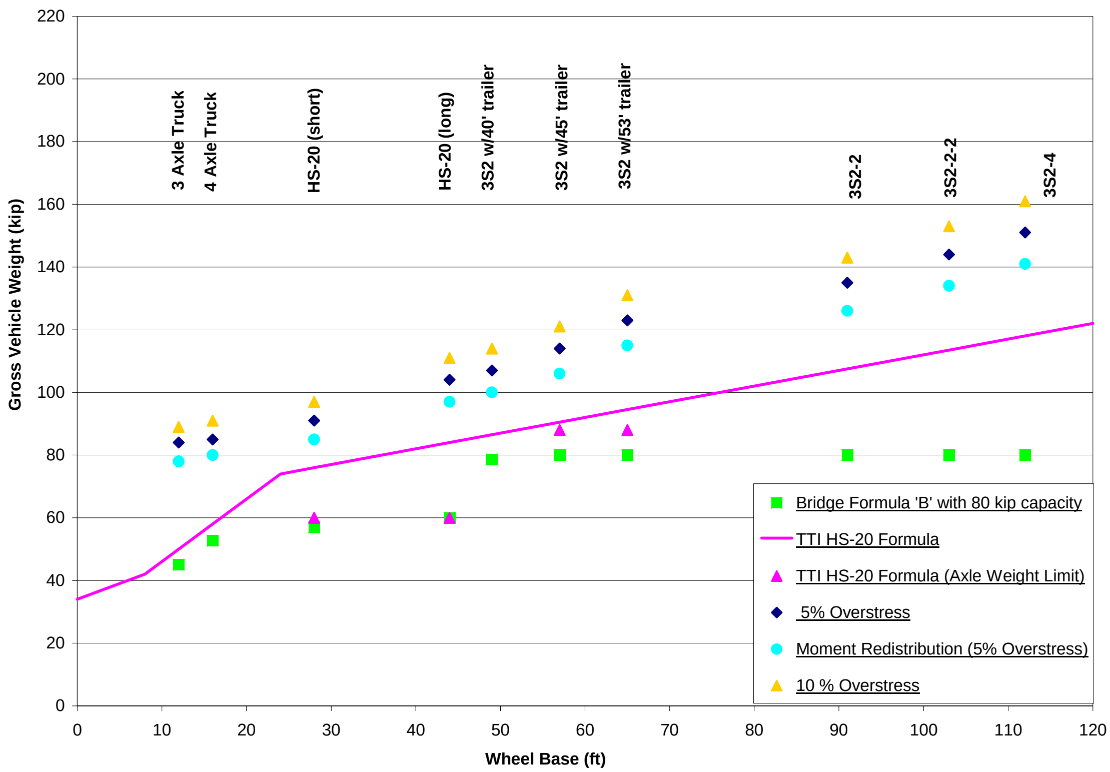


Figure 20. Formula B, TTI-HS20 and Critical Weights for Bridge 7

Bridge 8

Critical weights for Bridge 8 are tabulated in Table 70 and plotted in Figure 21.

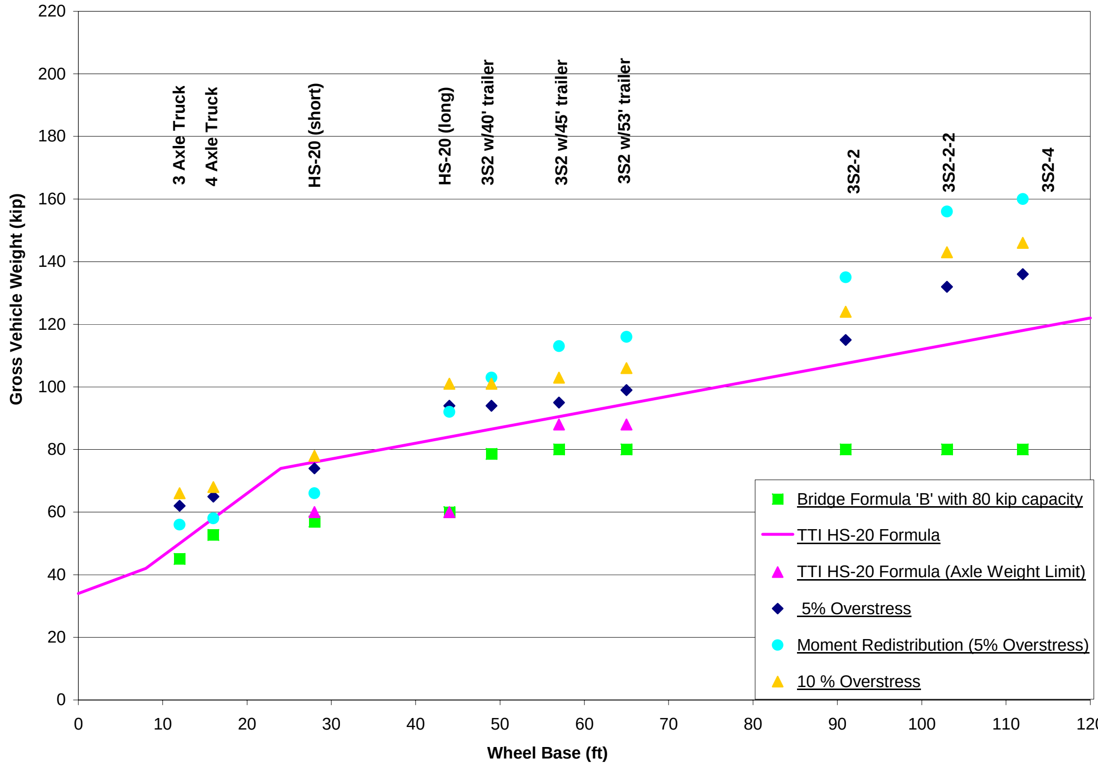


Figure 21. Formula B, TTI-HS20 and critical weights for Bridge 8

Bridge 9

Critical weights for Bridge 9 are tabulated in Table 71 and plotted in Figure 22.

Table 71. Critical Weights for Bridge 9

Truck Type	5% Overstress (kip)	Moment Redistribution (5% Overstress) (kip)	10% Overstress (kip)	TTI HS-20 (kip)
HS 20(short)	90	80	96	60
HS 20(long)	105	93	111	60
3S2 w/40' trailer	109	97	115	86.5
3S2 w/45' trailer	115	103	122	88
3S2 w/53' trailer	124	111	131	88
3S2-2(Rocky Mtn Dbl)	137	122	144	107.5
3S2-4(Turnpike Dbl)	155	138	164	118
3S2-2-2(Triple)	148	132	156	113.5
3 Axle Truck	81	73	86	50
4 Axle Truck	83	75	88	58

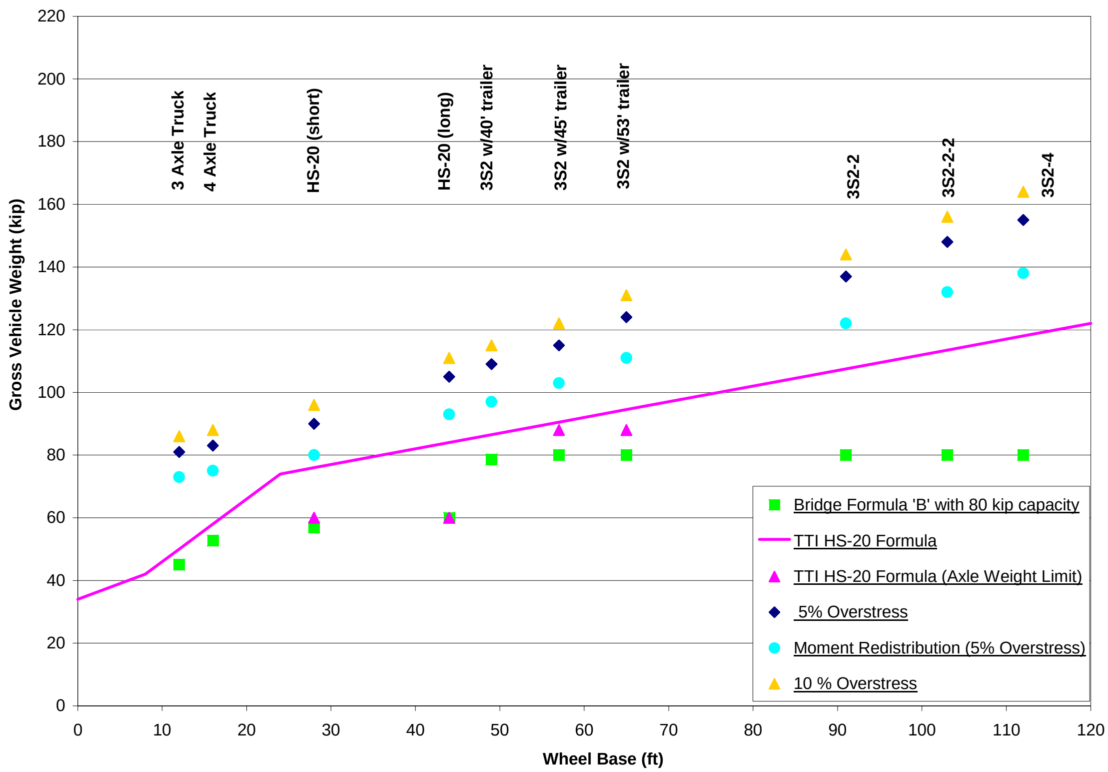


Figure 22. Formula B, TTI-HS20 and Critical Weights for Bridge 9

Combined Results for Bridges 1-9

5% Overstress

Table 72 and Figure 23 show critical weights for all the bridges considering 5% overstress but without moment redistribution. Tabulated in the table are allowable weights for each truck type according to TTI-HS20 Formula. Values in Bold Font in the table indicate cases when the allowable weights according to TTI-HS20 Formula are greater than the critical weights. In these cases TTI-HS20 does not protect the particular bridge against stress more than 5% greater than allowable design stress.

Table 72. Critical Weights for 5% Overstress, Not Considering Moment Redistribution and Allowable Weights According to TTI-HS20 Formula

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	TTI-HS20 (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	60
HS-20 (Long)	105	83	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	**84**	102	134	111	124	107	94	109	87
3S2 w/45' trailer	112	**87**	98	145	110	138	114	95	115	88
3S2 w/53' trailer	117	92	95	155	109	141	123	99	124	88
3S2-2 Rocky Mtn Dbl	124	114	**102**	140	120	156	135	115	137	108
3S2-4 Turnpike Dbl	129	125	**117**	147	142	185	151	136	155	118
3S2-2-2 Triple	136	127	**111**	148	133	175	144	132	148	114
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	58

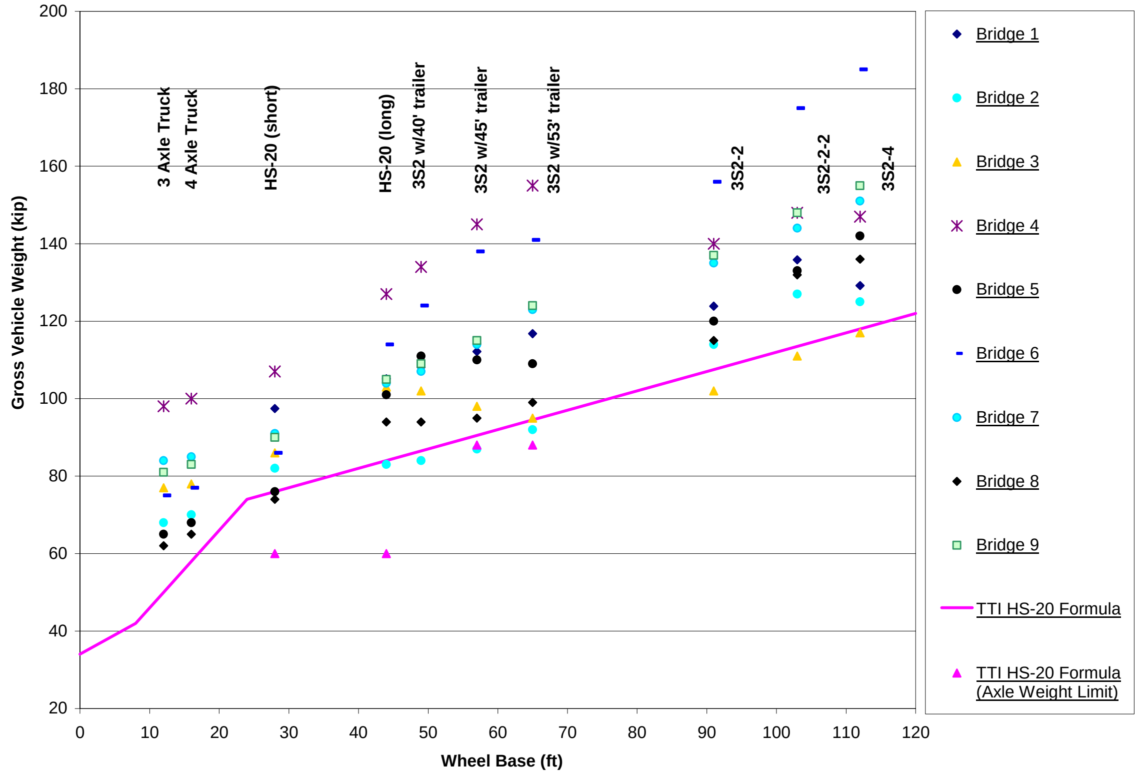


Figure 23. TTI-HS20 and Critical Weights for Selected Vehicles Considering 5% Overstress Without Moment Redistribution

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5% Overstress with Moment Redistribution

Table 73 and Figure 24 show critical weights for 5% overstress with moment redistribution. If moment redistribution is considered, TTI-HS20 is effective in all cases in restricting the stresses to within 5% overstress. Even the previous five cases where TTI-HS20 was not effective are now protected from excessive overstress due to moment redistribution. This occurs because the critical weight in these cases was governed by stresses at the interior support. Due to moment redistribution live loads stresses are reduced at supports, as a result of which the critical weight (causing 5% overstress) increases.

Table 73. TTI-HS20 and Critical Weights Considering 5% Overstress With Moment Redistribution

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	TTI-HS20 (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	60
HS-20 (Long)	105	100	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	101	111	134	111	124	107	103	109	87
3S2 w/45' trailer	112	104	120	145	111	138	114	113	115	88
3S2 w/53' trailer	117	110	117	155	120	141	123	116	124	88
3S2-2 Rocky Mtn Dbl	124	136	125	170	140	163	135	135	137	108
3S2-4 Turnpike Dbl	129	150	144	181	165	197	151	160	155	118
3S2-2-2 Triple	136	152	136	182	155	198	144	156	148	114
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	58

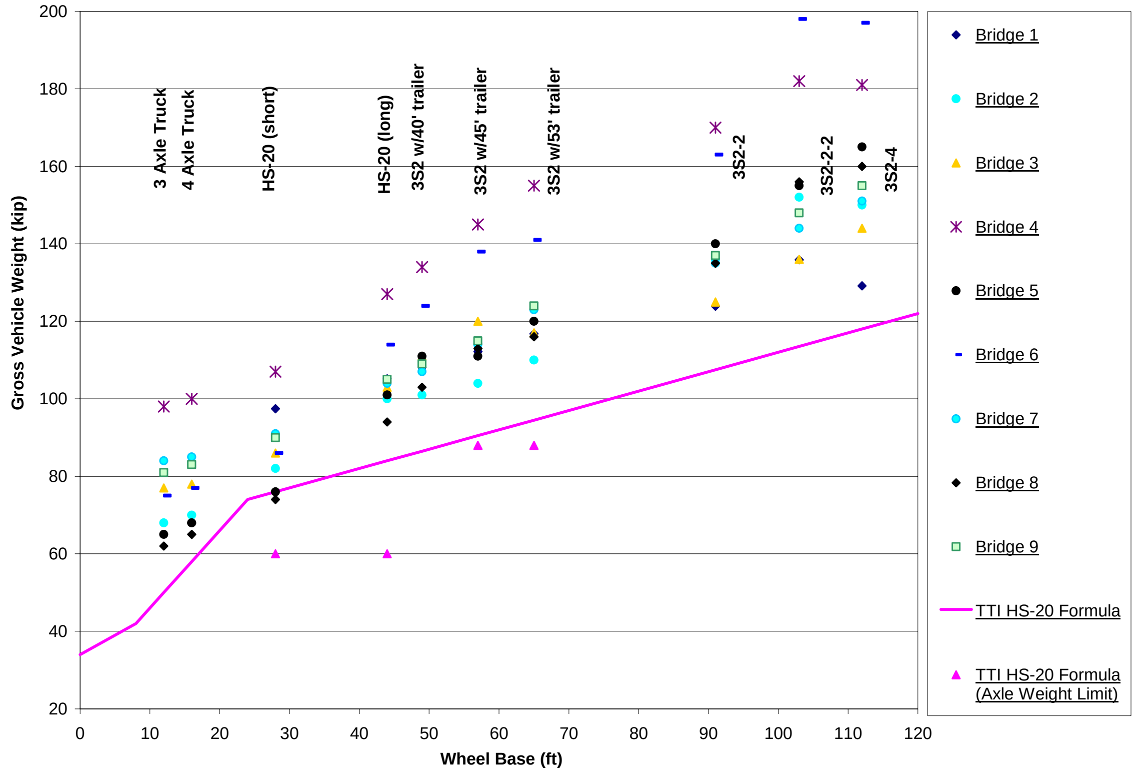

Figure 24. TTI-HS20 and Critical Weights for Selected Vehicles Considering 5% Overstress With Moment Redistribution

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10% Overstress

If stress in bridges up to 10 % greater than allowable design stress is permitted TTI-HS20 is able to restrict stresses in all bridges for all considered truck types within this limit. This is evident from Table 74 and Figure 25.

Table 74. Critical Weights for 10% Overstress Without Moment Redistribution

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	TTI-HS20 (kip)
HS-20 (Short)	103	86	91	114	80	91	97	78	96	60
HS-20 (Long)	103	90	113	135	107	120	111	101	111	60
3S2 w/40' trailer	107	91	111	142	117	131	114	101	115	86.5
3S2 w/45' trailer	116	94	107	154	118	146	121	103	122	88
3S2 w/53' trailer	119	100	104	168	116	150	131	106	131	88
3S2-2 Rocky Mtn Dbl	123	123	112	154	129	166	143	124	144	107.5
3S2-4 Turnpike Dbl	128	136	129	162	152	198	161	146	164	118
3S2-2-2 Triple	136	137	122	163	143	187	153	143	156	113.5
Three Axle Truck	142	72	81	105	69	79	89	66	86	50
Four Axle Truck	149	74	83	106	71	81	91	68	88	58

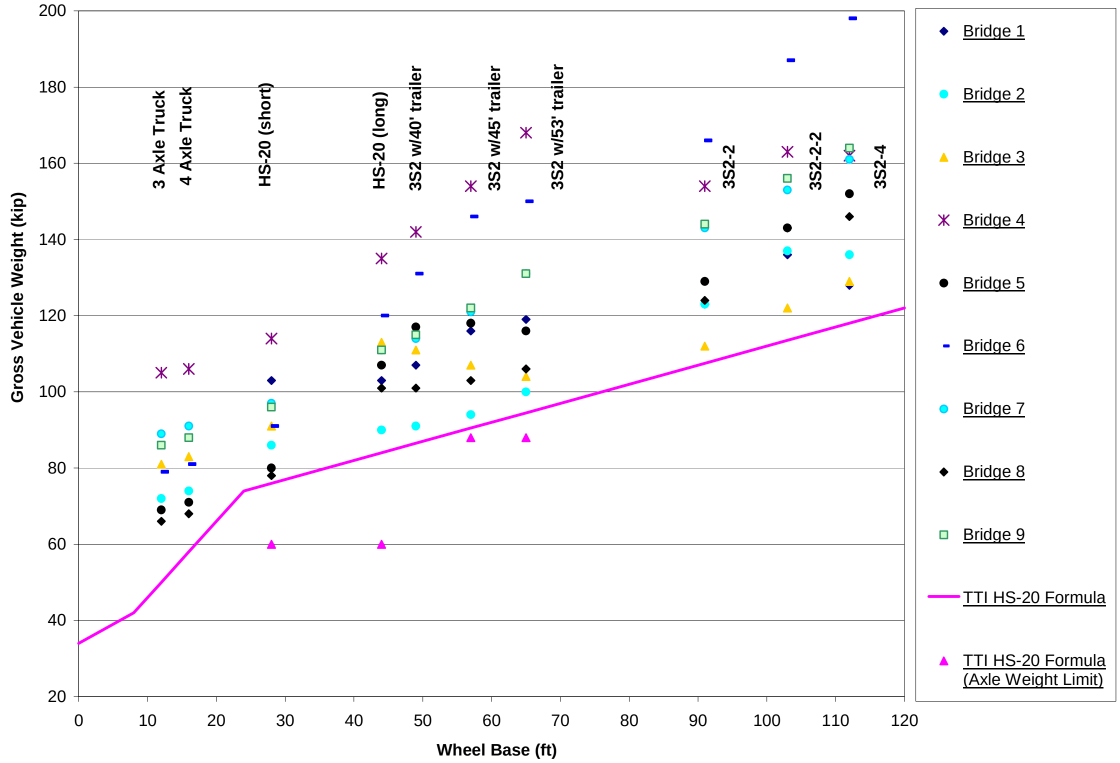

Figure 25. Critical Weights for 10% Overstress Without Moment Redistribution

COMPARISON OF FORMULAS

Several formulas have been proposed as replacement for the current Bridge Formula B. Some of the formulas have been presented here to check their effectiveness and compare them with TTI-HS20 Formula. Table 75 shows the allowable weights according to the current formula, Bridge Formula B and proposed formula, including TTI-HS20 Formula.

Figure 26 shows the various formulas as a plot of gross vehicle weight against wheelbase of the truck. It can be observed that the formula proposed in Ghosn 2000 is the most liberal, followed by TRB 1990, TTI-HS20/Formula B, Kurt 2000, TTI-HS20, and Bridge Formula B, Formula B being the most conservative due to 80,000 lb gross vehicle weight limit.

Table 75. Allowable Weights According to the Current and Proposed Formulas for Selected Vehicles

Vehicle Type	Bridge Formula 'B' (kip)	TTI-HS20 (kip)	Ghosn (kip)	Kurt (kip)	TTI HS20/ Formula B (kip)	TRB (kip)
HS-20 (Short)	57	60	76	63	60	60
HS-20 (Long)	60	60	102	75	60	60
3S2 w/40' trailer	79	87	110	79	87	83
3S2 w/45' trailer	80	88	118	84	88	83
3S2 w/53' trailer	80	88	124	89	88	83
3S2-2 Rocky Mtn Dbl	80	108	145	107	113	113
3S2-4 Turnpike Dbl	80	118	162	123	135	135
3S2-2-2 Triple	80	114	154	118	130	130
Three Axle Truck	45	50	50	51	50	50
Four Axle Truck	53	58	56	56	58	58

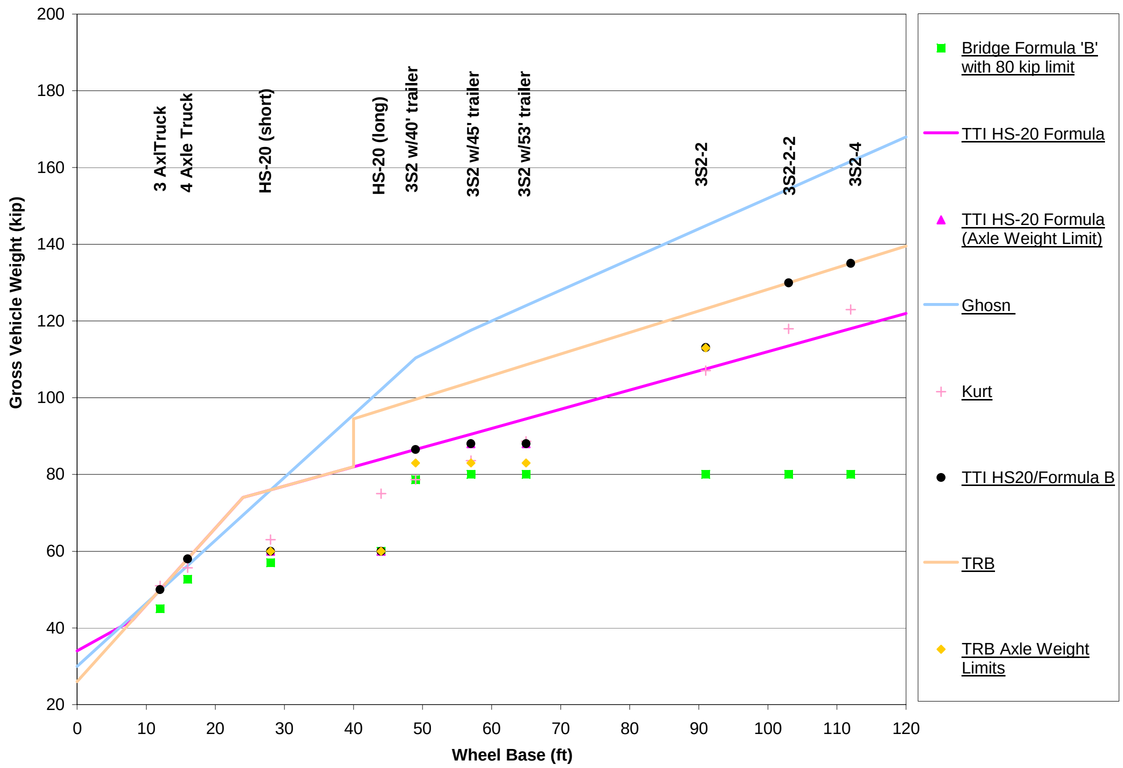

Figure 26. Gross Vehicle Weights of Selected Vehicles from Current and Proposed Formulas

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In this chapter the critical weights calculated for the selected trucks are plotted against the various formulas to check the effectiveness of each formula in restricting the stresses 5% more than the allowable stress. Each formula is plotted for two cases: (1) Critical weights for 5% overstress without considering moment redistribution and (2) Critical Weights for 5% overstress considering moment redistribution.

Bridge Formula B

Critical weights of selected vehicles on the studied bridges are shown in Table 76. Also shown in this table are the current gross truck weight limits according to Bridge Formula B. The critical weights are legal weight limits are plotted in Figure 27. The table and figure indicate that even when moment redistribution is not considered Formula B is over conservative.

The formula is good for medium length trucks, but there is room for more allowance for shorter trucks. Furthermore, the 80,000 lb arbitrary limit restricts longer trucks from carrying more loads, which they could without overstressing the bridge beyond the permissible limit. This is making Formula B uneconomical and calling for the development of a new formula.

If moment redistribution is considered usually critical weights for longer trucks tend to increase, though this not always the case. Table 77 and Figure 26 show critical weights when moment redistribution is considered. They indicate that the current legal weights are even more conservative when moment redistribution is considered.

Table 76. Critical Weights for 5% Overstress, Not Considering Moment Redistribution and Allowable Weights According to Bridge Formula B with 80 Kip Limit.

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	Bridge Formula B (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	57
HS-20 (Long)	105	83	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	84	102	134	111	124	107	94	109	79
3S2 w/45' trailer	112	87	98	145	110	138	114	95	115	80
3S2 w/53' trailer	117	92	95	155	109	141	123	99	124	80
3S2-2 Rocky Mtn Dbl	124	114	102	140	120	156	135	115	137	80
3S2-4 Turnpike Dbl	129	125	117	147	142	185	151	136	155	80
3S2-2-2 Triple	136	127	111	148	133	175	144	132	148	80
Three Axle Truck	94	68	77	98	65	75	84	62	81	45
Four Axle Truck	94	70	78	100	68	77	85	65	83	53

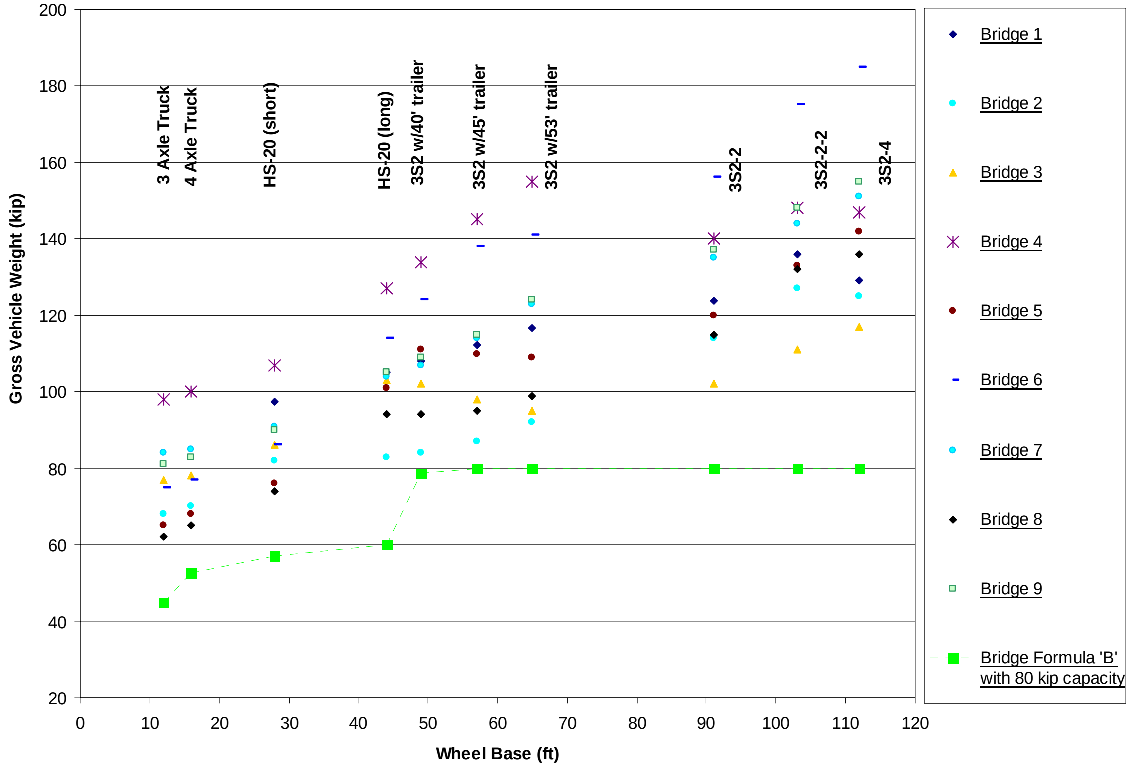

Figure 27. Bridge Formula B and Critical Weights for Selected Vehicles Considering 5% Overstress Without Moment Redistribution

Table 77. Critical Weights for 5% Overstress With Moment Redistribution

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	Bridge Formula B (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	57
HS-20 (Long)	105	100	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	101	111	134	111	124	107	103	109	79
3S2 w/45' trailer	112	104	120	145	111	138	114	113	115	80
3S2 w/53' trailer	117	110	117	155	120	141	123	116	124	80
3S2-2 Rocky Mtn Dbl	124	136	125	170	140	163	135	135	137	80
3S2-4 Turnpike Dbl	129	150	144	181	165	197	151	160	155	80
3S2-2-2 Triple	136	152	136	182	155	198	144	156	148	80
Three Axle Truck	94	68	77	98	65	75	84	62	81	45
Four Axle Truck	94	70	78	100	68	77	85	65	83	53

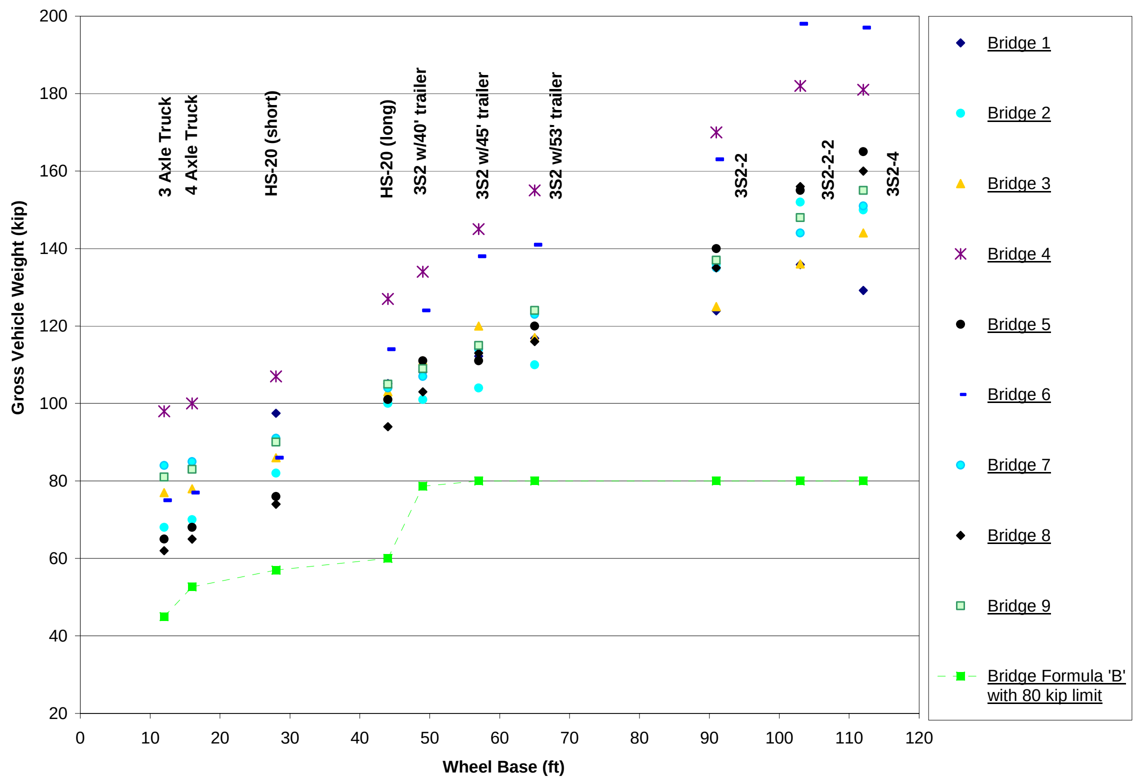

Figure 28. Bridge Formula B and Critical Weights for Selected Vehicles Considering 5% Overstress With Moment Redistribution

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Ghosn 2000

Formula proposed in Ghosn (2000) is plotted in Figure 29. The figure indicates that the formula is not effective, as many of the critical weights are lesser than the weight suggested by the formula. This is also suggested by Table 78, where the values in Bold indicate cases in which the Formula is not effective. The formula holds true for shorter trucks like the Three Axle and Four Axle Truck. But with increasing truck length the formula gets more ineffective; for the longest trucks: Rocky Mountain Double, Turnpike Double, and Triple the formula is effective in restricting the stresses within permissible limits only for Bridge 6.

Even when moment redistribution is considered performance of the formula for medium length trucks does not improve, though it improves slightly for the longer trucks. These values are tabulated in Table 79 and plotted in Figure 30.

Table 78. Critical Weights for 5% Overstress, Not Considering Moment Redistribution and Allowable Weights According to Formula Proposed in Ghosn 2000.

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	Ghosn (kip)
HS-20 (Short)	97	82	86	107	76	86	91	**74**	90	76
HS-20 (Long)	105	**83**	103	127	**101**	114	104	**94**	105	102
3S2 w/40' trailer	**108**	**84**	**102**	134	111	124	**107**	**94**	**109**	110
3S2 w/45' trailer	**112**	**87**	**98**	145	**110**	138	**114**	**95**	**115**	118
3S2 w/53' trailer	**117**	**92**	**95**	155	**109**	141	**123**	**99**	124	124
3S2-2 Rocky Mtn Dbl	**124**	**114**	**102**	**140**	**120**	156	**135**	**115**	**137**	145
3S2-4 Turnpike Dbl	**129**	**125**	**117**	**147**	**142**	185	**151**	**136**	**155**	162
3S2-2-2 Triple	**136**	**127**	**111**	**148**	**133**	175	**144**	**132**	**148**	154
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	56

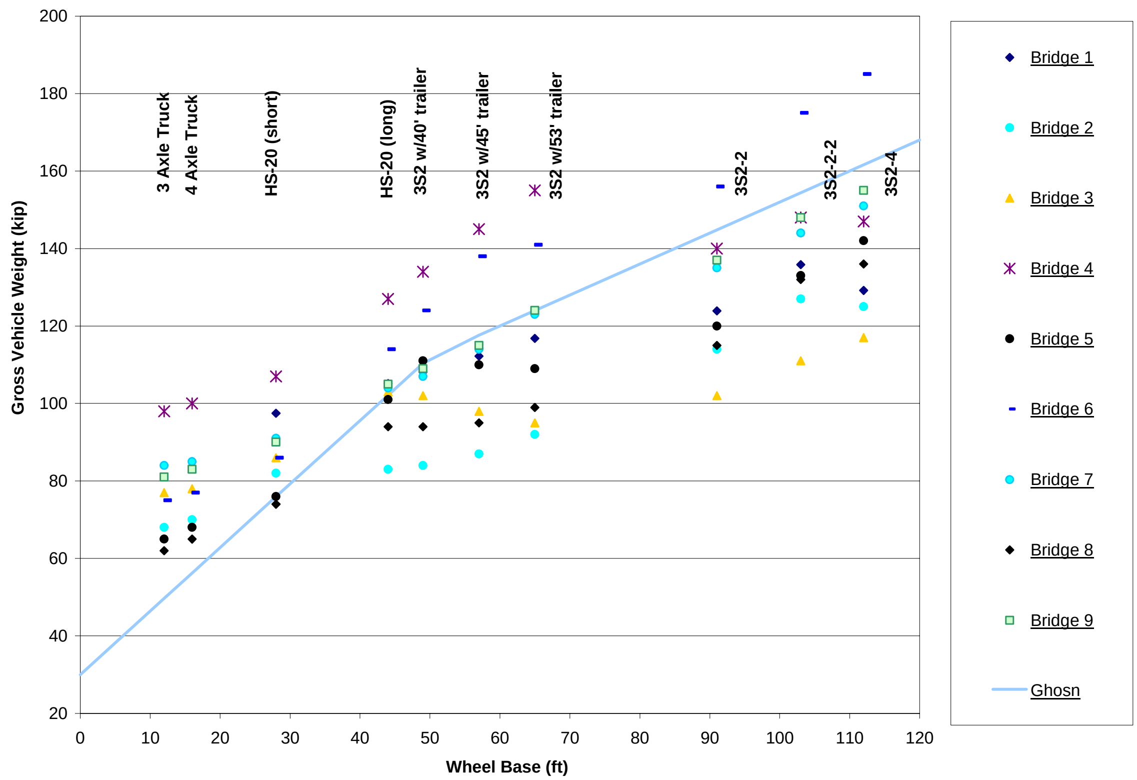

Figure 29. Ghosn (2000) and Critical Weights for 5% Overstress, No Moment Redistribution

Table 79. Critical Weights Considering 5% Overstress With Moment Redistribution

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	Ghosn (kip)
HS-20 (Short)	97	82	86	107	76	86	91	**74**	90	76
HS-20 (Long)	105	**100**	103	127	**101**	114	104	**94**	105	102
3S2 w/40' trailer	**108**	**101**	111	134	111	124	**107**	**103**	**109**	110
3S2 w/45' trailer	**112**	**104**	120	145	**111**	138	**114**	**113**	**115**	118
3S2 w/53' trailer	**117**	**110**	**117**	155	**120**	141	**123**	**116**	124	124
3S2-2 Rocky Mtn Dbl	**124**	**136**	**125**	170	**140**	163	**135**	**135**	**137**	145
3S2-4 Turnpike Dbl	**129**	**150**	**144**	181	165	197	**151**	**160**	**155**	162
3S2-2-2 Triple	**136**	**152**	**136**	182	155	198	**144**	156	**148**	154
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	56

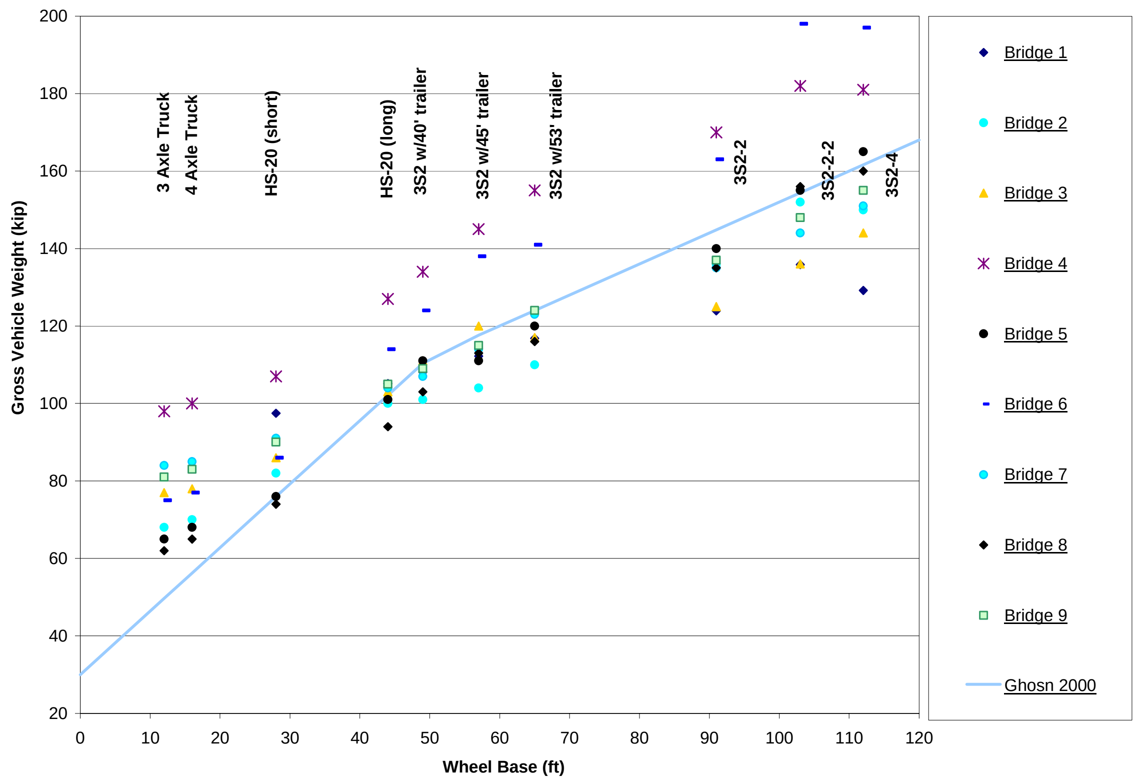

Figure 30. Ghosn (2000) and Critical Weights for 5% Overstress, With Moment Redistribution

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Kurt 2000

As evident from Table 80, formula proposed in Kurt 2000 is very effective in restricting stresses within permissible limits even when moment redistribution is not considered. Only for Bridge 3 the formula is not effective for the longer trucks, which was also the case for TTI-HS20 Formula. Table 81 shows that when moment redistribution is considered the formula holds true for all cases.

In Figure 31 and Figure 32 the formula proposed in Kurt (2000) is shown as discrete points connected by a dotted line to give a general idea of the formula. The formula depends on two variables, viz. number of axles in the truck and length between outermost axles. Since the graph only points the relationship between wheelbase and gross weight this formula cannot be plotted by a single line, hence the dotted line between critical weights.

In spite of this formula being so effective, it not receiving as much attention as TTI-HS20 may be attributed to the following reasons:

1. Its dependence on the number of axles is sometimes contrary to the dependence of stresses on the number of axles.
2. It is more restrictive than TTI-HS20 for short and medium length trucks.
3. Axle weight limits are not considered. These limits are required due to pavement damage considerations.
4. The formula is somewhat more complicated than TTI-HS20.

Table 80. Critical Weights for 5% Overstress, Not Considering Moment Redistribution and Allowable Weights According to TTI-HS20 Formula

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	Kurt (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	63
HS-20 (Long)	105	83	103	127	101	114	104	94	105	75
3S2 w/40' trailer	108	84	102	134	111	124	107	94	109	79
3S2 w/45' trailer	112	87	98	145	110	138	114	95	115	84
3S2 w/53' trailer	117	92	95	155	109	141	123	99	124	89
3S2-2 Rocky Mtn Dbl	124	114	**102**	140	120	156	135	115	137	107
3S2-4 Turnpike Dbl	129	125	**117**	147	142	185	151	136	155	123
3S2-2-2 Triple	136	127	**111**	148	133	175	144	132	148	118
Three Axle Truck	94	68	77	98	65	75	84	62	81	51
Four Axle Truck	94	70	78	100	68	77	85	65	83	56

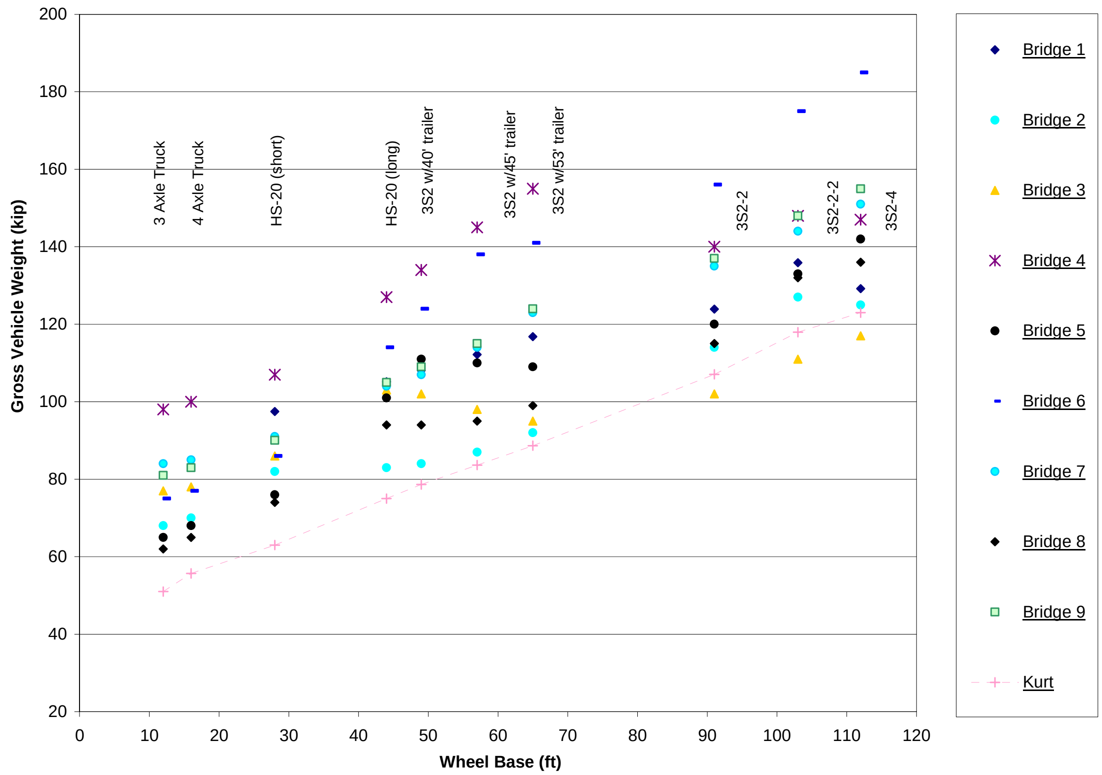

Figure 31. Kurt (2000) and Critical Weights for 5% Overstress Without Moment Redistribution

Table 81. Critical Weights Considering 5% Overstress With Moment Redistribution

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	Kurt (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	63
HS-20 (Long)	105	100	103	127	101	114	104	94	105	75
3S2 w/40' trailer	108	101	111	134	111	124	107	103	109	79
3S2 w/45' trailer	112	104	120	145	111	138	114	113	115	84
3S2 w/53' trailer	117	110	117	155	120	141	123	116	124	89
3S2-2 Rocky Mtn Dbl	124	136	125	170	140	163	135	135	137	107
3S2-4 Turnpike Dbl	129	150	144	181	165	197	151	160	155	123
3S2-2-2 Triple	136	152	136	182	155	198	144	156	148	118
Three Axle Truck	94	68	77	98	65	75	84	62	81	51
Four Axle Truck	94	70	78	100	68	77	85	65	83	56

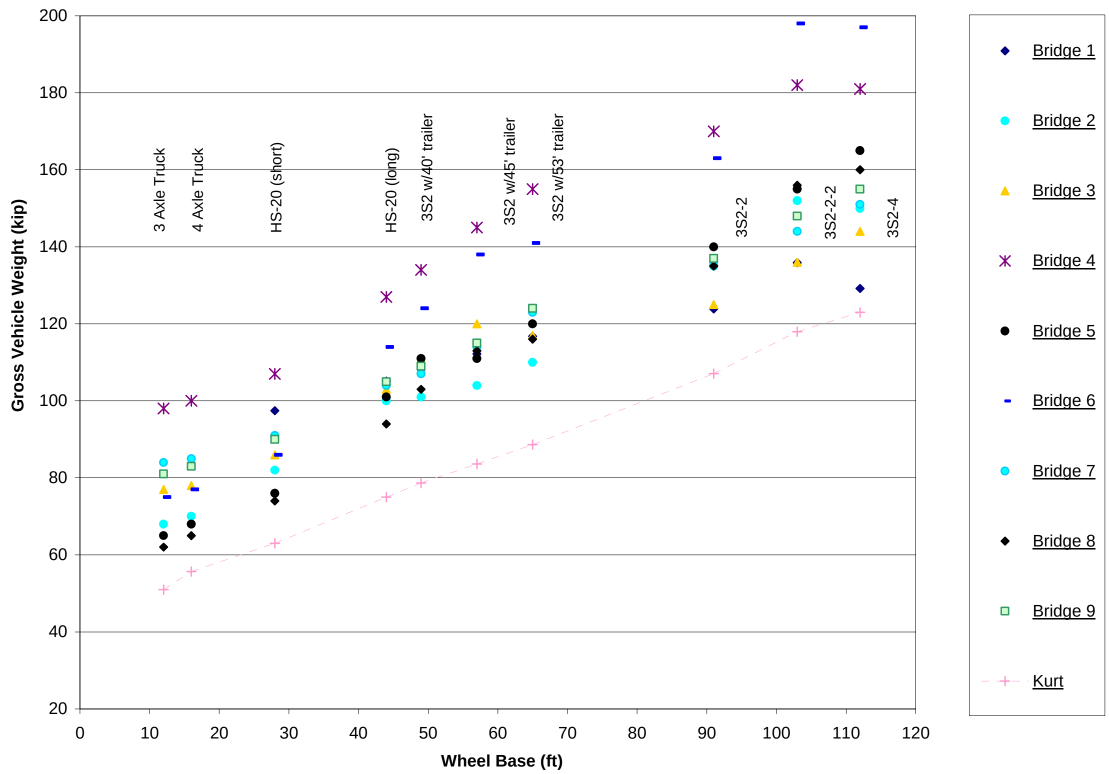

Figure 32. Kurt (2000) and Critical Weights when Moment Redistribution is Considered for 5% Overstress

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TTI-HS20/Formula B

This formula is suggested in Transportation Research Board Special Report 225 (1990). In this formula the TTI-HS20 Limits would be combined with those of Formula B and the 80,000 lb limit on gross vehicle weight would be removed. While applying this formula for the selected group of vehicles, TTI-HS20 Formula is applied for short and medium length trucks. For the longer trucks, namely Rocky Mountains Double, Turnpike Double, and Triple the Bridge Formula B is applied without considering the 80,000 lb gross weight limit. Formula B is applied for these trucks because they have 7 to 9 axles. Federal Axle Limits have been applied and checked for while calculating allowable weights.

In Figure 33 and Figure 34 allowable weights according to TTI-HS20/Formula B have been plotted as discrete points and connected by a dotted line to make the allowable more distinguishable in the figures.

While calculating critical weights for 5% overstress with no moment redistribution the formula is ineffective for two medium length trucks for Bridge 2. This is expected as this was also the case for TTI-HS20 Formula; the same allowable weights are being applied in this case also for trucks having less than seven axles.

For longer trucks which have seven to nine axles Bridge Formula B without the 80,000 lb limit is applied. This formula is less restrictive than TTI-HS20 for longer trucks. As such, cases where TTI-HS20 was ineffective for longer trucks this formula will also be ineffective. Additionally, this formula is also ineffective in restricting stresses within permissible limits for three other cases as indicated by bold values in Table 82. In the case for 5% overstress with moment redistribution the formula fails in a single case for Bridge 1 which is evident from Table 83.

Table 82. Critical Weights for 5% Overstress, Not Considering Moment Redistribution and Allowable Weights According to TTI-HS20 Formula

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	TTI - HS20/ Formula 'B' (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	60
HS-20 (Long)	105	83	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	**84**	102	134	111	124	107	94	109	87
3S2 w/45' trailer	112	**87**	98	145	110	138	114	95	115	88
3S2 w/53' trailer	117	92	95	155	109	141	123	99	124	88
3S2-2 Rocky Mtn Dbl	124	114	**102**	140	120	156	135	115	137	113
3S2-4 Turnpike Dbl	**129**	**125**	**117**	147	142	185	151	136	155	135
3S2-2-2 Triple	136	**127**	**111**	148	133	175	144	132	148	130
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	58

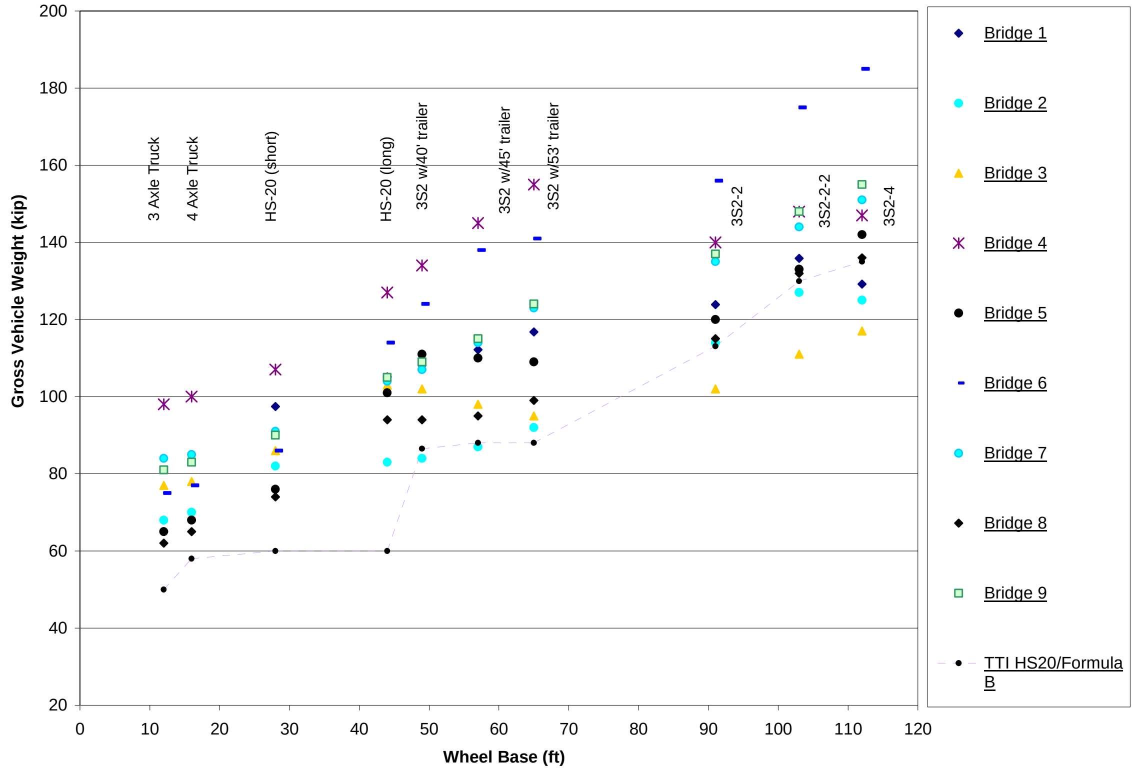

Figure 33. TTI-HS20/Bridge Formula B and Critical Weights Without Moment Redistribution

Table 83. Critical Weights Considering 5% Overstress With Moment Redistribution

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip)	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	TTI - HS20/ Formula 'B' (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	60
HS-20 (Long)	105	100	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	101	111	134	111	124	107	103	109	87
3S2 w/45' trailer	112	104	120	145	111	138	114	113	115	88
3S2 w/53' trailer	117	110	117	155	120	141	123	116	124	88
3S2-2 Rocky Mtn Dbl	124	136	125	170	140	163	135	135	137	113
3S2-4 Turnpike Dbl	**129**	150	144	181	165	197	151	160	155	135
3S2-2-2 Triple	136	152	136	182	155	198	144	156	148	130
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	58

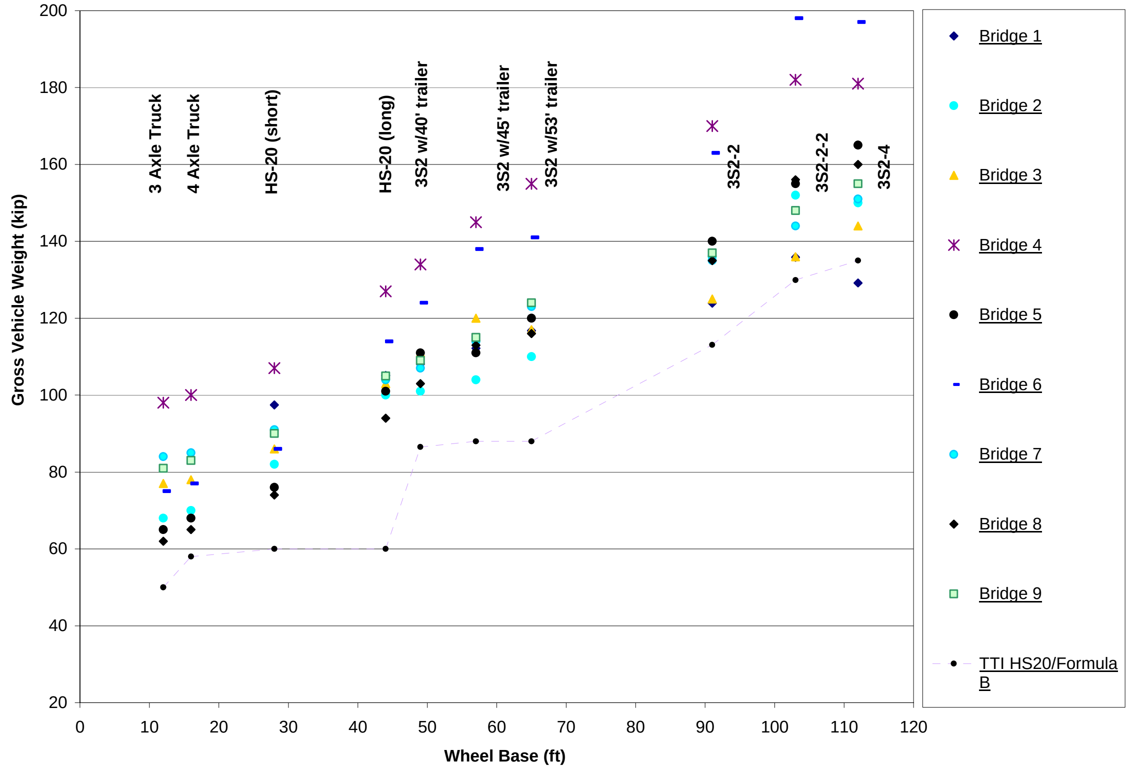

Figure 34. TTI-HS20/Bridge Formula B and Critical Weights for 5% Overstress With Moment Redistribution

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TRB 1990

This formula is the same as TTI-HS20 for gross weights less than 80,000 lb and wheelbase less than 40 ft. Above 40 ft the formula is the same as Bridge Formula B for nine axles. So the allowable weights according to TRB formula are the same as Formula B for Turnpike Double, and Triple as these trucks have nine axles. Therefore this formula like the previous formula is ineffective for the same cases of Turnpike Double and Triple. Additionally it is also fails for Rocky Mountain Double in the case of Bridge 3 when moment redistribution is not considered. Critical weights for 5% overstress without considering moment redistribution are tabulated in Table 84 and plotted in Figure 35. Table 85 and Figure 36 compare critical weights for 5% overstress with moment redistribution, and allowable weights according to the TRB formula.

Table 84. Critical Weights for 5% Overstress, Not Considering Moment Redistribution and Allowable Weights According to TRB Formula

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	TRB (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	60
HS-20 (Long)	105	83	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	84	102	134	111	124	107	94	109	83
3S2 w/45' trailer	112	87	98	145	110	138	114	95	115	83
3S2 w/53' trailer	117	92	95	155	109	141	123	99	124	83
3S2-2 Rocky Mtn Dbl	124	114	**102**	140	120	156	135	115	137	113
3S2-4 Turnpike Dbl	**129**	**125**	**117**	147	142	185	151	136	155	135
3S2-2-2 Triple	136	**127**	**111**	148	133	175	144	132	148	130
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	58

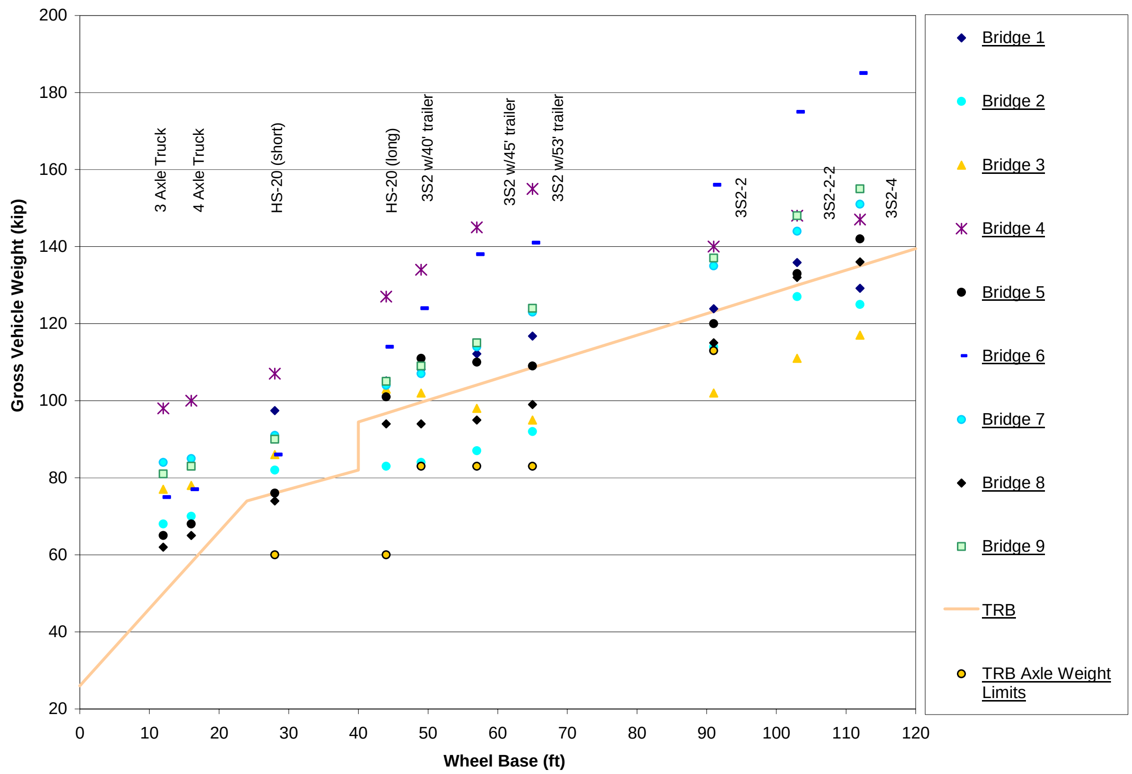

Figure 35. TRB 1990 Formula and Critical Weights Without Moment Redistribution

Table 85. TRB Formula and Critical Weights Considering 5% Overstress With Moment Redistribution

Vehicle Type	Bridge 1 (kip)	Bridge 2 (kip)	Bridge 3 (kip))	Bridge 4 (kip)	Bridge 5 (kip)	Bridge 6 (kip)	Bridge 7 (kip)	Bridge 8 (kip)	Bridge 9 (kip)	TRB (kip)
HS-20 (Short)	97	82	86	107	76	86	91	74	90	60
HS-20 (Long)	105	100	103	127	101	114	104	94	105	60
3S2 w/40' trailer	108	101	111	134	111	124	107	103	109	83
3S2 w/45' trailer	112	104	120	145	111	138	114	113	115	83
3S2 w/53' trailer	117	110	117	155	120	141	123	116	124	83
3S2-2 Rocky Mtn Dbl	124	136	125	170	140	163	135	135	137	113
3S2-4 Turnpike Dbl	**129**	150	144	181	165	197	151	160	155	135
3S2-2-2 Triple	136	152	136	182	155	198	144	156	148	130
Three Axle Truck	94	68	77	98	65	75	84	62	81	50
Four Axle Truck	94	70	78	100	68	77	85	65	83	58

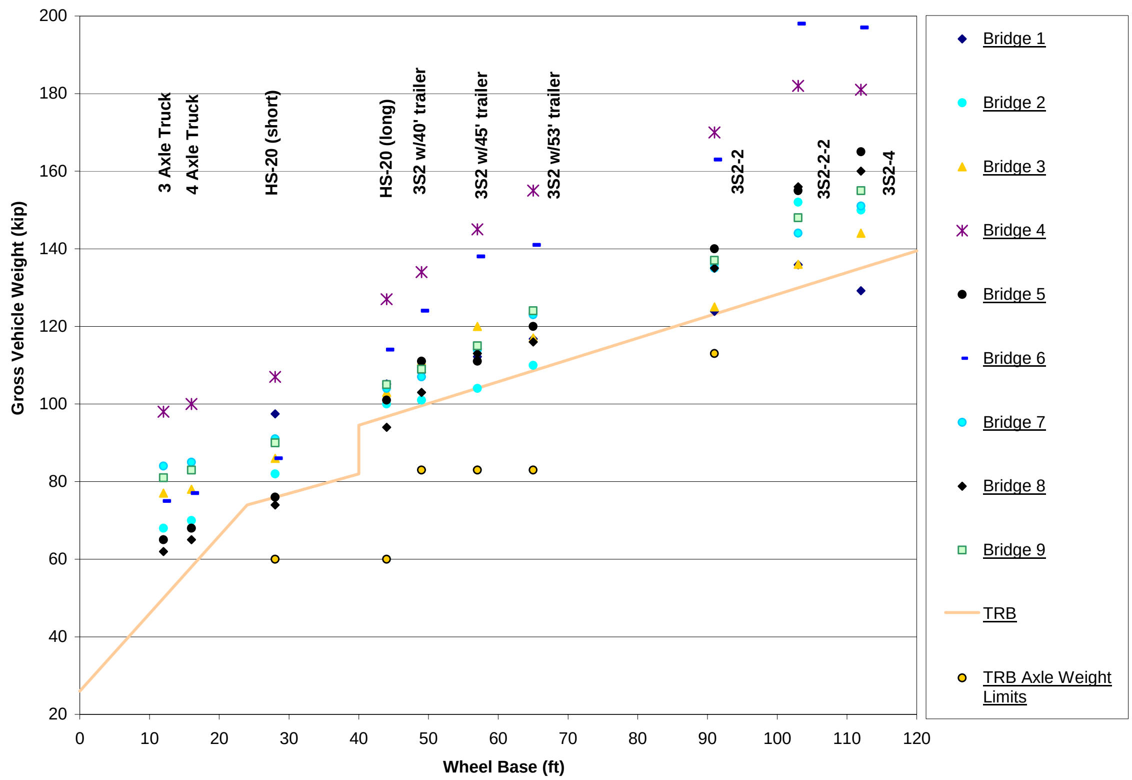

Figure 36. TRB Formula and Critical Weights for 5% Overstress With Moment Redistribution

CONCLUSION AND RECOMMENDATIONS

As shown in the previous chapter TTI-HS20 is very effective for most cases in restricting the stresses to within the 5% overstress limit. When moment redistribution is not considered it fails in five cases to restrict the stresses within 5% overstress. In case of Bridge 2 the formula fails for 3S2 with 40 ft trailer and 3S2 with 45 ft trailer; it restricts the stresses to 6.5% and 5.6%, respectively, above the allowable stress. For bridge 3 it is ineffective in three cases in restricting the stresses to within the limit. The three cases are: rocky mountain double, turnpike double, and triple. In these cases the formula restricts the overstress to 7.6%, 5.3%, and 6.2%, respectively.

Thus, it can be seen that the maximum stress allowable by TTI-HS20 is just 7.5% above the allowable stress. Note that Bridge 2 and Bridge 3 are examples from the Highway Structures Design Handbook (1986), United States Steel. These are not actual bridges and design for which might not be as conservative as it usually is for actual bridges. Also, the Design Handbook specifically mentions that in cases where it is advantageous the negative moments over supports of continuous beams are reduced up to ten percent and positive moments are proportionately increased; to assure compactness beam are adequately braced. If this procedure is adopted which is called as Moment Redistribution, then TTI-HS20 protects these bridges against excessive overstress.

Moment redistribution can only be applied when sections are compact, which is usually true for beam bridges. Plate girder bridges in most cases will not satisfy compactness requirements. Majority of the nation’s steel bridge inventory is expected to be plate girder bridge type. Additionally, application of moment redistribution only in cases where it is advantageous is questionable. Therefore, in spite of the fact that moment redistribution could be used as a justification of higher truck weights, it is recommended that the bridge formula not be based for all bridges on such redistribution of negative moments.

Simple Span Bridges account for 88% of the bridges in Texas and 74% of the bridges in the nation. During the development of the formula only simple span bridges were considered, the data was extensive and intensive, as such covered almost all bridge types. It can be said with some certainty that the formula in the case of simple span bridges will be effective in restricting stresses within permissible limits.

For continuous bridges, steel continuous bridges are the most critical, this is the reason they were the only type tested in this study and the previous study (James and Zhang, 1991). Bridge Inventory Data collected by FHWA shows that of the total number of concrete, steel and pre-stressed concrete bridges 7.35% are Steel-Continuous type. This figure for the nation is slightly higher at 8.67%. For this bridge type TTI-HS20 is successful in almost all cases in preventing excessive overstress. Hence, it can be safely said that this formula would be effective for a vast majority of bridges and an extremely small percentage of bridges would be left unprotected by this formula.

Recommendations

It is recommended that the TTI-HS20 formula be promoted as the nation's replacement for the current Bridge Formula B. This formula will allow economic operation of longer combination vehicles above the current 80,000 lb weight limit. Comparison with the other formulas shows that TTI-HS20 is neither too liberal to cause very high overstresses, nor too conservative to prevent the economical operation of long combination vehicles.

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APPENDIX

Table 86. Live Load Data for Example Bridge 1

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Effective Load (lb)
2S2	0	22000	2.086E+04
	14	29000	2.750E+04
	28	25000	2.371E+04
	32	25000	2.371E+04
		100000	
2S2	0	22000	2.086E+04
	14	29000	2.750E+04
	34	25000	2.371E+04
	38	25000	2.371E+04
		100000	
3S2-4	0	12000	1.138E+04
	18	13000	1.233E+04
	22	13000	1.233E+04
	54	10000	9.483E+03
	58	10000	9.483E+03
	66	10000	9.483E+03
	70	10000	9.483E+03
	94	13000	1.233E+04
	98	9000	8.535E+03
		100000	
3S2-4	0	12000	1.138E+04
	18	13000	1.233E+04
	22	13000	1.233E+04
	54	10000	9.483E+03
	58	10000	9.483E+03
	66	10000	9.483E+03
	70	10000	9.483E+03
	100	13000	1.233E+04
	104	9000	8.535E+03
		100000	

Table 87. Live Load Data for Example Bridge 2

Truck Type	Axle Spacing (ft)	Axle Spacing (increments)	Axle Load (lb)	Effective Load (lb)
2S2	0	0	22000	3.676E+04
	20	10	29000	4.846E+04
	46	23	25000	4.177E+04
	50	25	25000	4.177E+04
			100000	
3S2-4	0	0	12000	2.005E+04
	18	9	13000	2.172E+04
	22	11	13000	2.172E+04
	54	27	10000	1.671E+04
	58	29	10000	1.671E+04
	66	33	10000	1.671E+04
	70	35	10000	1.671E+04
	94	47	13000	2.172E+04
	98	49	9000	1.504E+04
			100000	
3S2-4	0	0	12000	2.005E+04
	18	9	13000	2.172E+04
	22	11	13000	2.172E+04
	54	27	10000	1.671E+04
	58	29	10000	1.671E+04
	66	33	10000	1.671E+04
	70	35	10000	1.671E+04
	100	50	13000	2.172E+04
	104	52	9000	1.504E+04
			100000	

Table 88. Live Load Data for Bridge 1

Truck Type	Axle Spacing (ft)	Proportioned Axle Spacing	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
HS-20 (short)	0	0	8000	11,111	1.749E+04
	14	10	32000	44,444	6.997E+04
	28	20	32000	44,444	6.997E+04
			72000	100,000	
HS-20 (long)	0	0	8000	11,111	1.749E+04
	14	10	32000	44,444	6.997E+04
	44	31	32000	44,444	6.997E+04
			72000	100,000	
3S2 w/40' trailer	0	0	9280	12,664	1.994E+04
	13	9	16000	21,834	3.438E+04
	17	12	16000	21,834	3.438E+04
	45	32	16000	21,834	3.438E+04
	49	35	16000	21,834	3.438E+04
			73280	100,000	
3S2 w/45' trailer	0	0	12000	15,000	2.362E+04
	16	11	17000	21,250	3.346E+04
	20	14	17000	21,250	3.346E+04
	53	38	17000	21,250	3.346E+04
	57	41	17000	21,250	3.346E+04
			80000	100,000	
3S2 w/53’ trailer	0	0	12000	15,000	2.362E+04
	16	11	17000	21,250	3.346E+04
	20	14	17000	21,250	3.346E+04
	61	44	17000	21,250	3.346E+04
	65	46	17000	21,250	3.346E+04
			80000	100,000	
3S2-2 (Rocky Mtn. Dbl)	0	0	11500	10,177	1.602E+04
	14.3	10	16000	14,159	2.229E+04
	18.63	13	16000	14,159	2.229E+04

Table 88. Continued

Truck Type	Axle Spacing (ft)	Proportioned Axle Spacing	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
	53.13	38	16500	14,602	2.299E+04
	57.63	41	16500	14,602	2.299E+04
	68.13	49	18500	16,372	2.578E+04
	91.13	65	18000	15,929	2.508E+04
			113000	100,000	
3S2-4 (Turnpike Dbl)	0	0	12000	9,375	1.476E+04
	16	11	15500	12,109	1.906E+04
	20	14	15500	12,109	1.906E+04
	56	40	13500	10,547	1.660E+04
	60	43	13500	10,547	1.660E+04
	66	47	13500	10,547	1.660E+04
	70	50	13500	10,547	1.660E+04
	106	76	15500	12,109	1.906E+04
	112	80	15500	12,109	1.906E+04
			128000	100,000	
3S2-2-2 (Triple)	0	0	10000	7,937	1.250E+04
	12.33	9	13000	10,317	1.624E+04
	16.33	12	13000	10,317	1.624E+04
	36	26	12000	9,524	1.499E+04
	40	29	12000	9,524	1.499E+04
	48	34	16000	12,698	1.999E+04
	71.5	51	17000	13,492	2.124E+04
	79.5	57	16000	12,698	1.999E+04
	103	74	17000	13,492	2.124E+04
			126000	100,000	
3 Axle Truck	0	0		37,000	5.825E+04
	8	6		31,500	4.959E+04
	12	9		31,500	4.959E+04
				100,000	
4 Axle Truck	0	0		25,000	3.936E+04
	8	6		25,000	3.936E+04
	12	9		25,000	3.936E+04
	16	11		25,000	3.936E+04
				100,000	

Table 89 Live Load Data for Bridge 2

Truck Type	Axle Spacing (ft)	Proportioned Axle Spacing	Axle Load (lb)	Effective Load (lb)
HS-20 (short)	0	0	8000	8.468E+03
	14	14	32000	3.387E+04
	28	28	32000	3.387E+04
			72000	
HS-20 (long)	0	0	8000	8.468E+03
	14	14	32000	3.387E+04
	44	44	32000	3.387E+04
			72000	
3S2 w/40' trailer	0	0	9280	9.822E+03
	13	13	16000	1.694E+04
	17	17	16000	1.694E+04
	45	45	16000	1.694E+04
	49	49	16000	1.694E+04
			73280	
3S2 w/45'	0	0	12000	1.270E+04
	16	16	17000	1.799E+04
	20	20	17000	1.799E+04
	53	53	17000	1.799E+04
	57	57	17000	1.799E+04
			80000	
3S2 w/53	0	0	12000	1.270E+04
	16	16	17000	1.799E+04
	20	20	17000	1.799E+04
	61	61	17000	1.799E+04
	65	65	17000	1.799E+04
			80000	
3S2-2 (Rocky Mtn Dbl)	0	0	11500	1.217E+04
	14.3	14	16000	1.694E+04
	18.63	19	16000	1.694E+04

Table 89. Continued

Truck Type	Axle Spacing (ft)	Proportioned Axle Spacing	Axle Load (lb)	Effective Load (lb)
	53.13	53	16500	1.746E+04
	57.63	58	16500	1.746E+04
	68.13	68	18500	1.958E+04
	91.13	91	18000	1.905E+04
			113000	
3S2-4 (Turnpike Dbl)	0	0	12000	1.270E+04
	16	16	15500	1.641E+04
	20	20	15500	1.641E+04
	56	56	13500	1.429E+04
	60	60	13500	1.429E+04
	66	66	13500	1.429E+04
	70	70	13500	1.429E+04
	106	106	15500	1.641E+04
	112	112	15500	1.641E+04
			128000	
3S2-2-2 (Triple)	0	0	10000	1.058E+04
	12.33	12	13000	1.376E+04
	16.33	16	13000	1.376E+04
	36	36	12000	1.270E+04
	40	40	12000	1.270E+04
	48	48	16000	1.694E+04
	71.5	72	17000	1.799E+04
	79.5	80	16000	1.694E+04
	103	103	17000	1.799E+04
			126000	
3 Axle Truck	0	0	37,000	39162.734
	8	8	31,500	33341.247
	12	12	31,500	33341.247
			100,000	
4 Axle Truck	0	0	25,000	26461.307
	8	8	25,000	26461.307
	12	12	25,000	26461.307
	16	16	25,000	26461.307
			100,000	

Table 90 Live Load Data for Bridge 3

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Scaled Axle Load (lb)	Effective Load (lb)
HS 20 (short)	0	8000	11111	1.220E+04
	14	32000	44444	4.880E+04
	28	32000	44444	4.880E+04
		72000	100000	
HS 20 (long)	0	8000	11111	1.220E+04
	14	32000	44444	4.880E+04
	44	32000	44444	4.880E+04
		72000	100000	
3S2 w/40' trailer	0	9280	12664	1.390E+04
	13	16000	21834	2.397E+04
	17	16000	21834	2.397E+04
	45	16000	21834	2.397E+04
	49	16000	21834	2.397E+04
		73280	100000	
3S2 w/45' trailer	0	12000	15000	1.647E+04
	16	17000	21250	2.333E+04
	20	17000	21250	2.333E+04
	53	17000	21250	2.333E+04
	57	17000	21250	2.333E+04
		80000	100000	
3S2 w/53' trailer	0	12000	15000	1.647E+04
	16	17000	21250	2.333E+04
	20	17000	21250	2.333E+04
	61	17000	21250	2.333E+04
	65	17000	21250	2.333E+04
		80000	100000	
3S2-2 (Rocky Mtn Dbl)	0	11500	10177	1.117E+04
	14	16000	14159	1.555E+04
	19	16000	14159	1.555E+04

Table 90. Continued

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Scaled Axle Load (lb)	Effective Load (lb)
	53	16500	14602	1.603E+04
	58	16500	14602	1.603E+04
	68	18500	16372	1.798E+04
	91	18000	15929	1.749E+04
		113000	100000	
3S2-4 (Turnpike Dbl)	0	12000	9375	1.029E+04
	16	15500	12109	1.330E+04
	20	15500	12109	1.330E+04
	56	13500	10547	1.158E+04
	60	13500	10547	1.158E+04
	68	13500	10547	1.158E+04
	72	13500	10547	1.158E+04
	108	15500	12109	1.330E+04
	112	15500	12109	1.330E+04
		128000	100000	
3S2-2-2 (Triple)	0	10000	7692	8.446E+03
	12	14000	10769	1.182E+04
	16	14000	10769	1.182E+04
	36	12000	9231	1.014E+04
	40	12000	9231	1.014E+04
	48	17000	13077	1.436E+04
	72	17000	13077	1.436E+04
	80	17000	13077	1.436E+04
	103	17000	13077	1.436E+04
		130000	100000	
3 Axle Truck	0	37000	37000	4.063E+04
	8	31500	31500	3.459E+04
	12	31500	31500	3.459E+04
		100000	100000	
4 Axle Truck	0	25000	25000	2.745E+04
	8	25000	25000	2.745E+04
	12	25000	25000	2.745E+04
	16	25000	25000	2.745E+04
		100000	100000	

Table 91. Live Load Data for Bridge 4

Truck Type	Axle Spacing (ft)	Proportioned Axle Spacing	Axle Load (lb)	Effective Load (lb)
HS 20 (short)	0	0	8000	8.589E+03
	14	14	32000	3.436E+04
	28	28	32000	3.436E+04
			72000	
HS 20 (long)	0	0	8000	8.589E+03
	14	14	32000	3.436E+04
	44	44	32000	3.436E+04
			72000	
3S2 w/40' trailer	0	0	9280	9.963E+03
	13	13	16000	1.718E+04
	17	17	16000	1.718E+04
	45	45	16000	1.718E+04
	49	49	16000	1.718E+04
			73280	
3S2 w/45' trailer	0	0	12000	1.288E+04
	16	16	17000	1.825E+04
	20	20	17000	1.825E+04
	53	53	17000	1.825E+04
	57	57	17000	1.825E+04
			80000	
3S2 w/53' trailer	0	0	12000	1.288E+04
	16	16	17000	1.825E+04
	20	20	17000	1.825E+04
	61	61	17000	1.825E+04
	65	65	17000	1.825E+04
			80000	
3S2-2 (Rocky Mtn Dbl)	0	0	11500	1.235E+04
	14.3	14	16000	1.718E+04

Table 91. Continued

Truck Type	Axle Spacing (ft)	Proportioned Axle Spacing	Axle Load (lb)	Effective Load (lb)
	18.63	19	16000	1.718E+04
	53.13	53	16500	1.771E+04
	57.63	58	16500	1.771E+04
	68.13	68	18500	1.986E+04
	91.13	91	18000	1.932E+04
			113000	
3S2-4 (Turnpike Dbl)	0	0	12000	1.288E+04
	16	16	15500	1.664E+04
	20	20	15500	1.664E+04
	56	56	13500	1.449E+04
	60	60	13500	1.449E+04
	68	68	13500	1.449E+04
	72	72	13500	1.449E+04
	108	108	15500	1.664E+04
	112	112	15500	1.664E+04
			128000	
3S2-2-2(Triple)	0	0	10000	1.074E+04
	12.33	12	13000	1.396E+04
	16.33	16	13000	1.396E+04
	36	36	12000	1.288E+04
	40	40	12000	1.288E+04
	48	48	16000	1.718E+04
	71.5	72	17000	1.825E+04
	79.5	80	16000	1.718E+04
	103	103	17000	1.825E+04
			126000	
3 Axle Truck	0	0	37,000	3.972E+04
	8	8	31,500	3.382E+04
	12	12	31,500	3.382E+04
			100,000	
4 Axle Truck	0	0	25,000	2.684E+04
	8	8	25,000	2.684E+04
	12	12	25,000	2.684E+04
	16	16	25,000	2.684E+04
			100,000	

Table 92. Live Load Data for Bridge 5

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
HS 20 (short)	0	8000	11111.11	1.140E+04
	14	32000	44444.44	4.561E+04
	28	32000	44444.44	4.561E+04
		72000	100000.00	
HS 20 (long)	0	8000	11111.11	1.140E+04
	14	32000	44444.44	4.561E+04
	44	32000	44444.44	4.561E+04
		72000	100000.00	
3S2 w/40' trailer	0	9280	12663.76	1.300E+04
	13	16000	21834.06	2.241E+04
	17	16000	21834.06	2.241E+04
	45	16000	21834.06	2.241E+04
	49	16000	21834.06	2.241E+04
		73280	100000.00	
3S2 w/45' trailer	0	12000	15000.00	1.539E+04
	16	17000	21250.00	2.181E+04
	20	17000	21250.00	2.181E+04
	53	17000	21250.00	2.181E+04
	57	17000	21250.00	2.181E+04
		80000	100000.00	
3S2 w/53' trailer	0	12000	15000.00	1.539E+04
	16	17000	21250.00	2.181E+04
	20	17000	21250.00	2.181E+04
	61	17000	21250.00	2.181E+04
	65	17000	21250.00	2.181E+04
		80000	100000.00	
3S2-2 (Rocky Mtn Dbl)	0	11500	10176.99	1.044E+04
	14.3	16000	14159.29	1.453E+04
	18.63	16000	14159.29	1.453E+04

Table 92. Continued

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
	53.13	16500	14601.77	1.498E+04
	57.63	16500	14601.77	1.498E+04
	68.13	18500	16371.68	1.680E+04
	91.13	18000	15929.20	1.635E+04
		113000	100000.00	
3S2-4 (Turnpike Dbl)	0	12000	9375.00	9.621E+03
	16	15500	12109.38	1.243E+04
	20	15500	12109.38	1.243E+04
	56	13500	10546.88	1.082E+04
	60	13500	10546.88	1.082E+04
	66	13500	10546.88	1.082E+04
	70	13500	10546.88	1.082E+04
	106	15500	12109.38	1.243E+04
	112	15500	12109.38	1.243E+04
		128000	100000.00	
3S2-2-2 (Triple)	0	10000	7936.51	8.145E+03
	12.33	13000	10317.46	1.059E+04
	16.33	13000	10317.46	1.059E+04
	36	12000	9523.81	9.774E+03
	40	12000	9523.81	9.774E+03
	48	16000	12698.41	1.303E+04
	71.5	17000	13492.06	1.385E+04
	79.5	16000	12698.41	1.303E+04
	103	17000	13492.06	1.385E+04
		126000	100000.00	
3 Axle Truck	0		37000.00	3.797E+04
	8		31500.00	3.233E+04
	12		31500.00	3.233E+04
			100000.00	
4 Axle Truck	0		25000.00	2.566E+04
	8		25000.00	2.566E+04
	12		25000.00	2.566E+04
	16		25000.00	2.566E+04
			100000.00	

Table 93 Live Load Data for Bridge 6

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
HS 20 (short)	0	8000	11111.11	1.094E+04
	14	32000	44444.44	4.378E+04
	28	32000	44444.44	4.378E+04
		72000	100000.00	
HS 20 (long)	0	8000	11111.11	1.094E+04
	14	32000	44444.44	4.378E+04
	44	32000	44444.44	4.378E+04
		72000	100000.00	
3S2 w/40' trailer	0	9280	12663.76	1.247E+04
	13	16000	21834.06	2.151E+04
	17	16000	21834.06	2.151E+04
	45	16000	21834.06	2.151E+04
	49	16000	21834.06	2.151E+04
		73280	100000.00	
3S2 w/45' trailer	0	12000	15000.00	1.477E+04
	16	17000	21250.00	2.093E+04
	20	17000	21250.00	2.093E+04
	53	17000	21250.00	2.093E+04
	57	17000	21250.00	2.093E+04
		80000	100000.00	
3S2 w/53' trailer	0	12000	15000.00	1.477E+04
	16	17000	21250.00	2.093E+04
	20	17000	21250.00	2.093E+04
	61	17000	21250.00	2.093E+04
	65	17000	21250.00	2.093E+04
		80000	100000.00	
3S2-2 (Rocky Mtn Dbl)	0	11500	10176.99	1.002E+04
	14.3	16000	14159.29	1.395E+04
	18.63	16000	14159.29	1.395E+04

Table 93. Continued

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
	53.13	16500	14601.77	1.438E+04
	57.63	16500	14601.77	1.438E+04
	68.13	18500	16371.68	1.613E+04
	91.13	18000	15929.20	1.569E+04
		113000	100000.00	
3S2-4 (Turnpike Dbl)	0	12000	9375.00	9.234E+03
	16	15500	12109.38	1.193E+04
	20	15500	12109.38	1.193E+04
	56	13500	10546.88	1.039E+04
	60	13500	10546.88	1.039E+04
	66	13500	10546.88	1.039E+04
	70	13500	10546.88	1.039E+04
	106	15500	12109.38	1.193E+04
	112	15500	12109.38	1.193E+04
		128000	100000.00	
3S2-2-2 (Triple)	0	10000	7936.51	7.817E+03
	12.33	13000	10317.46	1.016E+04
	16.33	13000	10317.46	1.016E+04
	36	12000	9523.81	9.380E+03
	40	12000	9523.81	9.380E+03
	48	16000	12698.41	1.251E+04
	71.5	17000	13492.06	1.329E+04
	79.5	16000	12698.41	1.251E+04
	103	17000	13492.06	1.329E+04
		126000	100000.00	
3 Axle Truck	0		37000.00	3.644E+04
	8		31500.00	3.103E+04
	12		31500.00	3.103E+04
			100000.00	
4 Axle Truck	0		25000.00	2.462E+04
	8		25000.00	2.462E+04
	12		25000.00	2.462E+04
	16		25000.00	2.462E+04
			100000.00	

Table 94. Live Load Data for Bridge 7

Truck Type	Axle Spacing (ft)	Axle Spacing (increments)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
HS 20 (short)	0	0	8000	11111.11	1.000E+04
	14	8	32000	44444.44	4.000E+04
	28	17	32000	44444.44	4.000E+04
			72000	100000.00	
HS 20 (long)	0	0	8000	11111.11	1.000E+04
	14	8	32000	44444.44	4.000E+04
	44	26	32000	44444.44	4.000E+04
			72000	100000.00	
3S2 w/40' trailer	0	0	9280	12663.76	1.140E+04
	13	8	16000	21834.06	1.965E+04
	17	10	16000	21834.06	1.965E+04
	45	27	16000	21834.06	1.965E+04
	49	29	16000	21834.06	1.965E+04
			73280	100000.00	
3S2 w/45' trailer	0	0	12000	15000.00	1.350E+04
	16	10	17000	21250.00	1.913E+04
	20	12	17000	21250.00	1.913E+04
	53	32	17000	21250.00	1.913E+04
	57	34	17000	21250.00	1.913E+04
			80000	100000.00	
3S2 w/53' trailer	0	0	12000	15000.00	1.350E+04
	16	10	17000	21250.00	1.913E+04
	20	12	17000	21250.00	1.913E+04
	61	37	17000	21250.00	1.913E+04
	65	39	17000	21250.00	1.913E+04
			80000	100000.00	
3S2-2 (Rocky Mtn Dbl)	0	0	11500	10176.99	9.159E+03
	14.3	9	16000	14159.29	1.274E+04
	18.63	11	16000	14159.29	1.274E+04

Table 94. Continued

Truck Type	Axle Spacing (ft)	Axle Spacing (increments)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
	53.13	32	16500	14601.77	1.314E+04
	57.63	35	16500	14601.77	1.314E+04
	68.13	41	18500	16371.68	1.473E+04
	91.13	55	18000	15929.20	1.434E+04
			113000	100000.00	
3S2-4 (Turnpike Dbl)	0	0	12000	9375.00	8.438E+03
	16	10	15500	12109.38	1.090E+04
	20	12	15500	12109.38	1.090E+04
	56	34	13500	10546.88	9.492E+03
	60	36	13500	10546.88	9.492E+03
	66	40	13500	10546.88	9.492E+03
	70	42	13500	10546.88	9.492E+03
	106	64	15500	12109.38	1.090E+04
	112	67	15500	12109.38	1.090E+04
			128000	100000.00	
3S2-2-2 (Triple)	0	0	10000	7936.51	7.143E+03
	12.33	7	13000	10317.46	9.286E+03
	16.33	10	13000	10317.46	9.286E+03
	36	22	12000	9523.81	8.571E+03
	40	24	12000	9523.81	8.571E+03
	48	29	16000	12698.41	1.143E+04
	71.5	43	17000	13492.06	1.214E+04
	79.5	48	16000	12698.41	1.143E+04
	103	62	17000	13492.06	1.214E+04
			126000	100000.00	
3 Axle Truck	0	0		37000.00	3.330E+04
	8	5		31500.00	2.835E+04
	12	7		31500.00	2.835E+04
				100000.00	
4 Axle Truck	0	0		25000.00	2.250E+04
	8	5		25000.00	2.250E+04
	12	7		25000.00	2.250E+04
	16	10		25000.00	2.250E+04
				100000.00	

Table 95. Live Load Data for Bridge 8

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
HS 20 (short)	0	8000	11111.11	1.106E+04
	14	32000	44444.44	4.426E+04
	28	32000	44444.44	4.426E+04
		72000	100000.00	
HS 20 (long)	0	8000	11111.11	1.106E+04
	14	32000	44444.44	4.426E+04
	44	32000	44444.44	4.426E+04
		72000	100000.00	
3S2 w/40' trailer	0	9280	12663.76	1.261E+04
	13	16000	21834.06	2.174E+04
	17	16000	21834.06	2.174E+04
	45	16000	21834.06	2.174E+04
	49	16000	21834.06	2.174E+04
		73280	100000.00	
3S2 w/45' trailer	0	12000	15000.00	1.494E+04
	16	17000	21250.00	2.116E+04
	20	17000	21250.00	2.116E+04
	53	17000	21250.00	2.116E+04
	57	17000	21250.00	2.116E+04
		80000	100000.00	
3S2 w/53' trailer	0	12000	15000.00	1.494E+04
	16	17000	21250.00	2.116E+04
	20	17000	21250.00	2.116E+04
	61	17000	21250.00	2.116E+04
	65	17000	21250.00	2.116E+04
		80000	100000.00	
3S2-2 (Rocky Mtn Dbl)	0	11500	10176.99	1.013E+04
	14.3	16000	14159.29	1.410E+04
	18.63	16000	14159.29	1.410E+04
	53.13	16500	14601.77	1.454E+04

Table 95. Continued

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
	57.63	16500	14601.77	1.454E+04
	68.13	18500	16371.68	1.630E+04
	91.13	18000	15929.20	1.586E+04
		113000	100000.00	
3S2-4 (Turnpike Dbl)	0	12000	9375.00	9.335E+03
	16	15500	12109.38	1.206E+04
	20	15500	12109.38	1.206E+04
	56	13500	10546.88	1.050E+04
	60	13500	10546.88	1.050E+04
	66	13500	10546.88	1.050E+04
	70	13500	10546.88	1.050E+04
	106	15500	12109.38	1.206E+04
	112	15500	12109.38	1.206E+04
		128000	100000.00	
3S2-2-2 (Triple)	0	10000	7936.51	7.903E+03
	12.33	13000	10317.46	1.027E+04
	16.33	13000	10317.46	1.027E+04
	36	12000	9523.81	9.483E+03
	40	12000	9523.81	9.483E+03
	48	16000	12698.41	1.264E+04
	71.5	17000	13492.06	1.343E+04
	79.5	16000	12698.41	1.264E+04
	103	17000	13492.06	1.343E+04
		126000	100000.00	
3 Axle Truck	0		37000.00	3.684E+04
	8		31500.00	3.137E+04
	12		31500.00	3.137E+04
			100000.00	
4 Axle Truck	0		25000.00	2.489E+04
	8		25000.00	2.489E+04
	12		25000.00	2.489E+04
	16		25000.00	2.489E+04
			100000.00	

Table 96. Live Load Data for Bridge 9

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
HS 20 (short)	0	8000	11111.11	1.087E+04
	14	32000	44444.44	4.347E+04
	28	32000	44444.44	4.347E+04
		72000	100000.00	
HS 20 (long)	0	8000	11111.11	1.087E+04
	14	32000	44444.44	4.347E+04
	44	32000	44444.44	4.347E+04
		72000	100000.00	
3S2 w/40' trailer	0	9280	12663.76	1.239E+04
	13	16000	21834.06	2.135E+04
	17	16000	21834.06	2.135E+04
	45	16000	21834.06	2.135E+04
	49	16000	21834.06	2.135E+04
		73280	100000.00	
3S2 w/45' trailer	0	12000	15000.00	1.467E+04
	16	17000	21250.00	2.078E+04
	20	17000	21250.00	2.078E+04
	53	17000	21250.00	2.078E+04
	57	17000	21250.00	2.078E+04
		80000	100000.00	
3S2 w/53' trailer	0	12000	15000.00	1.467E+04
	16	17000	21250.00	2.078E+04
	20	17000	21250.00	2.078E+04
	61	17000	21250.00	2.078E+04
	65	17000	21250.00	2.078E+04
		80000	100000.00	
3S2-2 (Rocky Mtn Dbl)	0	11500	10176.99	9.954E+03
	14.3	16000	14159.29	1.385E+04
	18.63	16000	14159.29	1.385E+04

Table 96. Continued

Truck Type	Axle Spacing (ft)	Axle Load (lb)	Proportioned Load (lb)	Effective Load (lb)
	53.13	16500	14601.77	1.428E+04
	57.63	16500	14601.77	1.428E+04
	68.13	18500	16371.68	1.601E+04
	91.13	18000	15929.20	1.558E+04
		113000	100000.00	
3S2-4 (Turnpike Dbl)	0	12000	9375.00	9.169E+03
	16	15500	12109.38	1.184E+04
	20	15500	12109.38	1.184E+04
	56	13500	10546.88	1.032E+04
	60	13500	10546.88	1.032E+04
	66	13500	10546.88	1.032E+04
	70	13500	10546.88	1.032E+04
	106	15500	12109.38	1.184E+04
	112	15500	12109.38	1.184E+04
		128000	100000.00	
3S2-2-2 (Triple)	0	10000	7936.51	7.762E+03
	12.33	13000	10317.46	1.009E+04
	16.33	13000	10317.46	1.009E+04
	36	12000	9523.81	9.315E+03
	40	12000	9523.81	9.315E+03
	48	16000	12698.41	1.242E+04
	71.5	17000	13492.06	1.320E+04
	79.5	16000	12698.41	1.242E+04
	103	17000	13492.06	1.320E+04
		126000	100000.00	
3 Axle Truck	0		37000.00	3.619E+04
	8		31500.00	3.081E+04
	12		31500.00	3.081E+04
			100000.00	
4 Axle Truck	0		25000.00	2.445E+04
	8		25000.00	2.445E+04
	12		25000.00	2.445E+04
	16		25000.00	2.445E+04
			100000.00	

VITA

Yateesh Jaykishan Contractor received his Bachelor of Engineering in Civil Engineering from University of Mumbai (Bombay) in June 2003. He began working towards his Master of Science in Civil Engineering in the fall of 2003. Mr. Contractor worked as a Graduate Assistant Researcher for Dr. Ray James.

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