Method to Compute Live-Load Distribution in Bridge Girders

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Abstract: Live-load distribution is an important step in the analysis of bridge superstructures. This paper introduces a new framework to compute live-load distribution for bridge girders. The model uses elastic spring elements to simulate the reaction of main girders to the deck system. The cross-section frame of the superstructure is supported by these elastic springs. Live-load distribution factors are derived according to the maximum reaction of each spring element under random truck loads. Results from the proposed model are compared with those from bridge-design specifications. Engineering practice shows that this model is easy to use and provides results comparable with current design standards. The significance of this framework is that it can be used to compute live-load distribution without limits to parameters such as girder space, span length, and truck-wheel space. This research will provide a convenient tool for engineers to perform bridge design or for researchers to compare research results from other methods. DOI: [10.1061/\(ASCE\)SC.1943-5576.0000091](https://doi.org/10.1061/(ASCE)SC.1943-5576.0000091). © 2011 American Society of Civil Engineers.

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Introduction

In bridge design, a live (or truck-wheel) load distribution method is required to simplify the analysis of complex bridge superstructures. Live-load distribution is a procedure to compute each girder's carrying proportion for the live load, such as the weight of trucks or cars. Depending on its geometric design or configuration, a bridge typically has two to five girders along the roadway direction. The capacity of each girder needs to exceed the maximum possible load induced by the live load plus dead load (e.g., the weight of girder itself and paving materials). Because of the random positions of trucks on the bridge as well as the specific configuration of each bridge, calculating the live-load distribution has been a challenging step in bridge design.

Two of the traditional simplified methods to calculate wheel-load distribution are the lever-rule and the rigid-diaphragm methods. With the lever-rule method, the wheel load is distributed to only two girders adjacent to the wheel load. With the rigid-diaphragm method, the wheel load is linearly distributed into each girder according to the rigid rotation of the transverse diaphragm. More details for these two methods can be found in Goodrich (2000) and Hu (1996). The lever-rule and rigid-diaphragm methods represent the extreme conditions of the relative stiffness between the deck system (including diaphragm) and the girders, as shown in Fig. 1. Results from these two methods may produce conservative or unsafe distribution factors because they fail to represent the actual behavior of bridge structures. For example, for interior

girders, the lever-rule method may result in overestimating the load distribution factors [as in Fig. 1(a)] because no load transfer to girders beyond the two closest girders is accounted for in the method. The rigid-diaphragm method may result in underestimating the load-distribution factors as a result of the assumed linear displacement for all girders [Fig. 1(b)]. For exterior girders, the accuracy of these two methods depends on the relative position between the lane and exterior girder. In this case, the lever-rule method may underestimate the factors if the live-load lane is inboard far from the exterior girder, whereas the rigid-diaphragm method may overestimate the distribution factors as a result of unrealistic over-rotating of the diaphragm and deck.

Bridge superstructures perform as an integral system under loading between the two extreme conditions modeled as the lever rule and rigid diaphragm. Previous research was focused on using three-dimensional finite-element simulations to calibrate the empirical equations for wheel-load distributions (Barr et al. 2001; Cai and Shahawy 2004; Nowak et al. 2000; Zokaie 2000). The AASHTO LRFD (2005) bridge-design specification also uses equations resulting from three-dimensional finite-element analysis. The empirical equations consider the main parameters that affect wheel-load distribution, such as girder space, deck stiffness, girder stiffness, and span length. They are applicable to common bridges from small to medium scale. Tables 1 and 2 summarize the LRFD equations for moment-load distribution factors for slab-on-girder bridges and multicell box-girder bridges as well as the applicability conditions. Empirical formulas were developed for some nonstandard gauge vehicle types, such as oversized permit trucks (Tabsh and Tabatabai 2001; Goodrich and Puckett 2000). These formulas were also developed by calibrating three-dimensional finite-element analysis, and they are applicable to slab-on-girder bridges.

There are also many cases in which bridge superstructures are used by special vehicles, such as airplanes and permit trucks. Tabsh and Tabatabai (2001) provided detailed background information for the occurrence of oversized truck loads and developed empirical load-distribution equations for the design of bridges subject to these loads. Goodrich and Puckett (2000) presented an alternative

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Fig. 1. Two extreme conditions of relative stiffness between the deck system and the girders; dashed lines represent deformed shape of the cross section under wheel load

method to compute live-load distribution factors for permit trucks with nonstandard axle configurations. The recommended equations are applicable to slab-on-girder bridges. As the previous discussion illustrates, bridge designers must rely on a multitude of equations to address various bridge types, structural configurations, lane configurations, and vehicle types when calculating live-load distribution factors. Moreover, these equations were developed using varied theoretical premises that may not be compatible. To help alleviate the complexity facing the designer, a single load-distribution method is presented in this paper that is applicable to a wide range of bridge types, loading vehicles, and structural configurations. The method applies to interior and exterior girders alike, and will be shown to be an intermediate method between the approximate methods and full three-dimensional finite-element methods presented previously.

In the proposed method, a beam-on-elastic-spring-supports model (BESM) (Hu 1996), is used to calculate the live- and dead-load reaction at each supporting girder. Here the beam is referred to as a transverse diaphragm and bridge-deck system. Spring supports are referred to the reaction of girders. This method can be used to analyze the linear elastic response of general bridges designed for various types of load, such as T- or I-girder bridges, box-girder bridges, and hollow- or solid-slab bridges. The geometric configuration of the bridge may be simply supported or continuous.

Proposed BESM Method for Live-Load Distribution

The theory behind BESM is directly reflected in the load-transfer mechanism in bridge superstructures. The truck loads pass from

Table 2. LRFD Load-Distribution Factors for Exterior Girders (in U.S. units)

Bridge type	Load-distribution equations	Applicability
Slab-on-girder bridge	Lever rule $g = e g_{\text{interior}}$ $e = 0.77 + d_e/9.1$	One designed lane load; Two or more designed lanes load: $-1.0 \leq d_e \leq 5.5$
Multicell box-girder bridge	$g = W_e/14$	One lane and multiple lanes $W_e \leq S$

Note: e = correction factor; d_e = distance from the exterior web of exterior girder to interior edge of curb; and W_e = half of the web spacing.

the bridge-deck system to the main longitudinal girders, then eventually to the bearings and substructure. Because the deck system and longitudinal girders are integral, the distribution of forces in individual girders depends on the geometric parameters of the structural model and stiffness of model elements. BESM assumes the cross section is a structural frame sitting on the girder springs. Fig. 2 shows the model geometries for four common bridge types.

These models not only reflect the reaction of girders, but also include the effect of cross-section geometries on the load distributions, such as torsional stiffness of the girders and deck system, which may affect the distribution of the load on the girders. After the geometric model is established, one can apply general frame analysis to calculate the response of each girder spring. The live-load distribution factor for a specific girder is the maximum possible proportion of the live-load applied to that girder under random positioning of the trucks on the bridge deck.

Using the proposed model, an influence line of reaction force for each spring along the transverse direction of the bridge is calculated. The live load is then applied on the influence line to calculate the maximum reaction of each girder spring by an automatic loading routine modified from Shi and Shi (1988). Thus, under a moving live load with a standard or nonstandard gauge, the maximum reaction of each girder spring is available. The ratio of maximum spring reaction divided by the vehicle weight is used as the live-load distribution factor.

Critical Parameters for BESM

The elastic spring coefficients and cross-section frame stiffness are two critical parameters for computing live-load distribution using the BESM. These two parameters should best reflect the real structural response. If the elastic spring is very stiff and the cross-section frame is very flexible, the live-load distribution will follow the results from the lever-rule computation. If the cross-section frame is rigid relative to the elastic spring, the live-load distribution

Table 1. LRFD Load-Distribution Factors for Interior Girders (in U.S. Units)

Bridge type	Load-distribution equations	Applicability
Slab-on-girder bridge	One designed lane load: $g = 0.06 + (S/14)^{0.4}(S/L)^{0.3}[K_g/(12.0L_s t^3)]^{0.1}$ Two or more designed lanes load: $g = 0.075 + (S/9.5)^{0.6}(S/L)^{0.2}[K/(12.0L_s t^3)]^{0.1}$	$3.5 \leq S \leq 16.0$, $4.5 \leq t_s \leq 12.0$, $20 \leq L \leq 240$, $Nb \geq 4$, $10,000 \leq K_g \leq 7,000,000$
Multicell box-girder bridge	One designed lane load: $g = (1.75 + S/3.6)(1/L)^{0.35}(1/Nc)^{0.45}$ Two or more designed lanes load: $g = (13/Nc)^{0.3}(S/5.8)^{0.35}(1/L)^{0.25}$	$7.0 \leq S \leq 13.0$, $60 \leq L \leq 240$, $Nc \geq 3$; if $Nc > 8$, use $Nc = 8$

Note: g = load-distribution factor; S = girder spacing; L = span length; t_s = deck thickness; K_g = longitudinal stiffness parameter; Nb = number of girders; and Nc = number of cells.

Fig. 2. Cross section of frame structures for different types of bridges

will follow the results from the rigid-diaphragm method. The stiffness of the spring element at each support is assumed to be the inverse of that girder's displacement under a unit-concentrated load placed at the support. For example, in Fig. 3, the stiffness of the spring is P/v_a , in which v_a = vertical displacement under load P at location a . The spring constants may vary if girders have different section properties.

The width of the cross-section frame along the longitudinal direction controls the stiffness of the frame. To better represent the integration of the superstructure performance, an energy method is used to derive the width of the cross-section frame. This width l_0 is calculated by assuming that the bending strain energy of the beam under a concentrated load is equivalent to the bending strain energy within width l_0 , which has a constant bending curvature, as shown in Fig. 3. The constant bending curvature is the curvature under the load point at location a . The wheel load is represented by a concentrated load P , the vertical deflection function $v(x)$ is represented by Eq. (1):

Fig. 3. Simply supported girder under concentrated load and equivalent elastic spring

$$v(x) = \frac{Pbx(L^2 - x^2 - b^2)}{6EIL}, \quad \text{for } 0 \leq x \leq a \quad (1a)$$

$$v(x) = \frac{P(L-b)(L-x)[L^2 - (L-x)^2 - (L-b)^2]}{6EIL}, \quad \text{for } a \leq x \leq L \quad (1b)$$

The bending strain energy is

$$U = \frac{EI}{2} \int_0^L [v''(x)]^2 dx = \frac{P^2 b^2 a^3}{6EIL^2} + \frac{P^2 (L-b)^2 (L-a)^3}{6EIL^2} \quad (2)$$

in which P = concentrated load at location a of the simply supported girder; L = girder span length; EI = stiffness of the girder; and $v(x)$ = girder displacement function.

The BESM reflects the overall flexural behavior of the bridge superstructure under a concentrated load. To make the cross-section frame model represent the entire girder's bending energy, assume the maximum bending curvature in the beam is within distance l_0 , with no bending outside l_0 , and the strain energy is

$$U' = \frac{EI}{2} l_0 [v''(x)]_{x=a}^2 = \frac{EI}{2} l_0 \left(-\frac{Pab}{EIL} \right)^2 \quad (3)$$

Let $U = U'$ and

$$l_0 = \frac{b^2 a^3 + (L-b)^2 (L-a)^3}{3a^2 b^2} = L/3 \quad (4)$$

Eq. (4) indicates that the equivalent bending stiffness of a simply supported beam is concentrated at one-third of the beam span. The bridge-deck system is assumed as a beam with an equivalent beam width of one-third of the bridge longitudinal span.

Using one-third of the bridge span with constant spring stiffness, the beam on an elastic-spring model represents the whole superstructure response under the wheel load. The one-third of the bridge span is used as the width of the cross-section frame to calculate the member stiffness in the cross-section frame. After the stiffness of the spring element and the frame element are available, the structural model is available for computing the load distribution for girders. The specific procedure of computing load-distribution factors is as follows:

1. Build finite-element model with line element for one or more longitudinal girders.
2. Compute the displacement under the concentrated unit load at each location at which the load-distribution factors are to be computed; the spring stiffness constant for this girder is the inverse of this displacement. Use effective flange or slab width of the girder for this step.
3. Build a cross-section frame finite-element model as recommended in Fig. 2; the element in the cross-section model has a width of one-third of the girder span, $l_0 = L/3$, and a height the thickness of the slab or girder web.
4. Random positioning of live-load axles along the cross-section model within the load range.
5. Compute the maximum vertical-reaction force of each girder spring considering multiple axle presentation factors; the proportion of the maximum reaction force to the total truck weight is the live-load distribution factor for this girder at this desired location.

Step 1 is necessary for bridge design; no extra efforts are needed to build the model. Steps 3–5 build an extra cross-section model to calculate the live-load distribution factors. However, this model can also be used to analyze the components' capacity in the transverse

Fig. 4. Concrete slab-on-steel-girder bridge configuration

Table 3. Geometric Data for Slab-on-Girder Bridges (See Fig. 3)

Span length (m)	Girder spacing (m)	Distance a (m)	Number of girders	Slab thickness (mm)	Flange thickness (mm)	Flange width (mm)	Web thickness (mm)	Web depth (mm)
14.6	1.22	0.61	7	150	22	292	15	497
29.3	2.44	1.22	5	200	43	423	24	848
43.9	3.66	1.83	4	250	45	405	26	1,328

direction. Therefore, this procedure can be used for both calculating live-load distribution factors and analyzing the whole bridge system.

Example Results and Comparisons

To verify the validity of the BESM, results from typical example problems are compared with those calculated using the LRFD equations, which in turn are based on calibrations to finite-element analysis. Field-test results and finite-element analysis results from previous publications are also used to verify the method. In these examples, the standard truck axle has two wheels with gauge width of 1.83 m, except for one example with nonstandard axle configurations with four wheels. One lane load and multiple lane loads are applied to the model in these examples.

Slab-on-Steel-Girder Bridges with Various Span Lengths and Girder Spacings

The first example uses a concrete slab-on-steel-girder bridge, as shown in Fig. 4. Three geometric configurations are considered (see Table 3). The results of moment distribution factors from the BESM and LRFD formulas are compared in Figs. 5–7 for maximum interior and exterior girders and single- and multilane loadings.

Fig. 5 shows the load-distribution factors for a bridge with a span length of 14.6 m and girder spacing of 1.22 m. For interior girders, results from the BESM are close to those calculated from LRFD for both one-lane and multilane loadings. For the exterior girder under a one-lane load, the BESM results predict a smaller factor than that predicted from LRFD, with an error range of 20%. For the exterior girder under multilane loading, BESM predicts a larger factor than that predicted from LRFD with an error range of 50%. For exterior girders, the difference between the BESM and LRFD results is because of the oversimplified

Fig. 5. Load-distribution factors from BESM and LRFD formulas for bridge geometry 1 in Table 3

Fig. 6. Load-distribution factors from BESM and LRFD formulas for bridge geometry 2 in Table 3

Fig. 7. Load-distribution factors from BESM and LRFD formulas for bridge geometry 3 in Table 3

procedure in LRFD. The load-distribution factors for exterior girders are not strictly calibrated by finite-element analysis but are from the rigid-diagram method.

Fig. 6 shows the load-distribution factors for a bridge with a span length of 29.3 m and girder spacing of 2.44 m. The maximum load-distribution factors of the interior girders are for girders 2 and 4, with slightly larger distribution factors than the LRFD results under multilane loadings, and smaller distribution factors than LRFD under single-lane loadings with an error range of less than 10%. For exterior girders, the model analysis yields a larger distribution factor compared to LRFD under multilane loadings and a smaller factor than LRFD under single-lane loadings.

Fig. 7 shows load-distribution factors for a bridge with a span length of 43.9 m and girder spacing of 3.66 m. The maximum factors of interior girders are for girders 2 and 3, with a slightly larger distribution factor than the LRFD results under multilane loadings, with error range of 5%. The difference is more obvious under single-lane loadings, for which the BESM yields a result that is 15% smaller than the LRFD. For exterior girders, the BESM has maximum distribution factors under single- and multilane loadings that are 10% higher than those from the LRFD equations.

Multicell Box Girder Bridges with Various Spans

The second example is for multicell concrete box girder bridges, as shown in Fig. 8. The geometric configurations are listed in Table 4. The results predicted from the BESM and LRFD equations are shown in Figs. 9 and 10. Only the distribution factors for interior girders using LRFD equations are presented because the exterior girder configurations of the bridges are not in the applicability range of the LRFD equations. In Fig. 9, under multilane loadings, the maximum load-distribution factors for interior girders from the BESM analysis occur at girders 2 and 6 and are very close to the LRFD factors. However, for a single-lane load, the BESM analysis predicts load-distribution factors 15% smaller than the LRFD factors. In Fig. 10, the BESM analysis factors at girders 2 and 6 are close to the LRFD factors under a single-lane load, whereas the BESM factors under multilane loadings are 5% higher than the LRFD factors.

Fig. 11 shows the sensitivity of load distribution to gauge width under single- and multilane loadings. For this bridge, the exterior girders are more sensitive to gauge width than the interior girders, and the multilane load-distribution factors are more sensitive to gauge width than the single-lane load-distribution factors.

Slab-on-Prestressed-Girder Bridges with Finite-Element Analysis and Field-Test Results

The third example is a three-span continuous prestressed concrete-girder bridge presented by Paul (2000). The bridge has five Washington State standard prestressed concrete girders, W74MG, with girder spacing of 2.44 m. On the top of the prestressed girder, the concrete slab is 190 mm, with extra thickness of 95 mm (lift) directly on the top of the girder. Detailed information for the girders and the bridge configurations are presented in Paul (2000). Fig. 12 shows the load-distribution factors for interior girders under multilane loadings. FEM model 1 is analysis with the simplification that the bridge is simply supported at the middle span of the three-span continuous bridge; the intermediate diaphragm and end diaphragm are ignored. FEM model 5 is a more refined finite-element analysis including all three spans, intermediate diaphragm, end diaphragm, and additional slab thickness (girder lift). Comparison of FEM model 5 and field-test data suggested that FEM model 5 can

Fig. 8. Multicell box-girder bridge cross section

Table 4. Geometric Data for Multicell Box-Girder Bridge (See Fig. 7)

Span length (m)	Web spacing (m)	Number of cells	Distance <i>a</i> (m)	Top slab thickness (mm)	Bottom slab thickness (mm)	Web thickness (mm)	Web depth (mm)
25	2.9	6	1.625	200	200	350	800
40	2.9	6	1.625	200	200	350	1,100

Fig. 9. Load-distribution factors for multicell box-girder bridge (1)

Fig. 10. Load-distribution factors for multicell box girder bridge (2)

simulate the live-load distributions that represent the field-test results (Paul 2000).

For a continuous bridge, the BESM computes the girder spring constant by a three-span continuous single-girder analysis. The width of the cross-section frame is still one-third of the middle span. From Fig. 12, the distribution factors predicted by BESM are larger than those from FEM model 1 and FEM model 5, but smaller than those from the LRFD equations.

Fig. 12. Multiple-lane load-distribution factors for a prestressed girder bridge [data adapted from Paul (2000)]

Slab-on-Steel-Girder Bridges with Field-Test Results

The fourth example is to compare the model results with field-test results by Nowak et al. (1999, 2000). Two slab-on-girder bridges (Bridge B and Bridge E) are analyzed with the BESM. Bridge B is a simple span of 16.1 m with 11 standard steel girders W33 × 152 (English standard) spacing at 1.44 m. Bridge E has a simple span of 11.7 m with 10 standard steel girders W24 × 100 (English standard) spacing at 1.42 m. Fig. 13 shows the moment-load distribution factors for Bridge B. The distribution factors from LRFD for interior girders and from the field test for all girders are presented in Nowak et al. (1999, 2000) and Eom and Nowak (2000). The field-test results include three scenarios: one truck posited in the left lane, one truck in the right lane, and two trucks side-by-side along the bridge centerline. The model analysis results include three similar scenarios: a truck in one lane, two trucks in two lanes, and multiple lane loads that will lead to the maximum distribution factors.

Fig. 13 shows that the model results for multilane and two-lane loadings are almost the same as for interior girders and very close to the LRFD results for multilane loads. The model results from a single-lane load are also very close to the LRFD results for a single lane. All these are far larger than the field-test results. This again proves that the BESM model is safe to use for design. The differences between field-test results and modeling results could be because of the different truck positions along the transverse direction on the bridge.

Fig. 11. Load-distribution factors with different gauge widths for multicell box-girder bridge

Fig. 13. Moment-load distribution results for Bridge B [data adapted from Nowak et al. (1999)]

Fig. 14. Moment-load distribution results for Bridge E [data adapted from Nowak et al. (1999)]

Fig. 14 shows the load-distribution factors for Bridge E. For interior girders 2–9, the peak load-distribution factor from the field-test data is slightly lower than that from the LRFD equations. The model analysis results are lower than those using LRFD equations but comparable with the test results. For exterior girders 1 and 10, the load-distribution factors from the BESM are slightly larger than those from the LRFD equations, but much larger than the test data. As the exterior girder-distribution factors are sensitive to the truck positions in the transverse direction, the differences between the modeling and test results could be because of the different truck arrangements on the bridge.

Slab-on-Steel-Girder Bridges under Four Wheel Axles

The fifth example is a concrete slab-on-steel-girder bridge under a permit truck with four wheel axles. The four wheels are evenly spaced at 1.2 m. The bridge has a simple span of 15.4 m, five girders spaced at 1.95 m, and a slab thickness of 19.5 cm. Table 5 shows the maximum moment-distribution factors for the interior girder under a one-lane load of the four wheel axle from model analysis and from results provided by Goodrich and Puckett (2000). In Table 5, g_{BESM} is from the BESM in this paper, g_{SM} is from the simplified method by Goodrich and Puckett (2000), g_{LRFD} is from LRFD equations, and g_{BRASS} is from the finite-strip-analysis

Table 5. Load Distribution Factors for a Concrete Slab-on-Steel-Girder Bridge under One-Lane Four-Wheel Axle [Adapted from Goodrich and Puckett (2000)]

Method	Interior girder	Exterior girder
g_{BESM}	0.33	0.33
g_{LRFD}	0.38	0.33
g_{SM}	0.37	0.38
g_{BRASS}	0.35	0.31

method by Goodrich and Puckett (2000). Multilane factors are not considered. For the interior girder, g_{BESM} is smaller than the other three groups of factors, with an error range of 6% to finite-strip analysis g_{BRASS} and 15% to g_{LRFD} and g_{SM} . For the exterior girder, g_{BESM} is close to g_{LRFD} and g_{BRASS} , with 15% difference from g_{SM} .

Summary and Conclusions

With reasonable simplification considering the coupling of longitudinal and transverse behavior, the complex three-dimensional bridge superstructures can be analyzed with two-dimensional frame structures in longitudinal and transverse directions separately. In the longitudinal direction, a single girder is the analysis object. In the transverse direction, a cross-section frame is modeled to

be sitting on the girder springs. The cross-section frame has an element section width of one-third of the longitudinal span. This is derived by an analytical method considering the equivalent girder-bending energy for the cross-section frame structure and the overall bridge. The coupling of the longitudinal behavior with transverse behavior is represented by the spring stiffness and the stiffness of the cross-section frame. Currently the model is applicable to analyze flexural behavior.

The model is validated against a series of typical example problems, which include concrete slab-on-steel-girder bridges with a simply supported single span, a continuous prestressed concrete-girder bridge, and two multicell box-girder simply supported bridges. A standard live load including single- and multilane loads and a permit truck with four wheel axle, are considered in the examples. The model results are compared with results calculated using the LRFD equations, finite-element analysis, and field tests. In most cases, the model results are close to the results using the LRFD equations with slightly lower numbers in some examples. However, the BESM analysis results are generally higher than the field-test data and full-scale finite-element analysis. Thus the BESM model provides load-distribution factors that can be used in bridge design.

This model is easy to implement to compute live-load distributions for the moment without the limitations of axle configurations and straight-bridge geometries. It has been implemented into a software package and successfully used for the design of airport taxiway bridges under Boeing 747 airplane loads. Detailed three-dimensional analysis of the taxiway bridge shows a smaller live-load distribution than that predicted by the proposed model.

In addition to the applicability of different bridge and load configurations, the significance of the model includes several aspects. First, the transverse cross-section frame model includes torsion stiffness automatically and can represent variations of girder or section geometries. Second, this model can be used to design bridges in the transverse direction, such as intermediate diaphragms

and top and bottom slabs for box-girder bridges. Finally, the model is more efficient in capturing the major structural behavior than full-scale three-dimensional finite-element analysis. The results from full-scale finite-element analysis vary with the choice of finite element, choice of element connection, and difficulty of automatic loading to get the maximum response. In contrast, this model only uses beam and spring elements, which are well understood and correspondingly easy to girder or slab section properties, which are more directly related with design.

References

- AASHTO. (2005). "LRFD bridge design specifications." Washington, DC.
- Barr, P. J., Eberhard, M. O., and Stanton, J. F. (2001). "Live-load distribution factors in prestressed concrete girder bridges." *J. Bridge Eng.*, 6(5), 298–306.
- Cai, C. S., and Shahawy, M. (2004). "Predicted and measured performance of prestressed concrete bridges." *J. Bridge Eng.*, 9(1), 4–13.
- Eom, J., and Nowak, A. S. (2001). "Live load distribution for steel girder bridges." *J. Bridge Eng.*, 6(6), 489–497.
- Goodrich, B. L., and Puckett, J. A. (2000). "Simplified load distribution for vehicles with nonstandard axle gauges." *Transp. Res. Rec.*, 1696(1), 158–170.
- Hu, Z. (1996). *Simplified analysis method for bridge structures—Lateral live load distribution*, People's Transportation, China.
- Nowak, A. S., Eom, J., and Sanli, A. (2000). "Control of live load on bridges." *Transp. Res. Rec.*, 1696(1), 136–143.
- Nowak, A. S., Eom, J., Sanli, A., and Till, R. (1999). "Verification of girder-distribution factors for short-span steel girder bridges by field testing." *Transp. Res. Rec.*, 1688(-1), 62–67.
- Shi, D., and Shi, Z. Y. (1988). *Computer method for bridge structures*, Tongji Univ. Press, China.
- Tabsh, W. S., and Tabatabai, M. (2001). "Live load distribution in girder bridges subject to oversized trucks." *J. Bridge Eng.*, 6(1), 9–16.
- Zokaie, T. (2000). "AASHTO-LRFD live load distribution specifications." *J. Bridge Eng.*, 5(2), 131–138.

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13. Please provide the publisher's city for Hu (1996).
14. The issue number 1 has been added to (Nowak, A. S., Eom, J., and Sanli, A. [2000]) Please confirm this is correct.
15. The issue number -1 has been added to (Nowak, A. S., Eom, J., Sanli, A., and Till, R. [1999]) Please confirm this is correct.
16. Please provide the publisher's city for Shi and Shi (1988).