# Load Distribution in Short Bridges Subjected to Oversize Vehicles

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**ABSTRACT**

Trucks that do not satisfy the legal weight and size limits sometimes need to use a transportation network. The effect of such vehicles on a pavement is not as detrimental as on a bridge. In such cases, the bridges along the route shall be checked to see if the imposed loading on them is acceptable from a structural point of view. The girder distribution factors in the AASHTO LRFD bridge design specifications (2017) cannot be used to evaluate the critical live load effect in individual girders if the truck gage width is different from 1830 mm. Consideration of the vehicle’s nonstandard gage width in the structural analysis of an existing bridge can help increase the allowable load. The objective of this study is to develop simple girder distribution factors for shear and flexure for short slab-on-girder bridges subjected to oversize vehicles. To develop the distribution factors, 126 bridges having different girder spacing and span length, and subjected to wide trucks were analyzed by the finite element method. Findings of the study showed that an increase in a truck’s gage width results in lower girder distribution factor, and this is more predominant for shear than for flexure, especially for bridges having large girder spacing. The GDF of bridges having small girder spacing is not affected much by the gage width because only one line of wheels is within the tributary area of the girder under consideration. The derived GDF formulas possess reasonable accuracy; hence, they can be used for evaluating an existing bridge subjected to oversized vehicle in lieu of a 3-dimensional finite element analysis.

## 1 INTRODUCTION

The majority of bridges around the world can be classified as short with respect to span length. For example, out of the approximately 595,000 bridges in the United States, about 310,000 (or 52%) belong to cities, counties, or townships (SSSBA 2019). Such bridges typically have maximum single span length less than 45 m. Short span bridges can be built with different materials, such as reinforced concrete, prestressed concrete, structural steel, timber or masonry. The most economical structural form for short span bridges consists of a concrete slab that is supported on several steel or concrete girders. Rigidly connecting the top flange of the girders to the deck slab by shear connectors can increase the cost-effectiveness of this form of construction. To enhance the stability of the girders during construction, cross-bracings are often transversely placed between the girders at various locations along the bridge length, particularly when the girders are made from steel.

The loads that greatly impact the structural members of a bridge superstructure are usually the result of gravitational effect. Dead load effect on girder bridges can be computed in a straight-forward fashion by considering the weight of all elements within tributary area of the girder under consideration. For the super-imposed dead load that is applied on the bridge after the concrete in the deck has hardened (e.g. parapets, luminaries and wearing surface), most design specifications allow them to be distributed equally to all the girders. With regard to live load, girder distribution factor (GDF) equations are useful in bridge design calculations because they provide a simple approach for determining the load effect in girders and eliminate time-consuming 3-dimensional analysis. The girder distribution factor is defined as the ratio of the maximum load effect that can be experienced by a single girder during its life-time over the maximum load effect due to a single truck on the bridge. This concept significantly simplifies the analysis of girder type bridges and has been included in many design specifications for decades, particularly in North America.

Accurate, inexpensive and time-efficient evaluation of existing bridge capacity against overloads or permit vehicles is an important issue for department of transportation officials. This is because the condition of the infrastructure in most countries around the globe is often sub par due to lack of funds available for regular maintenance. Therefore, in order to avoid high costs of bridge posting, replacement or repair, the structural evaluation must be capable of accurately capturing the load effect in the structural components due to the imposed load on the structure. A large majority of overloads and permit trucks are oversized, meaning that they are wider than 2590 mm. Furthermore, shipments exceeding 3660 mm in width may require pilot vehicles in front and/or at the back of the flatbed truck (Christiansen 2017). Simplified girder distribution factor formulas that are included in the bridge design specifications cannot be used for evaluating oversized vehicles because they are based on the design vehicle which has a standard truck gage width equal to 1830 mm. Consideration of the vehicle's nonstandard gage width in the analysis of existing bridges can help increase the allowable load on the bridge by distributing the load from the truck over a wider distance. Consequently, greater economy can be achieved by considering the actual gage width of a wide truck in the bridge evaluation process.

# 2 BACKGROUND

In this section, background is provided on the AASHTO's girder distribution factors formulas for interior girders in bridges subjected to single truck, the finite element method of analysis for girder type bridges, and recently published research on the topic of oversize truck's effect on bridges.

## 2.1 Girder Distribution Factors

In the AASHTO LRFD specifications (2017), simple girder distribution factors equations are included that allow for the determination of the critical fraction of the live load effect carried by a single girder. Such an approach replaces 3-dimensional modeling by 1-dimensional beam representation. For the case of flexure in an interior girder in a concrete slab-on-girders bridge subjected to single HL-93 truck having 1830 mm gage width, the girder distribution factor is given by:

$$GDF_M = 0.05 + \left(\frac{S}{6800}\right)^{0.4} \left(\frac{S}{L}\right)^{0.3} \left(\frac{K_g}{L\, t_s^3}\right)^{0.1} \qquad (1)$$

where S is the girder spacing (mm), L is the span length (mm), $t_s$ is the slab thickness (mm), and $K_g$ is a girder stiffness parameter ($mm^4$) that is a function of the slab and girder geometric and material properties.

The corresponding AASHTO's girder distribution factor for the case of shear in an interior girder in a concrete slab-on-girders bridge subjected to single truck is given by:

$$GDF_V = 0.3 + \left(\frac{S}{9120}\right) \qquad (2)$$

Note that the multiple truck presence factor of 1.2 is filtered out of the above two equations.

## 2.2 Finite Element Analysis

In the past, structural analysis of girder bridges has been carried out using the orthotropic plate theory, grillage-analogy, finite difference method, or finite-strip approach (Barker and Puckett 2013). Nowadays, the finite element method is the method of choice for bridge analysis due to its flexibility, reliability and rapid advancements in personal computing. The method approximates the unknown response of the structure over its domain by subdividing the large physical system into smaller, simpler parts that are called elements. The equations that model these elements are then assembled into a larger system of equations that represents the response of the entire problem. It then uses variational techniques to approximate the solution of the problem by minimizing an associated error function (Logan 2011).

In this study, the finite element method was used to analyze slab-on-girder bridge superstructures subject to the oversized trucks. All bridges were analyzed in the linearly-elastic range using a computer software (ALGOR 1998) based on a model proposed by Bishara et al. (1993). In the model, the top and bottom flanges of the I-girders as well as the members of the cross-bracings were modelled using 2-node beam elements. The web of the I-girders and concrete deck slab were modelled by 4-node rectangular shell elements. Rigid beam 2-node elements were used to connect the top flange beam elements to the centroids of the deck slab elements above them to satisfy composite action between the girders and concrete slab. Summary of the finite element model of a bridge consisting of a concrete slab on three I-girders is presented in Fig. 1.

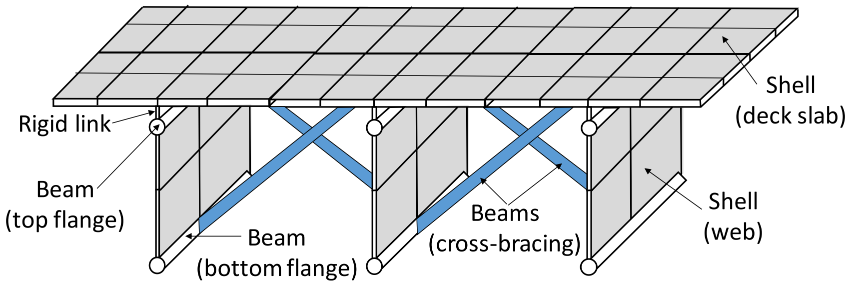


**Figure 1- Finite element model of a girder bridge superstructure**

The finite element-based GDF for flexure in an interior girder can be obtained by longitudinally positioning an oversized truck on the bridge so that the bending moment in the structure is maximized at a desired location. The critical transverse position of the truck on the bridge can then be obtained by trial-and-error by monitoring the flexural stress in the bottom flange of the critical interior girder corresponding to multiple transverse truck positions. Once the correct transverse truck position that leads to the highest load effect is determined, the GDF for flexure can be computed from:

$$GDF_M = \frac{f_j}{\sum_{i=1}^{N} f_i} \qquad (3)$$

where $f_j$ is flexural stress in the bottom flange of the critical interior girder, $f_i$ is flexural stress of beam i, and N is number of girders within the superstructure.

The corresponding GDF for shear in an interior girder can be determined in a similar fashion to that of the flexural GDF based on the support reactions of the individual girders at the loaded end of the bridge:

$$GDF_V = \frac{R_j}{\sum_{i=1}^{N} R_i} \qquad (4)$$

where $R_j$ is the support reaction of the critical interior girder and $R_i$ is the support reaction of beam i.

## 2.3 Recent Literature

Vigh and Kollar (2006) proposed a simple procedure for determining the effect of overweight trucks in bridges, with no limitations on the axle load and spacing. The method is robust and reliable; it just requires data on the span length. It can serve as the first step in the permitting procedure of overweight vehicles. It can be extended by considering the effect of distributed loads, width of the load and the position of the load perpendicular to the bridge axis.

Grimson et al. (2008) used field testing and finite element modeling of a bridge in Louisiana, USA, subjected to three different super loads. Emphasis was placed on the comparisons between the calculated and measured responses due to rotational restraint at the bearings, live load distribution within the bridge superstructure, and the stiffening effect of parapets. Results of the study indicated that the structure responded in a linearly-elastic mode when subjected to the snooper truck and the superload crossings. Measured strains at the extreme fibers of the interior girders were very close to the theoretical values; however, the same strains for the exterior girder were mush smaller in the field test than in the theoretical analysis due to the stiffening effect of the parapets.

Jacob, B., and Feypell-de La Beaumelle (2010) discussed the serious issues that overloads pose to road transport operations, including accident risk and severity, damage to the infrastructure, and economic impact. They investigated the advantages associated with the use of weigh-in-motion (WIM) bridge systems for efficient truck overload screening and enforcement over static weighing. The study includes explanation on the latest WIM technologies in relation to bending and load cell plates, strip sensors, and Video-WIM and automatic vehicle identification.

Bae and Oliva (2012) used a finite element analysis to develope formulas for girder distribution factors for both composite steel and precast pretressed concrete bridges subjected to nonstandard vehicle configurations. The authors considered a single-lane trailer with a fixed 2.44 m-gage width and dual-lane trailer with variable gage width, between 3.05 and 5.49 m. The derived girder distribution factors consisted of product of parameters related to span length, girder spacing, girder stiffness and gage width, raised to powers. The study considered the skew angle, number of spans, and presence of end diaphragms. On average, the developed factors predicted the load effect by 15% higher than the corresponding results from the finite element analyses.

Khan et al. (2014) evaluated an existing prestressed concrete highway bridge subjected to an overload vehicle using the SAP2000 software. Analysis of the results revealed that the bridge girders have serviceability problem because the stresses in the concrete on the tension side exceeded the allowable limit and resulting in large crack width and excessive deflection. Strengthening of the bridge using a steel plate bonding technique showed that the flexure capacity of the bridge was sufficient to withstand the heavy vehicular loads.

Chang et al. (2015) developed live load and rating factors for the state of Texas and validated the criteria for establishing superheavy-load status using field tests and finite element-based parametric analysis. The study showed that the superheavy-load criteria and load ratings based on newly proposed distribution factors for such loads in Texas are valid for the considered bridges. Field monitoring of live load frequency and level data from an existing bridge can help departments of transportation determine the effects of stress level variations on the life of the bridge.

Deng et al. (2017) researched the effect of wheel line spacing of four-wheel dual-lane truck loads on the live load distribution pattern in girder bridges. In the study, 40 bridges were considered, of which one-half were made from prestressed concrete and the remaining one-half from structural steel. The bridges were modeled by finite elements and subjected to 22 different types of axles consisting of four wheel-line loads at variable adjacent spacing. Results of the study showed that girder distribution factors for flexure and shear decrease with increases in the outside and inner wheel-line spacing of the dual-lane loads, and the lever rule is a good measure of the shear girder distribution factor.

Iatsko et al. (2017) addressed the effect of permit trucks and overloaded vehicles on the service life existing bridges that have signs of deterioration. Weigh-in-motion (WIM) records collected by national and state entities are used as a source for determining the statistical parameters of the permit and illegal live load models. Results of the study revealed that live loads have changed with regard to traffic volume over the years, mix, and weight. The obtained permit and illegal load statistics can serve as a basis for the design provisions for the strength, fatigue and extreme events limit states.

## 3 PROBLEM AND OBJECTIVES

Lack of financial resources for strengthening the deteriorating infrastructure necessitates the use of effective structural analysis techniques for checking the adequacy of existing bridges subjected to heavy oversized vehicles. While the load effect of such vehicles on the deck slab can be directly accounted for using the AASHTO's strip design method, the girder distribution factors that are included in the specifications cannot be directly utilized for oversized trucks because they were derived based on design trucks having standard gage length equal to 1830 mm. Hence, the objective of this research is to develop girder distribution factors for girder bridges subjected to oversized single-lane and dual-lane trailers for the case of shear and flexure.

## 4 APPROACH

Nine different composite steel girder bridges with various span length and girder spacing are considered in this study, as shown in Fig. 2. All the bridges are simply supported, have railings of negligible width, and contain cross-bracings at a spacing equal to 7.32 m along the length. In all the considered bridges, the overhang width is taken one-half the spacing between girders. According to the AASHTO's LRFD specifications, the bridge that has 1.22 m spacing is a 2-lane bridge, the one that has 2.44 m girder spacing is a 3-lane bridge, and the one that has 3.66 m girder spacing is a 3-lane bridge. Details of the concrete deck slab thickness and girder cross-section dimensions are provided in Table 1.

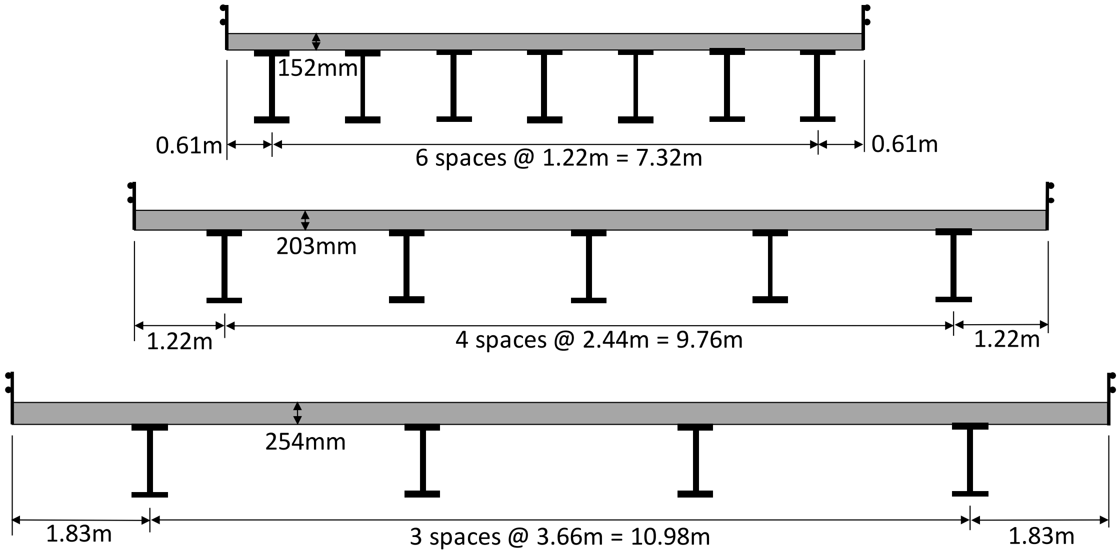


**Figure 3- Considered bridges**

**Table 1: Details of the geometry of considered bridges**

| Span Length (m) | Girder Spacing (m) | Slab Thickness (mm) | | Flange Thickness (mm) | Flange Width (mm) | Web Thickness (mm) | Web Depth (mm) |
|---|---|---|---|---|---|---|---|
| 14.64 | 1.22 | 152 | | 22 | 292 | 15 | 536 |
| | 2.44 | 203 | | 22 | 292 | 15 | 840 |
| | 3.66 | 254 | | 22 | 292 | 15 | 1145 |
| 29.28 | 1.22 | 152 | | 43 | 423 | 24 | 628 |
| | 2.44 | 203 | | 43 | 423 | 24 | 933 |
| | 3.66 | 254 | | 43 | 423 | 24 | 1238 |
| 43.92 | 1.22 | 152 | | 45 | 405 | 26 | 813 |
| | 2.44 | 203 | | 45 | 405 | 26 | 1118 |
| | 3.66 | 254 | | 45 | 405 | 26 | 1423 |

Each of the 9 bridge supestructures were modeled by finite elements and subjected to the truck component of the HL-93 live load (AASHTO 2017) with nonstandard gages. Other truck coonfigurations than the HL-93 were considered but found to be not critical because the AASHTO's truck had the shortest overall length and least number of axles. Figure 4 shows the finite element model of the 29.28 m long bridge which consists of a 203 mm thick concrete slab on four steel girders that are spaced at 2.44 m with cross-bracing placed at the quarter-points.

Both single lane trailers with gage widths of 1.83-3.66 m and dual lane trailers with gage widths of 3.66-5.49 m were used in the analysis, as shown in Fig. 5. In the study, focus was placed on shear force and bending moment in the critical interior girder since load effect in the exterior girder can only govern when the oversized truck is placed very close to the parapet, which is an unlikely condition. To determine the critical load effect in the interior girder, the oversize truck is first positioned on the bridge in the longitudinal direction such that the middle axle is at midspan. The truck is then positioned in transverse direction on the bridge close to the parapet and the GDF is computed from

Eq. (3) for the case of flexure or Eq. (4) for the case of shear. The truck is incrementally moved in the transverse direction and the GDF is calculated for the new positions. The computed GDF values are compared and the one that has the largest magnitude is chosen. The procedure is repeated for each of the 9 considered bridges subjected to the oversized trucks. The results of the structural analysis are used to develop girder distribution factors that are functions of the gage width and other bridge parameters.

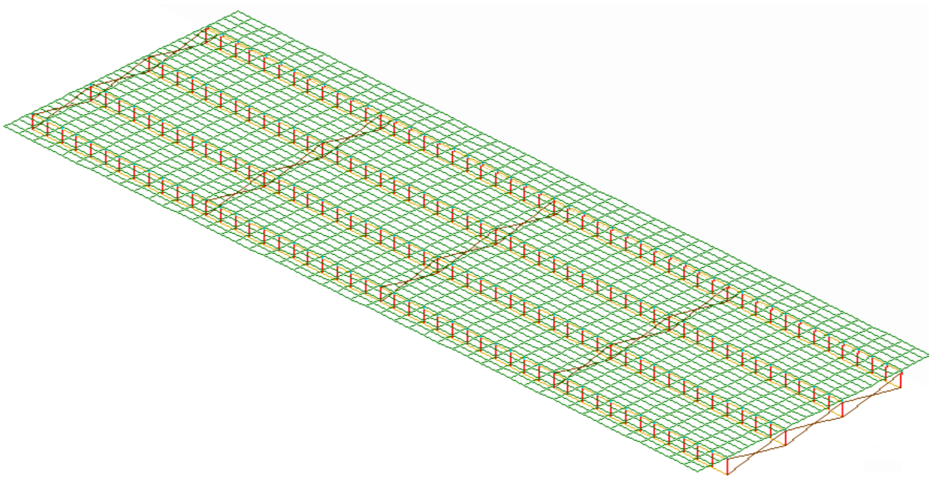

**Figure 4- Typical finite element bridge model**

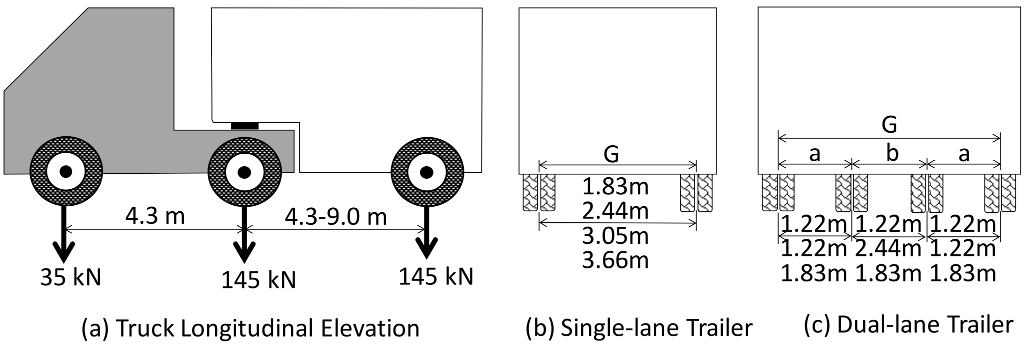


**Figure 5- Typical finite element bridge**

## 5 RESULTS

The results of the finite element analysis for the 9 considered bridge are presented in Figs. 6 and 7 for the cases of single and dual lane trailers, respectively. They confirm that the girder distribution factor for shear is always greater than that for flexure and the influence of the span length is not as significant in shear as it is in flexure. These two findings are in agreement with the AASHTO LRFD specifications (2017) based on the design truck with standard gage width.

Findings of the study also show that an increase in the gage width generally results in lower GDF because the axle load is distributed over a wider area on the bridge, and this is more profound in the case of shear than in flexure, especially when the girder spacing is large. The reason why the effect of the gage on GDF is more significant in shear than in flexure is due to the high level of load distribution at midspan where flexure is investigated than at the support where shear is examined. Also, bridges having small girder spacing are not affected much by the gage width because most of the GDF in such bridges is caused by one line of wheels, instead of the whole axles. Note that the decrease in the GDF for shear due to increase in the gage width is not always linear. For example, in the bridges that have a 2.44 m girder spacing, the GDF for shear decreases rapidly when the gage width of a single lane trailer increases from 1.83 m to 3.05 m and a dual lane trailer increases from 3.66 m to 4.88 m; thereafter, the decrease in the GDF becomes at a slower rate.

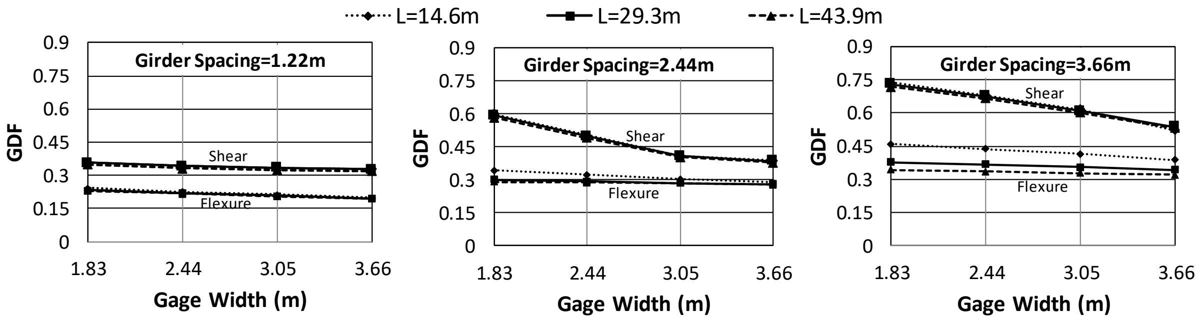


**Figure 6- Results of finite element analysis for the single lane trailer**

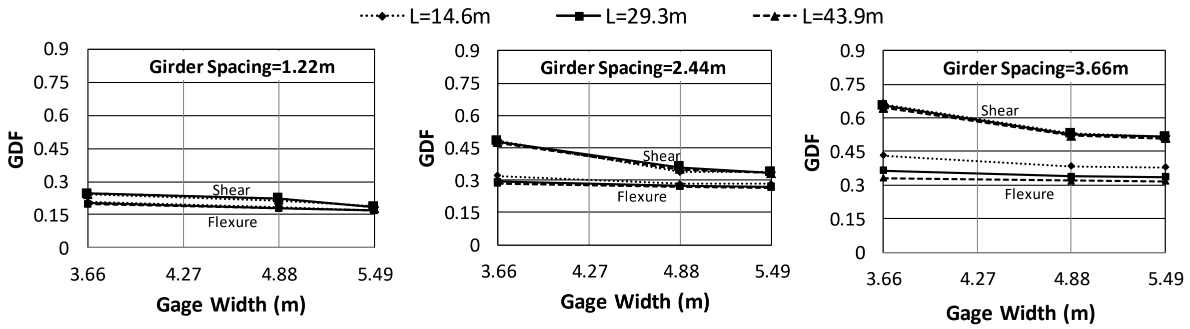


**Figure 7- Results of finite element analysis for the dual lane trailer**

Based on the results of the finite element analyses, equations for the GDF in shear and flexure due to single-lane and dual-lane trailers are proposed in a format similar that of the AASHTO Specifications (2017). For slab-on-girder bridges subjected to single-lane trailers, the GDF for interior girders in flexure, $GDF_M$, and shear, $GDF_V$, are:

$$GDF_M = 0.05 + \left(\frac{S}{4\,G}\right)^{0.4}\left(\frac{S}{L}\right)^{0.25}\left(\frac{K_g}{L\,t_s^3}\right)^{0.3} \quad (5)$$

$$GDF_V = 0.20 + \left(\frac{S}{31.7}\right)\left(\frac{1}{G}\right)^{0.7} \quad (6)$$

where G is gage width (mm) and all other parameters in the above expressions have been defined earlier.

The corresponding GDF for flexure and shear in girder bridges subjected to dual-lane trailers are:

$$GDF_M = 0.05 + \left(\frac{S}{4\,(G-a)}\right)^{0.4}\left(\frac{S}{L}\right)^{0.25}\left(\frac{K_g}{L\,t_s^3}\right)^{0.3} \quad (7)$$

$$GDF_V = 0.19 + \left(\frac{S-915}{8.75}\right)\left(\frac{1}{a}\right)^{0.5}\left(\frac{1}{G-2a}\right)^{0.4} \quad (8)$$

where a = the distance between the exterior and interior dual wheels (mm), as reference to Fig. 5.

Accuracy of the proposed GDF is demonstrated in Fig. 8 based on the 126 analyzed bridges. The results show the finite element based GDF against the corresponding proposed GDF for cases of single and dual lane trailers. On average, the proposed GDF values for girder bridges subjected to single lane trailers are 8.25% higher than the corresponding finite element results. Likewise, the proposed GDF values for girder bridges subjected to dual lane trailers are on average 11.0% higher than the corresponding finite element results. This level of conservatism can be considered reasonable in engineering practice; hence, the proposed factors can be used for evaluating existing girder bridges subjected to oversized vehicles in an efficient manner.

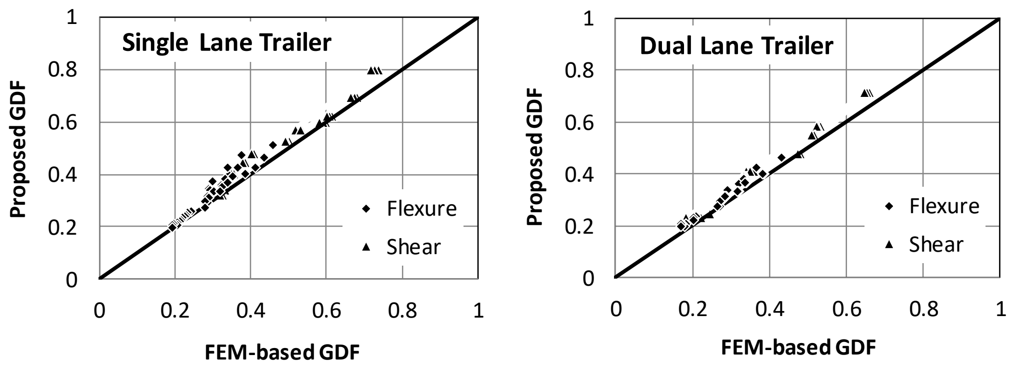


**Figure 8- Accuracy of the proposed GDF equations**

## 6 CONCLUSIONS

Results of the study lead to the following conclusions:

1. In general, an increase in a truck's gage width results in lower GDF, and this is more significant in the case of shear than in flexure, especially when the girder spacing is large.
2. The GDF of bridges having small girder spacing is not affected much by the gage width because only one line of wheels is within the tributary area of the girder under consideration.
3. The GDF for bridges subjected to wide trucks is more nonlinearly related to shear than to flexure.
4. Accuracy of the proposed GDF for bridges subjected to oversize trucks is reasonable, resulting on average in 9.6% higher values than the corresponding finite element results.
5. The proposed GDF expressions can be used for evaluating existing bridges subjected to oversized vehicles in lieu of a 3-dimensional finite element analysis.

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## 9 AUTHOR BIOGRAPHY

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