USER'S GUIDE:

BRIDGE ANALYSIS AND EVALUATION OF EFFECTS UNDER OVERLOAD VEHICLES

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Department of Civil and Environmental Engineering
University of Wisconsin, Madison

Authors: Han-Ug Bae and Michael Oliva;
University of Wisconsin-Madison, Madison, WI.

Principal Investigator: Michael Oliva;
Professor, Department of Civil and Environmental Engineering,
University of Wisconsin-Madison

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16. Abstract

Movement of industrial freight infrequently requires special overload vehicles weighing 5 to 6 times the normal legal truck weight to move across highway systems. The gross vehicle weight of the overload vehicles frequently exceeds 400 kips while the normal interstate legal limit for gross vehicle weight is 80 kips. Examples of the loads carried by the vehicles are pressure vessels and transformers used in power plants, huge boilers, military hardware, beams and barges. Transportation agencies are asked to provide special permits for these vehicles along a specified pathway. Because of the unusual configuration of the vehicles it is difficult for those agencies to evaluate the effect of the vehicles on highway bridges. It is a time consuming job for the local agency since simple analysis methods for determining effects on bridges subjected to those overloads are not well established and the possibility of errors in estimating the impact of the loads on these structures could affect safety.

A user's guide, with example calculations, is provided here to apply the simple method of calculating forces induced in the girders of multi-girder bridges by overload vehicle in both single trailer and dual trailer configurations.

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Executive Summary

This user's guide provides simplified equations for estimating the portion of an overload vehicle's load or force that is resisted by an interior girder in a multi-girder highway bridge.

Two examples calculations are completed showing how the simplified equations for estimating highway bridge girder forces can be used. The first example looks at a single trailer overload vehicle with 11 axles and total weight of 312,000 lbs. on a single span bridge of 120ft length. The second example focuses on the same bridge, but with a dual trailer vehicle having 16 axles and total weight of 500,000 lbs.

Recommendations are also provided on limiting the weight carried by any dual tire/wheel combination of an overload truck to avoid damage to the bridge deck.

CONTENTS

INTRODUCTION

Background

Movement of industrial freight infrequently requires special overload vehicles weighing 5 to 6 times the normal legal truck weight to move across highway systems. Figure 1 shows one example of a special overload vehicle. The gross vehicle weight of the superload vehicles frequently exceeds 400 kips while the normal interstate legal limit for gross vehicle weight is 80 kips. Examples of the loads carried by the vehicles are pressure vessels and transformers used in power plants, wind turbine components, boilers, military hardware, beams and barges.

Figure 1. Special overload vehicle (from Perkins Motor Transport)

Transportation agencies are asked to provide special permits for these vehicles along a specified pathway. Because of the unusual configuration of the vehicles it is difficult for those agencies to evaluate the effect of the vehicles on highway bridges. It is a time consuming job for the agency since simple analysis methods for determining the effects on bridges subjected to non-standard trucks are not well established and the possibility of errors in estimating the impact of the loads on these structures could affect safety. The techniques provided here aim to help agencies in evaluating the impact of these vehicles on structures.

The method for calculating and using simple girder distribution factors to calculate the forces created in individual girders of multi-girder bridges are provided in this guide. Two examples are included to demonstrate the ease of application of the suggested method for determining the girder forces created by unusual truck-trailer loads.

SIMPLIFIED MULTI-GIRDER BRIDGE ANALYSIS

The key problem in evaluating the effect of an overload vehicle on a multi-girder bridge, such as the steel girder bridge under construction in Figure 2, is determining what portion of the vehicle load is carried by an individual girder.

Figure 2. Multi-girder steel bridge with concrete deck to be applied.

“Girder Distribution Factors” (GDF’s) are normally used to define the portion of a vehicle induced force that is resisted in a single girder. For the bending moment in a girder – the total bending moment caused by the vehicle on the bridge is multiplied by a GDF to find the girder moment. For shear force in a girder – the total shear force caused by the vehicle on the bridge is multiplied by another GDF to find the girder shear.

GDF’s for both shear and moment caused by single or dual trailer overload vehicles can be calculated using simple equations provided here.

Limitations for using the GDF equations:

The following limitations must be applied in using the simplified GDF equations.

1) ≥ 4 girders — The equations shall only be used for bridges with four or more equally spaced girders;

2) Interior girders — The equations shall be only used to find moment or shear force GDFs for interior girders;

3) Single lane overload vehicles, 8ft. or wider wheel spacing, OR
Dual lane overload vehicle with 4 ft. or wider exterior transverse wheel spacing and 2 to 10 ft. interior transverse wheel spacing;

4) Bridge spans of 40ft to 160ft;

5) Girders spacing of 5 to 15ft

6) Deck thickness of 6 to 13in.;

7) Type a, e, I, j, & k bridges — The factors only apply to these normal girder bridges shown in AASHTO LRFD Table 4.6.2.2.1-1;

8) No multi-presence factor is applied;

9) No dynamic allowance factor is applied.

The analysis of exterior girders is excluded here since it should be done simply by using the lever rule described in AASHTO LRFD (C4.6.2.2.1). Since the forces in exterior girders are strongly dependent on the length of any deck overhang, a simple equation for the GDF in an exterior girder is inappropriate.

Normal AASHTO GDF factors for design trucks:

The normal AASHTO LRFD distribution factors for design trucks are calculated as follows for type a, e, I, j, & k bridges (Figure 3) :

moment, 1 lane loaded:
$$0.06+\left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{12Lt^3}\right)^{0.1}$$

moment, 2 lanes loaded:
$$0.075+\left(\frac{S}{9.5}\right)^{0.6}\left(\frac{S}{L}\right)^{0.2}\left(\frac{K_g}{12Lt^3}\right)^{0.1}$$

shear, 1 lane loaded:
$$0.36+\left(\frac{S}{25.0}\right)$$

shear, 2 lanes loaded:
$$0.2+\frac{S}{12}-\left(\frac{s}{35}\right)^{2.0}$$

The variables in the equations are:

S = Girder spacing (ft),
L = Span (ft),
t = Deck depth (in),
$K_g = n(I + Ae_g)$ = Longitudinal stiffness parameter (in^4),
$n = E_B / E_D$, modular ratio: beam/deck
I = Moment of inertia of girder (in^4),
A = Cross-sectional area of girder (in^2),
e_g = Distance between the centers of gravity of the basic girder and the deck (in).

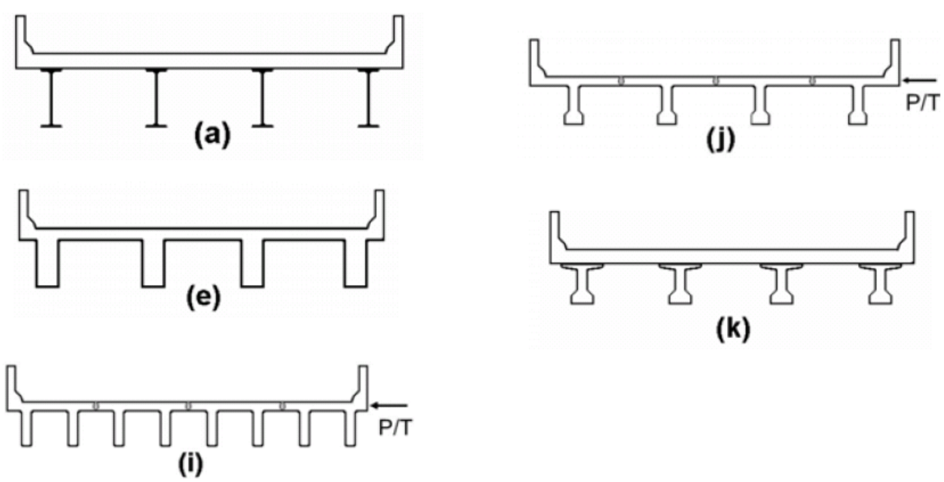


Figure 3. AASHTO LRFD Bridge types a, e, I, j &k.

GDF equations for overload vehicles:

Both moment and shear distribution factors (GDFs) for overload vehicles are calculated by modifying the factors given by AASHTO GDF's for the design truck as shown below using Equations 1&2 with information from Tables 1 and 2.

The AASHTO single lane GDF (moment or shear) is used for the single lane trailer calculation. The AASHTO two lane GDF (moment or shear) is used with the dual trailer overload vehicle.

$$\text{Single lane trailer: } CR\,S^{a}L^{b}t^{c}K_{g}^{\ d} \times \text{(AASHTO GDF)} \qquad (1)$$

$$\text{Dual lane trailer: } CR\,S^{a}L^{b}t^{c}K_{g}^{\ d}S_{w}^{\ e} \times \text{(AASHTO GDF)} \qquad (2)$$

S_w = Spacing of interior wheels for dual lane overload vehicle (ft.).

Table 1: Constants and exponents for GDF equations with overload vehicles

		C	a	b	c	d	e
Single lane loading	Moment	1.61	-0.21	0.02	0.02	-0.03	-
	Shear	0.72	0.14	-0.09	-0.08	0.03	-
Dual lane loading	Moment	1.70	-0.22	0.04	0.19	-0.08	-0.14
	Shear	2.03	0.06	-0.25	-0.12	0.03	-0.28

Table 2: R factor for GDF equation with overload vehicles

		R
Negative moment GDF (for single lane and dual lane loading)		1.3
Bridges with Skew* (θ= skew angle)	Moment GDF for single lane loading	$1-0.05\tan^2\theta$
	Shear GDF for single lane loading	$1-0.23\tan\theta$
	Moment GDF for dual lane loading	$1+0.19\tan^2\theta-0.55\tan\theta$
	Shear GDF for dual lane loading	$1+0.25\tan^2\theta-0.76\tan\theta$
All other cases		1.0

* Valid for $\theta = 0^\circ \sim 60^\circ$

The GDF equations for multi-girder bridges subjected to overload vehicles were developed based on the results from 118 multi-girder bridge analyses. Various configurations of multi-girder bridges and overload vehicles, i.e. span length, deck depth, girder spacing, girder type, girder stiffness, skew angle, number of spans, diaphragms, transverse spacing of center wheels for dual lane vehicles, and single lane and dual lane overload vehicles, were considered in the development.

The equations were developed on the assumptions that the dynamic load allowance for the overload vehicles is 0% by restricting the velocity of the overload vehicles to be less than 5 mph. The multiple presence factors in the AASHTO LRFD Bridge Design Specifications [1] should not be used; they are already explicitly included in the AASHTO GDFs and should not be applied separately. It is assumed that only one overload vehicle will be on a bridge at a time.

The new equations were developed in a manner to insure that the predicted GDFs would not be less than those obtained from accurate FEM analysis, i.e. on the safe side. The predicted distribution factors were on average 113% of the values from the FEM analysis results, showing that the equation is conservative (predicting higher girder loading than the FEM). The standard deviation was 9.5 %. The relationship between the GDFs using the simple equation and those using the finite element analyses is shown in Figure 4. The bold line in the figure indicates the expected result if the two analyses matched perfectly. Most of the data points in the figure are at the upper side of the bold line indicating that the analysis using the simple equations is conservative (predict larger GDFs than the FEM).

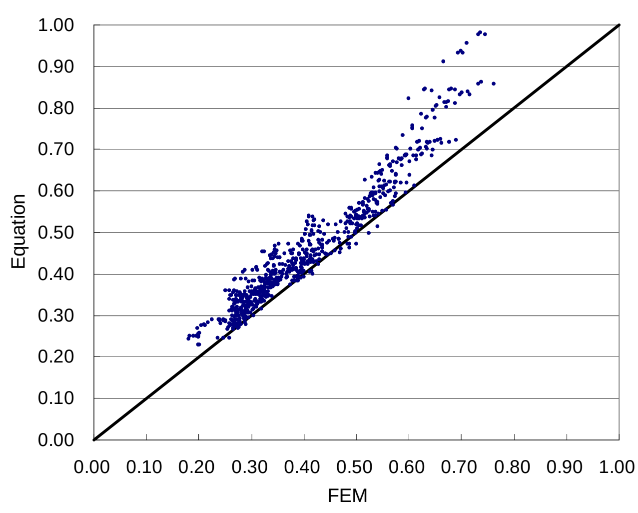
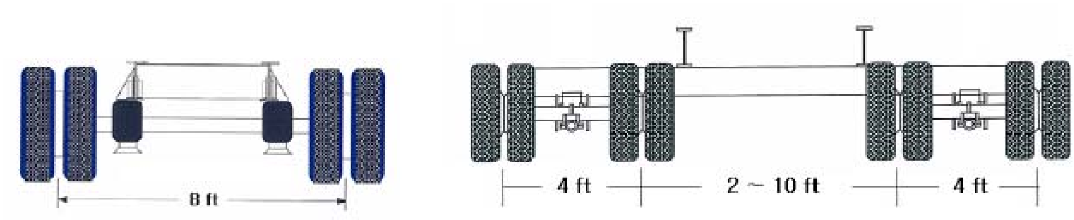


Figure 4. GDF’s predicted by simple equation and accurate FEM analysis for 118 bridges.



a) Single lane trailer b) Dual lane trailer

Figure 5. Transverse wheel spacing of the single lane and dual lane trailers.

Derivation of the simplified equations was based on the two types of vehicle trailers shown in Figure 5. The GDF's provided by the equations will be satisfactory for any single lane vehicles with 8ft or wider wheel set spacings. The GDF's for dual trailers are satisfactory for trailers with a range of spacings between units of 2ft to 10ft.

The GDF's calculated from the equations will be lower than those found using the normal AASHTO LRFD equations. The difference is shown for one bridge configuration in Figure 6. Since the overload vehicle GDF's are smaller than normal AASHTO values, using the new GDF values will allow permitting of heavier overload vehicles than if the AASHTO factors were used. This should facilitate the movement of heavier freight over bridges while still maintaining a safety factor as the comparison with the accurate FEM GDF values in Figure 6 shows.

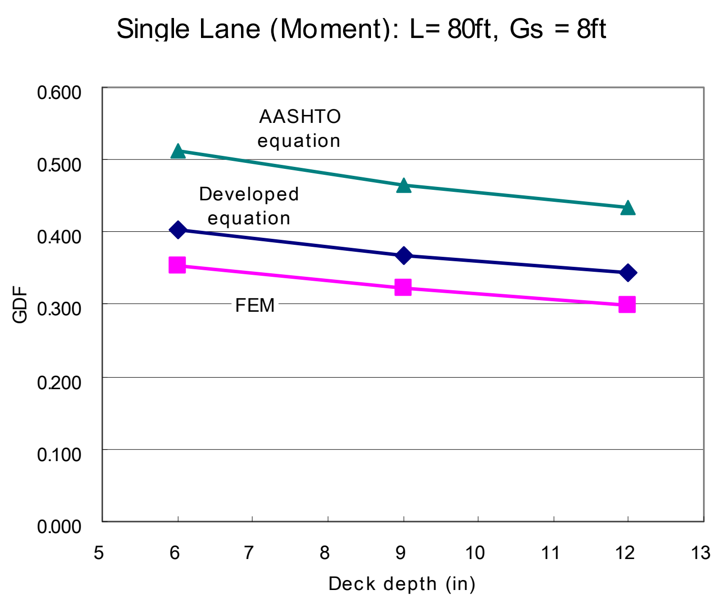


Figure 6. Comparison of GDFs for an 80ft span bridge with 8ft girder spacing.

EXAMPLES USING THE PROPOSED GDF EQUATION FOR MULTI-GIRDER BRIDGES

Step 1) Calculate axle loads of the overload vehicle:
All the wheel set loads at the same longitudinal location on the bridge shall be added to find the total vehicle axle load at that location. The two wheel set loads per axle shall be added for single trailer overload vehicles and four wheel loads shall be added for dual trailer overload vehicles. Multiple presence factors or dynamic allowance shall not be applied in this procedure.

Step 2) Perform a 2-dimensional analysis:
Find the total maximum moment and shear force created by the full overload vehicle in the bridge.
This procedure can be performed using assorted analysis packages and should provide a plotted envelope moment and shear diagram for the bridge subjected to the overload vehicle represented by the axle loads from Step 1. The envelope shall be found by moving the axle loads and vehicle across the bridge. The maximum moment and shear forces found in this step are total bridge forces at a cross-section and are resisted by all the girders.

Step 3) Find AASHTO GDFs for the interior girders:
Table 4.6.2.2.2b-1 (for moment GDF) and Table 4.6.2.2.3a-1 (for shear GDF) in the AASHTO LRFD Bridge Design Specifications [1] shall be used to fine the AASHTO GDFs. The AASHTO "one design lane loaded" equations shall be used for single trailer overload vehicles and the "two or more design lanes loaded" equations shall be used for dual lane – dual trailer overload vehicles.

Step 4) Find the overload truck GDFs for the interior girders using equations 1&2:
This procedure can be performed by using the results from Step 3 with equation (1) for a single trailer overload vehicle or equation (2) for a dual trailer overload vehicle.

Step 5) Calculate maximum moment and shear force in the interior girder:
The maximum member force in an interior girder can be calculated by multiplying the maximum member force found in Step 2 by the GDF found in Step 4.

Step 6) Check safety of the girder:
The maximum member forces found in Step 5 are unfactored live load forces. They must be combined with other forces (DL) using the appropriate load combinations and load factors in Table 3.4.1-1 in the AASHTO LRFD Bridge Design Specifications to check the safety of the girder under the overload vehicle. It is recommended that the Strength II limit state be used, the limit state for permit vehicles.

Exterior girders:

A similar analysis should be conducted starting at Step 4, but substituting the "Lever Rule" method of AASHTO for determining the GDFs for exterior girders as affected by the length of the roadway overhangs. Then Steps 5&6 are conducted as above.

Example for a single trailer overload vehicle:

Configuration of the example bridge is as follows:

- Number of spans = 1
- Number of girders = 5
- Type of girders = Steel girder
- Span (L) = 120 ft
- Girder Spacing (S) = 8 ft.
- Deck depth (t) = 9in
- Cross-section of steel girder (Figure 7)
- Moment of inertia of the girder (I) = 28,709 in^4
- Elastic modulus ratio of girder to deck ($n = E_B / E_D$) = 29000 psi / 3605 psi = 8.044
- Cross-sectional area of the girder (A) = 65.5 in^2
- Distance between the centers of gravity of the girder and deck (e_g) = 31.72 in
- Longitudinal stiffness parameter [$K_g = n(I + Ae_g)$] = 761,098 in^4

The cross-section of the steel girder for the sample bridge is shown in Figure 7.

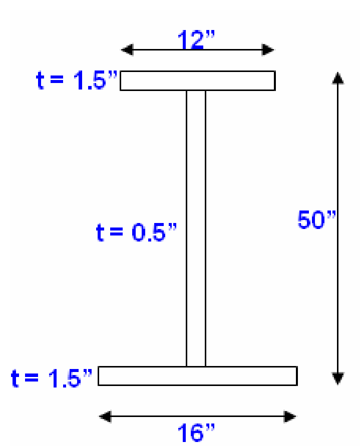
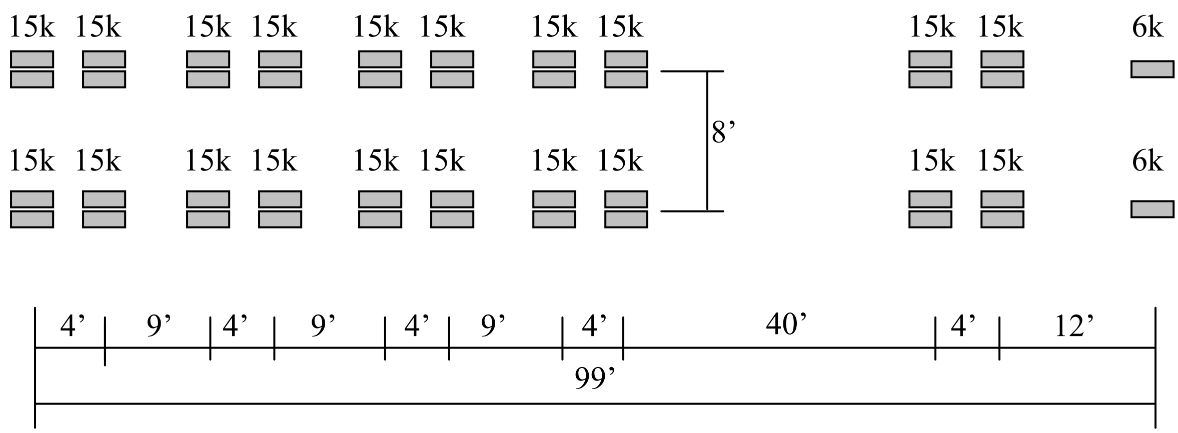
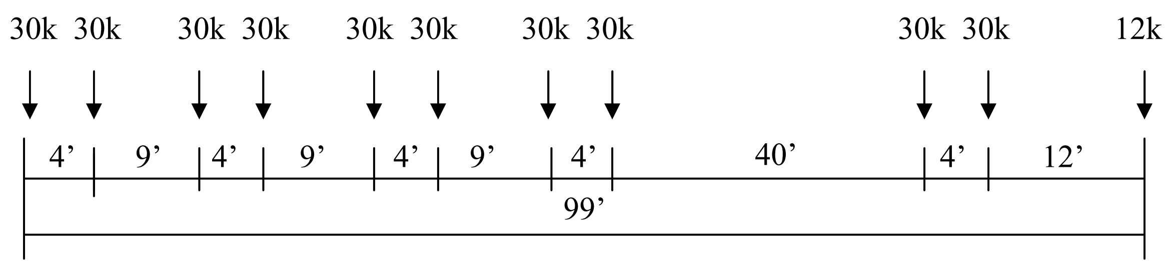


Figure 7. Cross-section of the girder for the sample bridge

The wheel and axle configuration of the single trailer/lane overload vehicle desiring to cross the bridge is shown in Figure 8 with the tractor at the right and trailer at left.



(a) Plan view of wheel loads



(b) Axle loads

Figure 8. Configuration of single trailer overload vehicle used for bridge analysis.

<u>Step 1) Calculate axle loads of the overload vehicle</u>

The axle loads are shown in Figure 8-b.

<u>Step 2) Perform 2 dimensional analysis to find maximum 2-dimensional moment and shear force</u>

The analysis was performed by moving the vehicle across the bridge, as illustrated in Figure 9, and calculating the maximum shear and moment created. The axle loads shown in Figure 8-b were used in a software analysis package to determine the forces. The results of the analysis are shown in Figures 10 & 11 in the form of envelopes. The envelopes show the maximum forces occurring at every location along the bridge span. The maximum moment induced in the bridge by the overload truck was 5712.0 kip-ft and the maximum shear force was 215.3 kips.

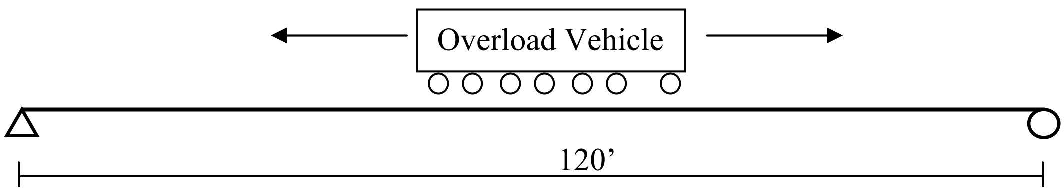


Figure 9. Two dimensional analysis to find maximum moment and shear force.

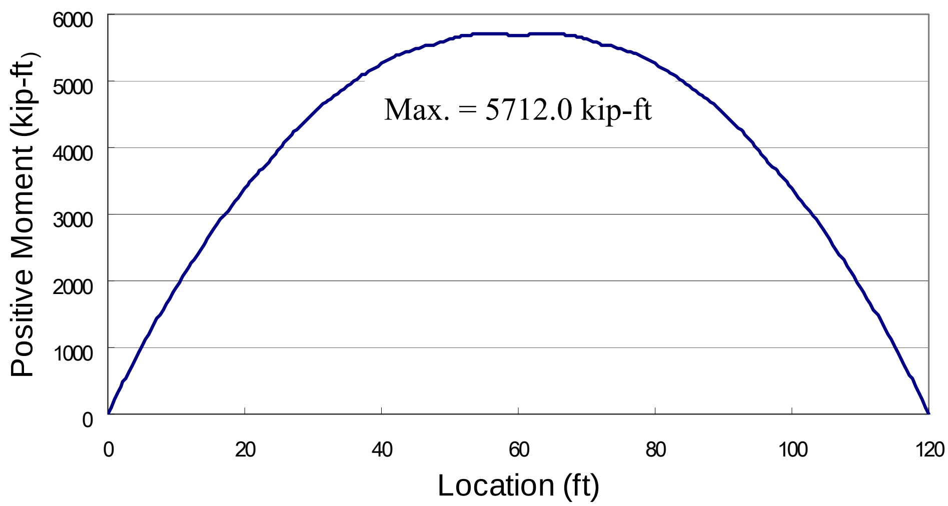


Figure 10. Maximum positive LL moment envelope from the single trailer overload vehicle as it moved across the bridge.

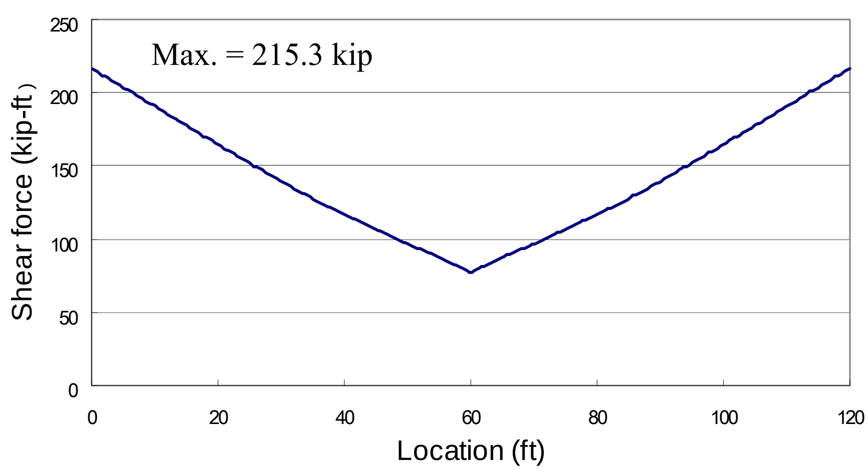


Figure 11. Maximum absolute LL shear force envelope under single trailer overload vehicle as it moved across the bridge.

Step 3) Find standard AASHTO GDFs for the interior girders with single lane load

- Span (L) = 120 ft
- Girder Spacing (S) = 8 ft.
- Deck depth (t) = 9in
- Longitudinal stiffness parameter [$K_g = n(I + Ae_g)$] = 761,098 in^4

single lane moment: $$0.06+\left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{12Lt^3}\right)^{0.1}=0.404$$

single lane shear: $$0.36+\left(\frac{S}{25}\right)=0.680$$

The AASHTO GDFs were found to be 0.404 for moment and 0.680 for shear force from the variables defined above. Table 4.6.2.2.2b-1 (for moment GDF) and Table 4.6.2.2.3a-1 (for shear GDF) in the AASHTO LRFD Bridge Design Specifications were used to find the AASHTO factors with one lane loaded – since a single trailer vehicle is present.

Step 4) Find overload GDFs for the interior girders using the developed equations

- Span (L) = 120 ft
- Girder Spacing (S) = 8 ft.
- Deck depth (t) = 9in
- Longitudinal stiffness parameter [$K_g = n(I + Ae_g)$] = 761,098 in^4

Factors for moment distribution, from Table 1:

C = 1.61
a = -0.21
b = 0.02
c = 0.02
d = -0.03

Factors for shear distribution, from Table 1:

C = 0.72
a = 0.14
b = -0.09
c = -0.08
d = 0.03

The "R" factor for shear and moment, from Table 2, is 1.0 since there is no skew and we are not looking at negative moment over an interior pier.

The moment GDF modification factor for an overload truck is from Eq 1:

$$CR\,S^a L^b t^c K_g{}^d =$$

$$(1.61)(1.0)(8)^{-0.21}(120)^{0.02}(9)^{0.02}(761{,}098)^{-0.03} =$$

$(1.61)(1.0)(.65)(1.10)(1.04)(.67) = 0.80$

The distribution factor is obtained by factoring the AASHTO value:

the distribution factor: $GDF_{mom} = 0.80(0.404) = 0.32$

The shear force GDF modification factor for an overload truck is from Eq 1:

$$CR\, S^a L^b t^c K_g{}^d =$$
$$(0.72)(1.0)(8)^{0.14}(120)^{-0.09}(9)^{-0.08}(761{,}098)^{0.03} =$$
$$(0.72)(1.0)(1.34)(0.65)(0.84)(1.50) = 0.79$$

The distribution factor is obtained by factoring the AASHTO value:

the distribution factor: $GDF_{shear} = 0.79(0.68) = 0.54$

The overload GDFs for the interior girder were found to be 0.32 for moment and 0.54 for shear force using Equation 1.

Step 5) Calculate maximum moment and shear force in an interior girder

The girder moment and shear forces are obtained by multiplying the total bridge moment and shear (Step 2) by the modified GDF's.
Maximum moment in an interior girder = (0.32) (5712.0 kip-ft) = 1839 kip-ft
Maximum shear force in an interior girder = (0.54) (215.3 kips) = 115 kips

Step 6) Check safety of the girder

Use the AASHTO LRFD Strength II limit state to combine the maximum moment or shear force with results from all other loads (i.e. DL) to check safety of the interior girder as follows.

All other factored loads + (1.35)(Member force found in Step 5) ≤ Girder M Capacity

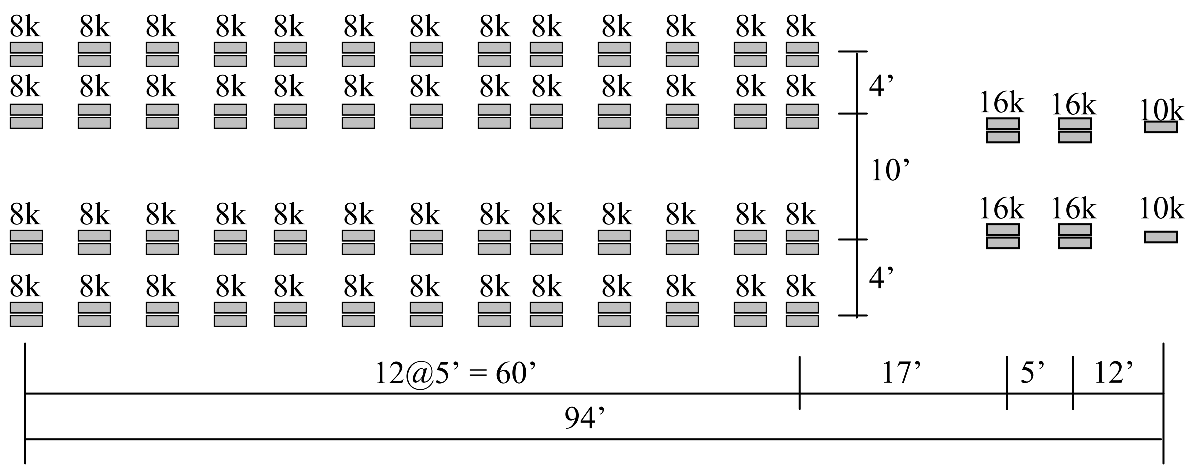
All other factored loads + (1.35)(Member force found in Step 5) ≤ Girder V Capacity

Example for a dual trailer overload vehicle:

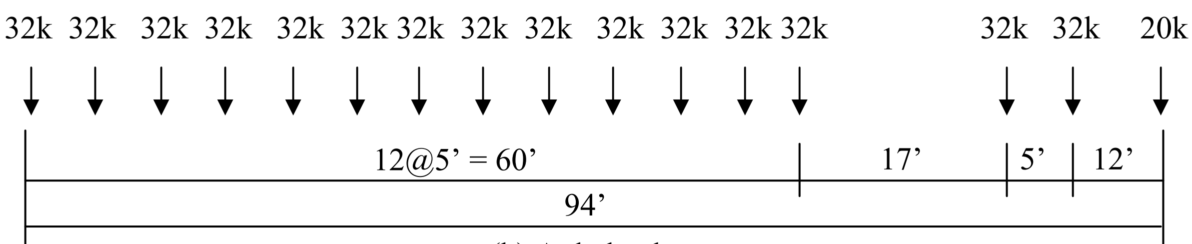
The configuration of the example bridge is the same as that previously used for the single trailer overload vehicle example.

- Number of spans = 1
- Number of girders = 5
- Type of the girders = Steel girder
- Span (L) = 120 ft
- Girder Spacing (S) = 8 ft.
- Deck depth (t) = 9in
- Cross-section of steel girder (Figure 4.1)
- Moment of inertia of the girder (I) = 28,709 in^4
- Elastic modulus ratio of girder to deck ($n = E_B / E_D$) = 29000 psi / 3605 psi = 8.044
- Cross-sectional area of the girder (A) = 65.5 in^2
- Distance between the centers of gravity of the girder and deck (e_g) = 31.72 in
- Longitudinal stiffness parameter [$K_g = n(I + Ae_g)$] = 761,098 in^4

The configuration of the dual trailer overload vehicle used for this example analysis is shown in Figure 12 with the spacing between trailers or middle wheel sets as (S_w) of 10 ft.



(a) Plan view of wheel loads



(b) Axle loads

Figure 12. Configuration of dual trailer overload vehicle.

Step 1) Calculate axle loads of the overload vehicle

The axle loads are shown in Figure 12(b).

Step 2) Perform 2-dimensional analysis to find maximum moment and shear force

The analysis of the bridge was conducted with a software package with the axle loads of the vehicle in Figure 12(b) moved across the bridge. The results of the analyses are shown in Figures 13 & 14. The maximum bridge moment was 9561.8 kip-ft and the maximum bridge shear force was 335.9 kips.

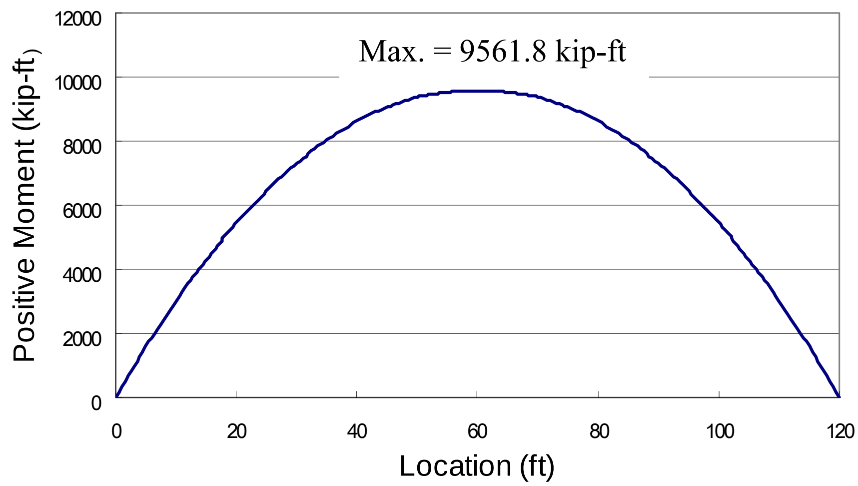


Figure 13. Maximum positive LL moment envelope caused by dual trailer overload vehicle crossing the bridge.

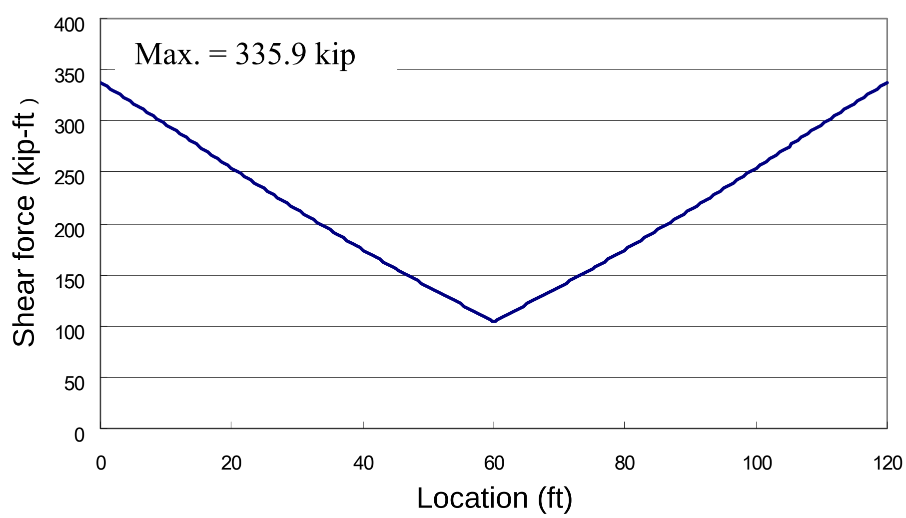


Figure 14. Maximum LL absolute shear force envelope caused by the dual trailer overload vehicle crossing the bridge.

Step 3) Find AASHTO GDFs for the interior girders, two lanes loaded

- Span (L) = 120 ft
- Girder Spacing (S) = 8 ft.
- Deck depth (t) = 9in
- Longitudinal stiffness parameter [$K_g = n(I + Ae_g)$] = 761,098 in^4

two lane moment: $$0.075+\left(\frac{S}{9.5}\right)^{0.6}\left(\frac{S}{L}\right)^{0.2}\left(\frac{K_g}{12Lt^3}\right)^{0.1}=0.583$$

two lane shear: $$0.2+\left(\frac{S}{12}\right)-\left(\frac{S}{35}\right)^{2.0}=0.814$$

The AASHTO GDFs were found to be 0.583 for moment and 0.814 for shear force from the variables defined above. Table 4.6.2.2.2b-1 (for moment GDF) and Table 4.6.2.2.3a-1 (for shear GDF) with "two or more lanes loaded" were used from AASHTO.

Step 4) Find overload GDFs for the interior girders using the developed equations

- Span (L) = 120 ft
- Girder Spacing (S) = 8 ft.
- Deck depth (t) = 9 in
- Longitudinal stiffness parameter [$K_g = n(I + Ae_g)$] = 761,098 in^4
- Spacing of center wheels (S_w) = 10 ft

Factors for two lane moment distribution, from Table 1:

C = 1.70
a = -0.22
b = 0.04
c = 0.19
d = -.08
e = -0.14

Factors for two lane shear distribution, from Table 1:

C = 2.03
a = 0.06
b = -0.25
c = -0.12
d = 0.03
e = -0.28

The "R" factor for shear and moment, from Table 2, is 1.0 since there is no skew and we are not looking at negative moment over an interior pier.

The moment GDF modification factor for an overload truck with S_w of 10ft is from Eq 2:

$$CR\,S^a L^b t^c K_g{}^d S_w{}^e =$$

$$(1.70)(1.0)(8)^{-0.22}(120)^{0.04}(9)^{0.19}(761{,}098)^{-0.08}(10)^{-0.14} =$$
$$(1.70)(1.0)(.63)(1.21)(1.52)(.34)(.97) = 0.49$$

Multiply the AASHTO GDF by this modifying factor.

The distribution factor: $GDF_{mom} = 0.49(0.583) = 0.28$

The shear force GDF modification factor for an overload truck is from Eq 2:

$$CR\,S^a L^b t^c K_g{}^d S_w{}^e =$$

$$(2.03)(1.0)(8)^{0.06}(120)^{-0.25}(9)^{-0.12}(761{,}098)^{0.03}(10)^{-0.28} =$$
$$(2.03)(1.0)(1.13)(0.30)(0.77)(1.50)(0.52) = 0.41$$

Multiply the AASHTO GDF by this modifying factor.

The distribution factor: $GDF_{shear} = 0.41(0.814) = 0.34$

The overload GDFs for an interior girder were found to be 0.28 for moment and 0.34 for shear force using Equation 2 for the dual lane two trailer loading.

Step 5) Calculate maximum moment and shear force at the interior girder

The girder moment and shear forces are obtained by multiplying the total bridge moment and shear (Step 2) by the modified GDF's.

Maximum LL moment in the interior girder = (0.28) (9561.8 kip-ft) = 2706kip-ft
Maximum LL shear force in the interior girder = (0.34) (335.9 kips) = 115 kips

Step 6) Check safety of the girder

Use Strength II limit state to combine the maximum LL moment or shear force with all other loads to check safety of the interior girder as follows.

All other factored loads + (1.35)(Member force found in Step 5) ≤ Girder M Capacity

All other factored loads + (1.35)(Member force found in Step 5) ≤ Girder V Capacity

INVESTIGATION OF DECKS

Two types of failure, i.e. punching failure and flexural failure, need to be considered for investigating loading of decks on multi-girder bridges. Shear and punching failure is not usually included in designing decks according to AASHTO LRFD (C4.6.2.1.6).

Overload vehicles may, however, have closer longitudinal or transverse wheel spacing compared to the AASHTO standard truck with 32k axles. It is, therefore, suggested that consideration be given to the wheel spacing of the overload vehicles when checking safety of the bridge for punching failure of the deck. The closer wheel spacing of the overload vehicles may induce premature punching failure and the weight of the single wheel of an overload vehicle might need to be limited to ensure safety of the deck in punching.

An equation to limit non-factored weight of a single wheel set of an overload vehicle to ensure safety of the deck for punching failure is suggested as shown in Equation 3. The equation reflects an interpolation between the condition with a single wheel set and two wheel sets spaced 6ft apart as in the AASHTO design truck.

$$P_{all\_punching} = 1.5\, k_1\, k_2\, P_{DT} \tag{3}$$

where $P_{all\_punching}$ = Allowable non-factored single wheel set load for the overload vehicle just considering punching failure of the deck.

k_1 = A factor related to minimum longitudinal wheel spacing of overload vehicle

$= 1.0$ (when $S_1 \geq 6\text{ft}$), $\dfrac{S_1 + 6}{12}$ (when $S_1 < 6\text{ft}$)

k_2 = A factor related to minimum transverse wheel spacing of overload vehicle

$= 1.0$ (when $S_2 \geq 6\text{ft}$), $\dfrac{S_2 + 6}{12}$ (when $S_2 < 6\text{ft}$)

S_1 = Minimum longitudinal wheel spacing of overload vehicle (ft)

S_2 = Minimum transverse wheel spacing of overload vehicle (ft)

P_{DT} = Maximum non-factored single wheel load of design truck (for HL93 and HS20: P_{DT} = 16 kips)

The constant '1.5' in equation (3) is used to consider the difference of the dynamic allowance (33% for AASHTO standard HL-93 trucks and 0% for overload vehicle) and load factor (1.75 for AASHTO standard trucks and 1.35 for overload vehicle).

[(1.33)(1.75)/(1.35)] is equal to 1.72 and it is reduced to '1.5' for safety. The variables k_1 and k_2 in equation (3) are used to consider reduction of punching capacity of the deck when the minimum wheel spacing of the overload vehicle is closer than the minimum wheel spacing of the AASHTO standard truck.

Flexural failure is considered in design of decks subjected to AASHTO HL-93 standard truck loads using the strip method (AASHTO LRFD T4.6.2.1.3-1). A strip of the deck is considered to resist a single axle load. Overload vehicles may, however, have closer transverse wheel spacing compared to the AASHTO standard truck and it is required to consider the wheel spacing of the overload vehicles when checking safety of the bridge for flexural failure of the deck. The AASHTO LRFD Appendix A-4 moments should not be used. The longitudinal wheel spacing of the AASHTO standard truck is generally wider than the AASHTO equivalent strip width, while the longitudinal wheel spacing of the overload vehicle may be narrower than the AASHTO equivalent strip.

Steps to determine flexural strength:

- Perform moment analysis on the transverse deck strip under a line of the overload vehicle's axles.
- Select the max + and - LL moments.
- Combine the LL moments and DL moments using Strength 2 load factors.
- Do not add dynamic allowance to the LL.
- Design the strip (AASHTO LRFD T4.6.2.1.3-1) for the combined factored LL and DL moments. If the truck axle spacing is greater than the AASHTO T4.6.2.1.3-1 strip width use that width. If the truck axle spacing, S_1, is less than the AASHTO strip width use S_1 as the effective strip width.

Deck analysis should be combined with the additional analyses described in this project to ensure safety of the entire bridge.

9. REFERENCES

1. AASHTO, (2009), "AASHTO LRFD Bridge Design Specifications, 2009 Interims", 4th Ed., American Association of State Highway and Transportation Officials, 2009