Live Load Distribution Factors of Rural Bridges Subjected to Farming Vehicles

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Authorization to Submit Thesis

This thesis of Laura E. Skinner, submitted for the degree of Master of Science with a Major in Civil Engineering and titled "Live Load Distribution Factors of Rural Bridges Subjected to Farming Vehicles," has been reviewed in final form. Permission, as indicated by the signatures and dates below is now granted to submit final copies for the College of Graduate Studies for approval.

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Abstract

The Pacific Northwest region has no data on the assessment of rural bridge design and safety subjected to Agricultural Vehicle (AV) loading. This thesis examines how different types of AVs with different characteristics distribute their loads on bridges. Live load distribution factors for girders in short span bridges under the critical loading conditions have been determined. The selected bridges are representative of rural bridges in the region. The computer models have been verified using field data in order to explore a number of bridges under various AVs. It is concluded that some of the AVs resulted in loads on the girders greater than the design values obtained from the AASHTO LRFD specifications.

Acknowledgements

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AV	Agricultural Vehicle
FE	Finite Element
FEA	Finite Element Analysis
LLDF	Live Load Distribution Factor
LRFD	Load and Resistance Factor Design
NIATT	National Institute of Advanced Transportation Technology
PACTRANS	Pacific Northwest Transportation Consortium
SCF	Skew Correction Factor

Chapter 1: Introduction

Bridges are typically designed and evaluated using Live Load Distribution Factors (LLDFs). These LLDFs are defined as the ratio of the effect of maximum live load in a single bridge member to the effect of the maximum live load in the members of the whole bridge. The American Association of State Highway and Transportation Officials (AASHTO) has provided ways to determine the LLDFs of a bridge. These are based on the shear and bending moments a typical highway vehicle place on a bridge. LLDFs quantify how much live load is distributed to a certain girder. If the LLDFs are too high, the bridge will be over-designed and if they are too low the bridge may not be able to carry the weight required [6]. Although values obtained through the AASHTO code tend to be conservative for typical highway vehicles, there is little to no data on how reliable they are when used to design for unusual types of vehicles such as agricultural vehicles, which often have very different configurations and loading patterns than standard highway vehicles.

1.1 The Problem

As of 2017 there were 614,387 bridges in the United States [4]. A large portion of these bridges are part of rural road systems. Rural transportation systems are a key factor in food supply chains; however, approximately 13% of rural bridges are considered structurally deficient and 10% more are considered functionally obsolete [10].

In addition to a large number of rural bridges not meeting current design standards, many of the vehicles that travel on these rural road systems are agricultural vehicles. These vehicles are designed for use on farms, but often travel on roadways as well. Agricultural vehicles can have vastly different wheel spacings, footprints, and axle weights than other vehicles. Because of this, they very likely create different effects on bridges than the standard highway vehicle the AASHTO specifications design for create. There are currently no standards to determine how to design for agricultural vehicles.

1.2 Objective

The overall objective of this study is to evaluate the live load distribution factors' provisions in the *AASHTO LRFD Bridge Design Specifications* for steel girder bridges under agricultural vehicle loadings. The goal of this study is to perform an analysis of bridge LLDFs under different agricultural vehicles using a Finite Element Analysis (FEA). A review of LLDF provisions in the *AASHTO LRFD Bridge Design Specifications* for steel girder bridges has been conducted and the factors obtained were compared to the results obtained from the finite element study.

1.3 Methodology

A finite element model of a steel girder bridge was created and validated in order to determine the live load distribution factors under specific agricultural vehicles. Five vehicle types were used in the analysis: a Terragator, a tractor with a grain wagon, a tractor with one manure applicator tank, a tractor with two manure applicator tanks, and a five-axle semi. The parametric study was performed to observe the differences and distribution of live loads that might affect variety of different bridges. The spacing of the girders, number of girders, and speed of the vehicles were considered key factors under the aforementioned vehicle types.

1.4 Organization

This thesis examines the LLDFs of a steel girder bridge under different types of agricultural vehicle loading. It is divided into five chapters. Chapter 2 summarizes previous works performed on the impacts of agricultural vehicles on bridges and pavements as well as a literature review of LLDFs. Chapter 3 describes the finite element process used to determine the LLDFs. The specifications of the vehicles and bridge used are detailed in

Chapter 3 along with the SAP2000 model used. Chapter 4 describes the results obtained from the finite element simulation. The analytical values obtained are compared to the values obtained using the *AASHTO LRFD Bridge Design Specifications*. Lastly, Chapter 5 summarizes the results and conclusions obtained from those results.

Chapter 2: Literature Review

2.1 Bridges

Bridges and culverts in rural areas in the State of Idaho are subjected daily to unusual loads such as agricultural and farming vehicles. Agricultural Vehicles (AVs) have varied dimensions, axle loads and characteristics. Traditional bridge design and load rating systems are based on codes and procedures that examine the capability of a bridge to resist loads from a "typical design" vehicle, generally a highway truck. Agricultural Vehicles, such as farm equipment and trucks carrying different agricultural commodities have characteristics and axle load distributions that are quite different from conventional highway trucks. Specifically, they have different wheel spacing, track widths, wheel footprints, loading configurations, and dynamic coupling characteristics. Additionally, these vehicles tend to drive a major portion of their trips on local rural roads and bridges. To date, there are no laws regulating axle loads permitted for agricultural vehicles. Severe damage and failures of rural bridges in conjunction with AV loading have been reported in the literature as shown in Figure 2.1. The current AASHTO LRFD Bridge Design Specifications do not specifically address AVs as a separate category of vehicles and do not consider the effect of their heavy loads on fewer axles as well as their operational characteristics.

Figure 2.1: Bridge failures initiated by agricultural vehicles. [11]

Therefore, AASHTO LRFD Bridge Design Specifications provide an option to the states to choose live load factors that are different than those listed in the specifications. Therefore, the study of the influence of AV loads on rural bridges is a local phenomenon, and warranted for the Pacific Northwest region.

Truck weigh-in data indicates that the Pacific Northwest agricultural vehicles are getting larger, causing unanticipated loads on local rural and off-road bridges. However, there are limited recommendations for the size and weight of AVs considering the safety of off-road bridges. One of the major problems with AV loading is that the gross load is distributed over a relatively few number of wheels with a gross weight of sometimes over 100,000 lbs., exceeding the average design gross weight of conventional trucks (80,000 lbs.). Currently, bridge load limits are not based off agricultural vehicles, which have different axle configurations and wheel dimensions. "Their geometry is atypical; their length, widths are different; they have different suspension characteristics," explains Brent Phares, director of the Bridge Engineering Center at Iowa State University [11].

The farming industry has grown in the last 20 years, which has led to use of larger AVs. Furthermore, during harvest season, grain wagons are typically used to transport crops. These vehicles were exempt from size, weight and load provisions on all roads except interstates in a law passed 14 years ago.

Bending moment distribution factors for steel girder bridges were developed by Tarhini et al. in 1992. They concluded that the live load distribution factors for agriculture vehicles are lower those obtained from the AASHTO specifications [23].

D. L. Wood and T. J. Wipf in 1999 tested four timber bridges to examine the influence of AV loading on rural bridges at Iowa State University. The four bridges were constructed from nominal 4 in. by 12 in. timber stringers removed from an existing bridge. Other bridge components, including nominal 3 in. by 12 in. deck planks, sill plates, and blocking, were fabricated from new timber. Loading of the 16-ft span bridges was applied at midspan through a 30 in. by 20 in. footprint to simulate a tire of a grain cart. The study ignored

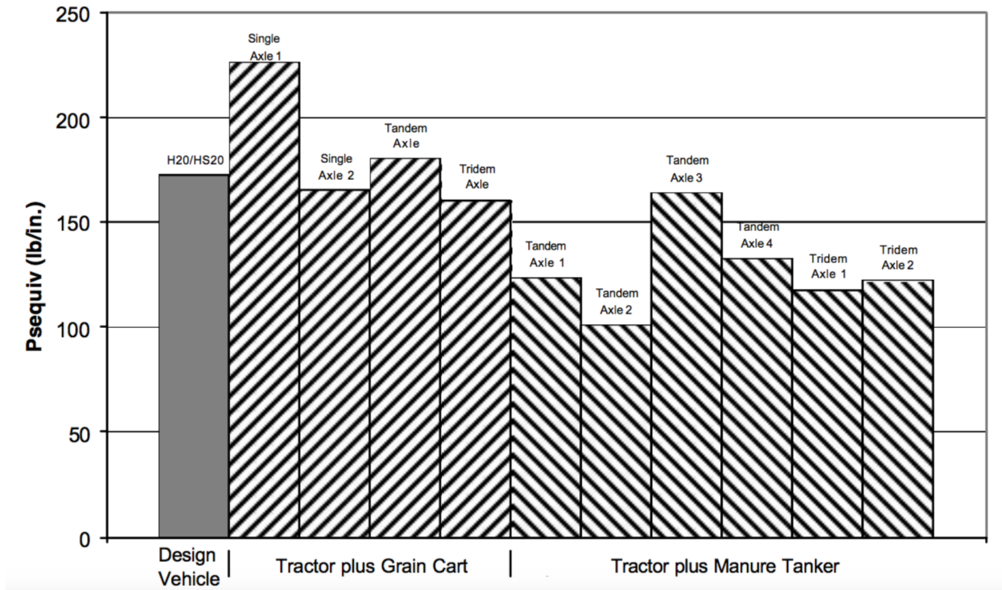


Figure 2.2: Bridge deck punching condition; design vehicles, grain carts, and manure tank implements. [11].

the effect of dynamic impact and multiple lane loads and assumed that the lateral load distribution for AVs and standard trucks were the same. This work indicates that AVs are causing demands greater than those considered during design, and increasing the likelihood of damage or failure [24]. In Minnesota, AVs have punched through the decks of a bridge [14] and most bridge failures are related to two failure modes: bending and punching. Figure 2.2 shows the punching shear conditions for different vehicles. As shown in the figure, a few of the axles exceeded the shear punching conditions resulting from the design vehicle [11].

Phares et al. developed a procedure to estimate the punching shear demands on a bridge deck, proportional to the perimeter of the tire patch. Therefore, the punching shear demands for different AVs and the standard design vehicle could be compared, as shown in Figure 2.2. Several AV configurations produced punching shear conditions exceeding the values obtained from the design vehicles [11].

Seo et al. investigated the effects of AVs on load distribution factors of existing steel girder bridges. The study involved five simply supported bridges on rural roads, and it included field load testing, finite element simulations, and statistical analyses. The field response of bridges was measured using strain gauges mounted on the bottom flanges of girders. The AVs were driven across all bridges at a very slow speed while the response of girders was recorded. The study indicated the distribution factors for unusual vehicles, such as a Terragator, were higher than the AASHTO design values [17].

Collapses of rural bridges have been observed in conjunction with agricultural loads [8],[21]. A report published by Iowa DOT observes that the vehicles that are used as implements of husbandry are not required to obey the maximum legal axle weights, instead having their own set of allowable axle weights and gross weight. However, vehicles that carry heavy loads on fewer axles, such as grain carts and liquid manure tanks, create significantly more shear stress on bridges than commercial vehicles (see Figure 2.3) which can shorten the service life of the bridge and can cause visible and hidden damages [13].

Seo et al. examined the effects of a variety of different agricultural vehicles on steel-concrete composite bridges. Five steel girder bridges were field tested with four agricultural vehicles and a semi and analytically tested with over 120 agricultural vehicles in order to determine the effects on the Live Load Distribution Factors (LLDFs). The results indicated that the LLDFs were sensitive to different agriculatural vehicle characteristics, especially different axle weights, and transverse positions. Also, the stiffness of the exterior girders significantly affected the LLDFs. In most cases the LLDFs were smaller than the AASHTO code values, but in some cases, they exceeded the code as can been seen in Figure 2.4 [18].

Seo et al. also tested a large number of vehicles on a timber bridge and compared the LLDFs obtained from field and analytical tests to those from AASHTO methods. They found that the LLDFs again occasionally exceeded the AASHTO values [20].

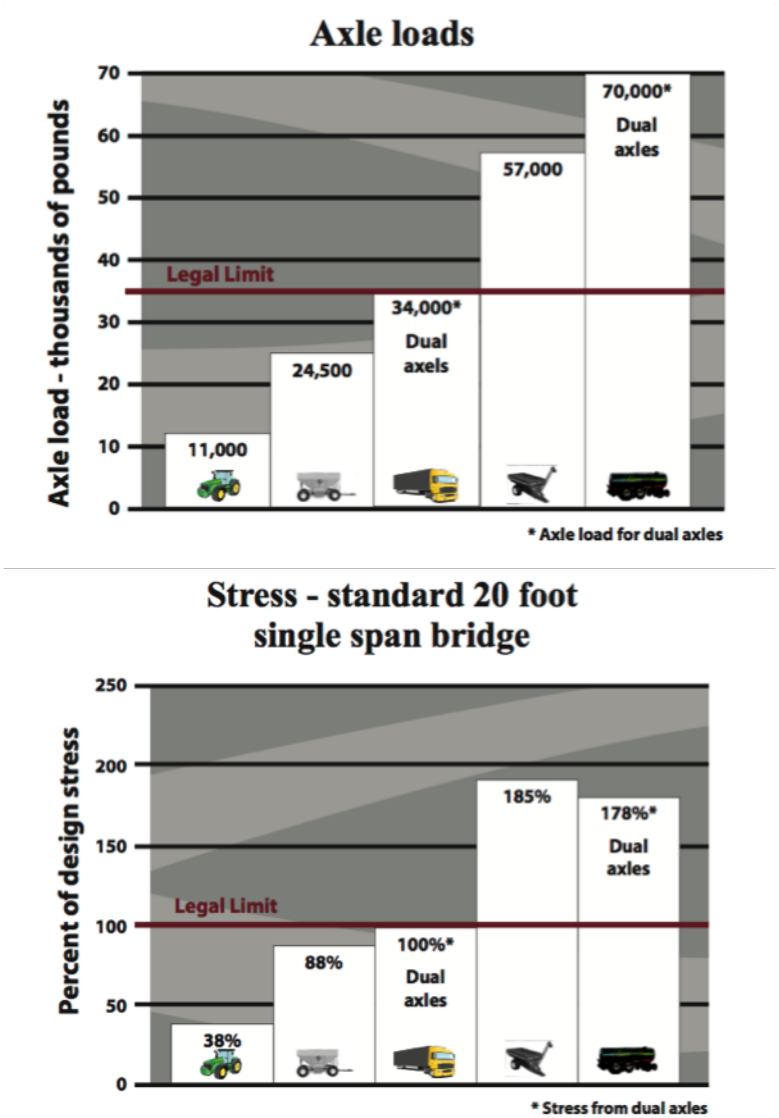


Figure 2.3: A comparison of the axle loads and shear stress on a bridge due to a large row crop tractor, a grain wagon, a five-axle semi, a grain cart, a liquid manure tank. The loads and stresses of certain AVs can be many times that of a semi [13].

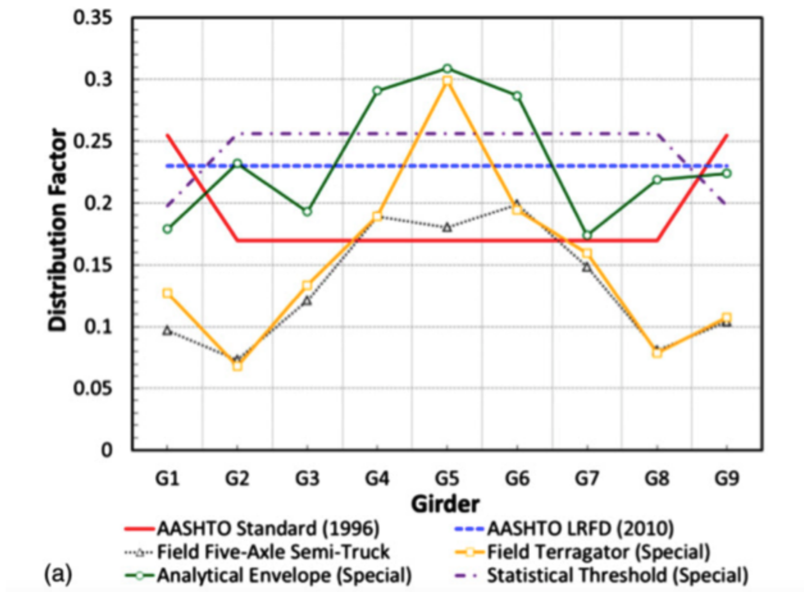


Figure 2.4: Envelope functions of special agricultural vehicle-induced distribution factors for a steel-concrete bridge [18].

2.2 Pavements and Roads

It is widely believed that agricultural vehicles play a significant role in the degradation of rural roads due to three attributes: exceeding the 20,000-lb single-axle weight limit, wide tire spacing placing heavy loads on pavement edges, and moving slowly increasing the load duration and creating rutting [9].

In 1999 Wood and Wipf studied the effect of a heavily loaded grain cart on a section of PCC pavement. A grain cart was rolled across a section of pavement, which was analyzed for excessive strains in the concrete. They found that there was a potential for over-stressing the pavement and that there were a few instances where the tension stress level exceeded the concrete rupture strength [24].

A study conducted by Sebaaly observed the impact of various agricultural vehicles on pavements compared to an 18,000-lb single-axle truck. They found that one trip of an empty Terragator, an agricultural vehicle with a single tire on the steering axle and a dual tire on the drive axle, consumed the planned design life 51 to 150 times faster than a standard single-axle truck. One trip of a loaded Terragator was 230 to 605 times than that of the 18,000-lb single-axle truck, a legally loaded grain cart was 77 to 240 times than that of the truck, and an overloaded grain cart was 264 to 799 times worse than that the truck [16].

2.3 Live Load Distribution Factors

Live load distribution factors, or LLDFs, are used to design new bridges and evaluate existing bridges, quantifying how much live load a girder must be able to hold. If the LLDFs are estimated too high the bridge will be over-designed and if they are too low the bridge may not be able to carry the weight required [6].

2.3.1 Analytical LLDFs

LLDFs are defined as the ratio of the effect of maximum live load in a component to the effect of the maximum live load in a system. Stallings and Yoo derived an equation to determine bending moment distribution factors using field data:

$$\mathrm{DF}_i = \max_{\forall(t),i}\left(\frac{M_{t,i}}{\sum_{\substack{i=1\\\forall(t),i}}^{j} M_{t,i}}\right) = \max_{\forall(t),i}\left(\frac{ES_{t,i}\varepsilon_{t,i}}{\sum_{\substack{i=1\\\forall(t),i}}^{j} ES_{t,i}\varepsilon_{t,i}}\right) \tag{2.1}$$

where DF_i is the flexure distribution factor of the i^{th} girder, E is the modulus of elasticity, $S_{t,i}$ is the section modulus of the i^{th} girder at time t, $\varepsilon_{t,i}$ is the strain at time t at the i^{th} girder, $M_{t,i}$ is the bending moment at time t at the i^{th} girder, and j is the number of girders [22].

The shear distribution factors can be determined using a similar equation:

$$\mathrm{DF}_i = \max_{\forall(t),i}\left(\frac{V_{t,i}}{\sum_{\substack{i=1\\\forall(t),i}}^{j} V_{t,i}}\right) \tag{2.2}$$

where DF_i is the shear distribution factor of the i^{th} girder, and $V_{t,i}$ is the shear force at time t at the i^{th} girder, and j is the number of girders [22].

2.3.2 AASHTO Standard Specifications

The American Association of State Highway and Transportation Officials (AASHTO) has provided specifications to determine LLDFs for bridges [1], [3]. The AASHTO *Standard Specifications for Highway Bridges*, henceforth referred to as the Standard Specifications, bases the calculations for LLDFs on a function of girder spacing, S, and bridge type [1]. These are easy to use but are often unnecessarily conservative [5]. The Standard Specifications for the bending moment distribution factors for interior girders are given below.

For steel-concrete bridges:

$$\text{LLDF}_{\text{single lane}} = \frac{S}{7.0} \tag{2.3a}$$

$$\text{LLDF}_{\text{multiple lane}} = \frac{S}{5.5} \tag{2.3b}$$

where S is the girder spacing in feet.

For steel-timber bridges:

$$\text{LLDF}_{\text{single lane}} = \frac{S}{4.5} \tag{2.4a}$$

$$\text{LLDF}_{\text{multiple lane}} = \frac{S}{4.0} \tag{2.4b}$$

where S is the girder spacing in feet.

For timber-timber bridges:

$$\text{LLDF}_{\text{single lane}} = \frac{S}{4.0} \tag{2.5a}$$

$$\text{LLDF}_{\text{multiple lane}} = \frac{S}{3.75} \tag{2.5b}$$

where S is the girder spacing in feet. The Standard Specifications' equations are based on wheel loads and must therefore be divided by a factor of 2 in order to compare them with the LRFD specifications and analytical LLDFs, which are based on axle loads [6].

2.3.3 AASHTO LRFD Specifications

The *AASHTO LRFD Bridge Design Specifications*, henceforth referred to as the LRFD Specifications, take into account bridge geometries and other factors and are more sophisticated than the standard specifications [2]. LLDFs determined using the LRFD Specifications are generally considered to be more consistent than those determined using standard specifications, particularly for bridges with long spans [5]. The LRFD Specifications for the bending moment distribution factors for interior girders are given below.

For interior girders of steel-concrete bridges:

$$\text{LLDF}_{\text{single lane}} = 0.06 + \left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{12Lt_s^3}\right)^{0.1} \tag{2.6a}$$

$$\text{LLDF}_{\text{multiple lane}} = 0.075 + \left(\frac{S}{9.5}\right)^{0.6}\left(\frac{S}{L}\right)^{0.2}\left(\frac{K_g}{12Lt_s^3}\right)^{0.1} \tag{2.6b}$$

where S is the girder spacing in feet, L is the length of the span in feet, t_s is the deck thickness in inches, and K_g is the longitudinal stiffness in in.^{4}. $K_g = n(I + Ae^2)$, where n is the modular ratio between steel and concrete, I is the girder stiffness in in.^{4}, A is the area of the cross-section of the girder in in.^{2}, and e is eccentricity between the centroids of the girder and the slab in inches.

For exterior girders of steel-concrete bridges:

$$\text{LLDF}_{\text{multiple lane}} = \left(0.77 + \frac{d_e}{9.1}\right)\text{LLDF}_{\text{interior}} \tag{2.7}$$

where d_e is the distance from the center-line of the web of the exterior girder to the interior edge of the curb in feet, and $\text{LLDF}_{\text{interior}}$ is the distribution factor specified in Equation 2.6b. For single-lane bridges exterior LLDFs can be determined based on the lever rule specified in the LRFD Specifications [3].

Skew Correction Factors (SCFs) are provided by the LRFD Specifications for steel-concrete bridges, which are then multiplied with the LLDFs of non-skewed bridges. The equation to determine SCFs is:

$$\text{SCF} = 1 - 0.25 \left(\frac{K_g}{12Lt_s^3}\right)^{0.25} \left(\frac{S}{L}\right)^{0.5} \left(\tan\theta^{1.5}\right) \tag{2.8}$$

where S is the girder spacing in feet, L is the span length in feet, K_g is the longitudinal stiffness in in.^{4}, t_s is the deck thickness in inches, and θ is the skew angle in degrees.

The LRFD Specifications for the LLDFs of steel-timber and timber-timber bridges are based on the S-over rule for interior girders.

For steel-timber bridges:

$$\text{LLDF}_{\text{single lane}} = \frac{S}{8.8} \tag{2.9a}$$

$$\text{LLDF}_{\text{multiple lane}} = \frac{S}{9.0} \tag{2.9b}$$

where S is the girder spacing in feet.

For timber-timber bridges:

$$\text{LLDF}_{\text{single lane}} = \frac{S}{6.7} \tag{2.10a}$$

$$\text{LLDF}_{\text{multiple lane}} = \frac{S}{7.5} \tag{2.10b}$$

where S is the girder spacing in feet. The LLDFs of exterior girders for steel-timber and timber-timber bridges can be determined by the lever rule as seen in the LRFD Specifications [3].

The LRFD Specifications also provide equations to determine the shear distribution factors:

$$\text{LLDF}_{\text{single lane}} = 0.36 + \frac{S}{25.0} \tag{2.11a}$$

$$\text{LLDF}_{\text{multiple lane}} = 0.2 + \frac{S}{12} - \left(\frac{S}{35}\right)^{2.0} \tag{2.11b}$$

where S is the girder spacing in feet [2].

Chapter 3: Finite Element Analysis

3.1 General Description

Bridges in rural areas are usually designed under standard highway truck loads using AASHTO specifications. This study is focused on analyzing steel girder bridges with concrete decks under agricultural vehicles. The effect of agricultural vehicles' loading on live load distribution factors was analyzed using the structural analysis software SAP2000. The models consider the 3-D effect on the load distributions between girders under various agricultural vehicles where the code was validated using field data conducted through a study done by Seo et al. [18]. This study included five different types of vehicles: four agricultural vehicles and one standard highway truck. The finite element analysis details of the studied bridges will be introduced and discussed.

3.1.1 Bridge Description

The initial bridge studied is a simply supported, short-span, steel I-girder bridge with zero skew taken from a study done by Seo et al. in 2014 [18]. This bridge was chosen so that the strains from my Finite Element (FE) model could be compared with previous field results. The bridge has a span of 42.0-ft and a 7.5-in thick concrete deck. The steel

Figure 3.1: Representative steel girder bridge.

girders have 23 x 0.4-in webs with 7-in-wide x 0.5-in-thick flanges. The initial bridge used to verify the FE model has 9 girders with the interior girders spaced every 3.0-ft with the exterior girders were spaced 3.3-ft from the nearest interior girders. The total bridge width was 24.3-ft. The moduli of elasticity for the concrete and steel were used as 3,200 ksi and 29,000 ksi, respectively. Figure 3.1 shows a local bridge that has steel girders supported with a concrete deck.

3.1.2 Vehicle Descriptions

Five vehicles were used in the analysis of the bridge: a Terragator with a single-wheel front axle and two rear axles, a tractor with a grain wagon, a tractor with one manure applicator tank, a tractor with two manure applicator tanks, and a five-axle semi. The agriculture vehicles are shown in Figure 3.2 and the axle spacing and configurations are presented in Table 3.1.

(a) Terragator

(b) Tractor with grain wagon

(c) Tractor with one tank

(d) Tractor with two tanks

(e) Semi-truck

Figure 3.2: Vehicles used in testing: (a) Terragator, (b) Tractor with a grain wagon, (c) Tractor with one tank, (d) Tractor with two tanks, (e) Semi Truck.

Table 3.1: Configurations of the vehicles.

Vehicle	Axle	Axle Weight (kips)						Axle Spacing (ft.)				
	Number	W1	W2	W3	W4	W5	W6	S1	S2	S3	S4	S5
Terragator	3	11.06	16.21	16.21	NA	NA	NA	19.4	6.2	NA	NA	NA
Tractor with one tank	5	11.80	15.92	16.28	16.28	16.28	NA	10.8	18.4	5.9	5.9	NA
Tractor with two tanks	6	20.26	16.07	7.15	7.15	9.15	9.15	12.8	21.0	6.2	17.1	6.2
Tractor with grain wagon	3	18.84	18.66	15.67	NA	NA	NA	11.2	24.0	NA	NA	NA
Five-axle semi	5	11.04	17.38	17.38	17.02	17.02	NA	12.1	4.3	31.8	3.9	NA

*Axle weights are the total weights of all the wheels on each axle.

NA = Data not applicable

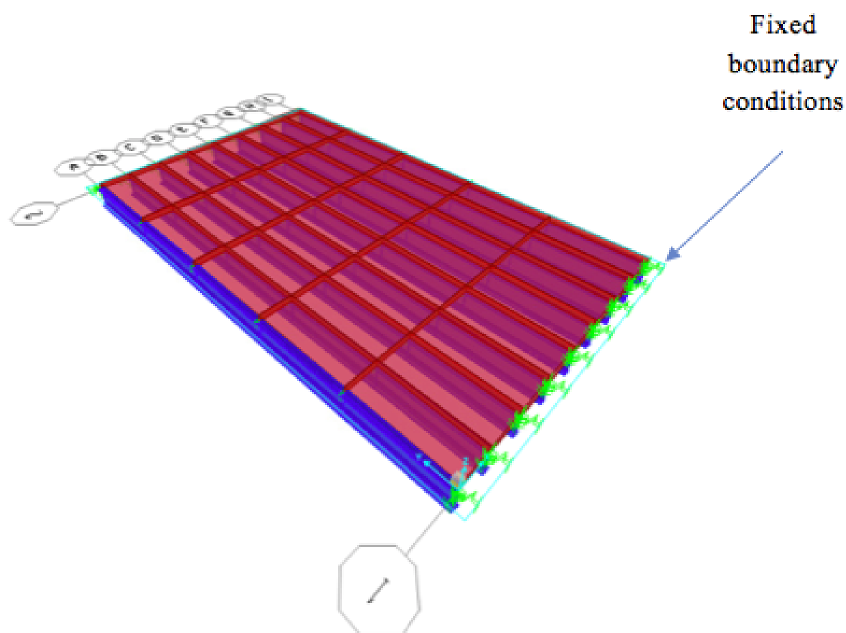


Figure 3.3: Snapshot of the bridge model developed in SAP2000.

3.2 SAP2000

The finite element model was created using SAP2000. SAP2000 is a general finite element software that is used for linear and nonlinear structural analysis. The code is designed to perform static and dynamic load analyses with multiple capabilities of data extractions. The girders were modeled using frame elements and the bridge deck was modeled using a quadrilateral shell element due to its uniform thickness and properties. Linear links were created between the frame elements (girders) and the shell elements (deck) to achieve a full interaction between the girders and the concrete deck. The frames and shells were meshed to create a finite element model (see Figure 3.3). The bridge supports were fixed. A vehicle was moved across the center of the bridge at a crawl speed of 2 mph, simulating a static load.

3.2.1 Element Types

Frame elements were used to model the girders of the bridge. According to the SAP2000 manual frame elements use "a general, three-dimensional, beam-column formulation with includes the effects of biaxial bending, torsion, axial deformation, and biaxial shear deformations." Shell elements, defined in the SAP2000 manual as a "three- or four-node formulation that combines membrane and plate-bending behavior," were used to model the concrete bridge deck. Linear links are described as "a two-joint connecting link composed of six separates 'springs,' one for each of the six deformational degrees of freedom" and were used to tie the bridge deck and girders together [15]. The links were fixed in all six directions to create a full interaction between the bridge deck and girders.

3.2.2 Verification of the Model

In order to verify the FE model, the girder strains were compared to field results. The field results were obtained from a previous study that was done on the subject by Seo et al. [18]. The model of the bridge was built in SAP2000 and a Terragator was run across it. Figure 3.4 shows the comparison between the FE strain results and girder strains measured in the field. Those strains were measured at the bottom flange of the steel girders at the mid-span of the bridge. Due to the symmetrical shape of the bridge, the strains of girders 1 and 9, girders 2 and 8, girders 3 and 7, and girders 4 and 6 are the same, while girder 5 is the middle girder of the bridge. Figure 3.4 shows the strain versus time history in seconds, where the Terragator was modeled to move over the bridge at 2 mph simulating a static load. The pattern of the strains obtained from the FE code compares very well with the field data. The strain values are not exact, but the strain results in the literature are taken from strain gauges placed on an actual bridge, so there may be some errors in their values. It was also noticed that the value of the maximum strain in girder 5 (middle girder) is 65 microstrain which is less than the yield strain of the structural steel used in the bridge. Since the maximum strain was less than the yield

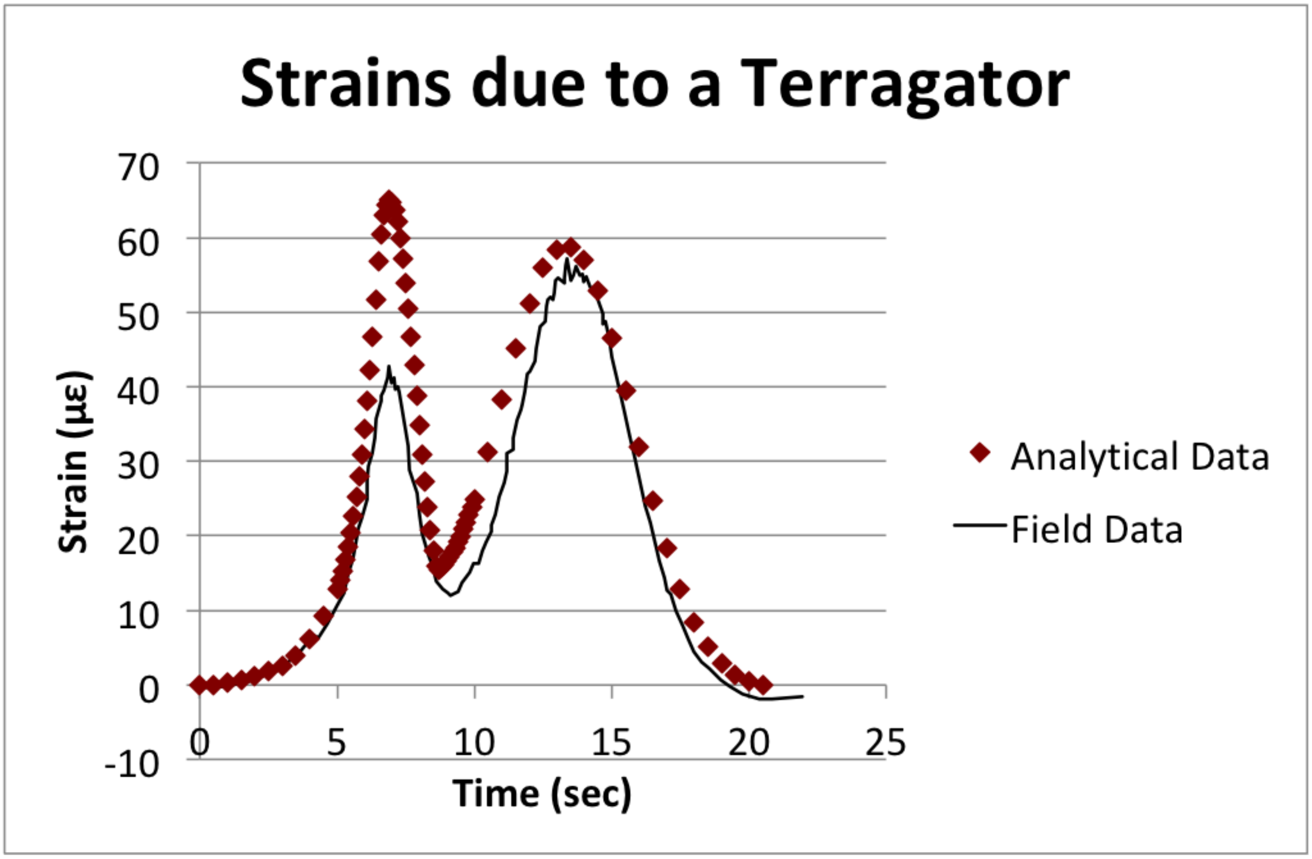


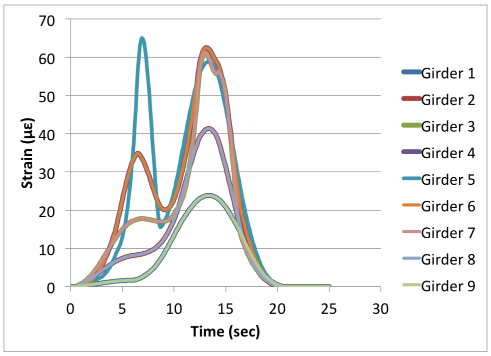
Figure 3.4: Comparison of the resulting analytical strains to the strains from previous literature at the midspan of the middle girder of the bridge due to the loading of a Terragator over time.

strain, a linear analysis was used. Due to the very limited experimental data related to the behavior of bridges loaded with agricultural vehicles, this was the only validation testing that has been done.

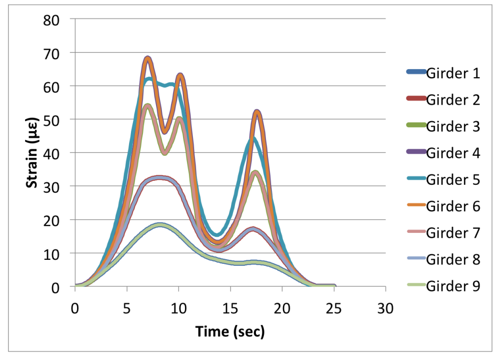
3.3 Strain Time History

The strain time histories under the various vehicles have been investigated. Figure 3.5 shows the normal strain at the mid-span of the bottom flange of the bridge created by the different vehicles crossing the bridge at a speed of 2 mph. It can be seen from Figure 3.5 that the maximum strain of girder 5 due to the Terragator was 62.5 microstrain at a time of 3.1 seconds, while the tractor with the grain wagon induced a strain of 86.5

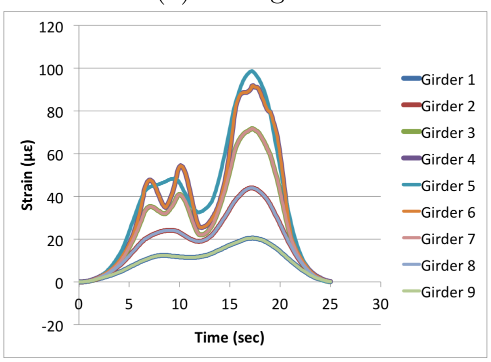
microstrain at 7 seconds on girder 6. The tractor with one and two tanks produced maximum strains of 98.4, and 69.1 at 17.2 and 7 seconds, respectively. Finally, the semi generated a maximum strain of 86.6 at 10.2 seconds. The variability of strain was mainly due to the axle configurations, axle loads and spacings of all the vehicles. Some of the farming vehicles such as the tractor grain wagon and tractor with one tank produced tensile strain greater than those of the semi, which indicates that some AVs should be considered by AASHTO for rural bridge designs.



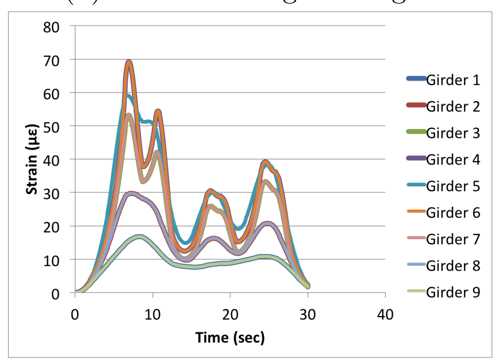
(a) Terragator



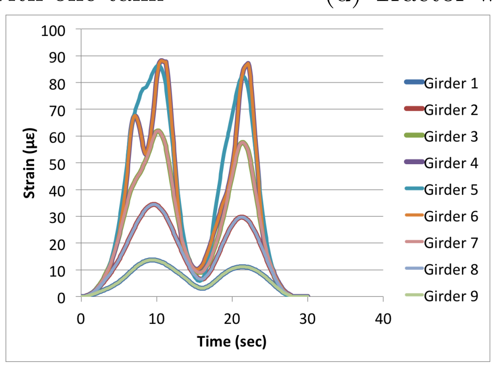
(b) Tractor with grain wagon



(c) Tractor with one tank



(d) Tractor with two tanks



(e) Semi Truck

Figure 3.5: Tensile strains due to a) Terragator, b) Tractor with grain wagon, c) Tractor with one tank, d) Tractor with two tanks, and e) Semi Truck.

Chapter 4: Results and Discussion

4.1 Parametric Study

This chapter presents the results obtained from the FE analysis conducted on various cases of bridges under combinations of agricultural vehicles. The span of the bridge was kept constant at 42-ft, and it was kept as a single span, simply supported, steel-concrete bridge. Different parameters were varied in the study including girder spacing, number of girders, and the speed of vehicles. The analytical LLDFs were determined from the resulting moments and shears and compared to LLDFs derived using the AASHTO LRFD manual. Figure 4.1 shows the various combinations of the FE models generated to predict the live load distribution factors.

After the finite element model had been verified, a number of different parameters were varied and the effects of these parameters on the LLDFs of the bridge were observed. The parameters that were changed were the spacing of the girders while keeping a constant number of girders, the number of the girders while keeping a constant bridge width, and the speed of the vehicles. The results obtained from each parameter are detailed below.

4.1.1 Effects of Girder Spacing

The effect of different girder spacing was investigated under various agricultural vehicles, where the span of the bridge and number of girders were kept constant at 42-ft and 9 girders, respectively. The girder spacing ranged from 1.64-ft to 4.96-ft between the girder center lines, while the bridge width varied from 13-ft to 40-ft accordingly. The five vehicles were modeled on the bridge. The effects the changing girder spacing had on the LLDFs were observed.

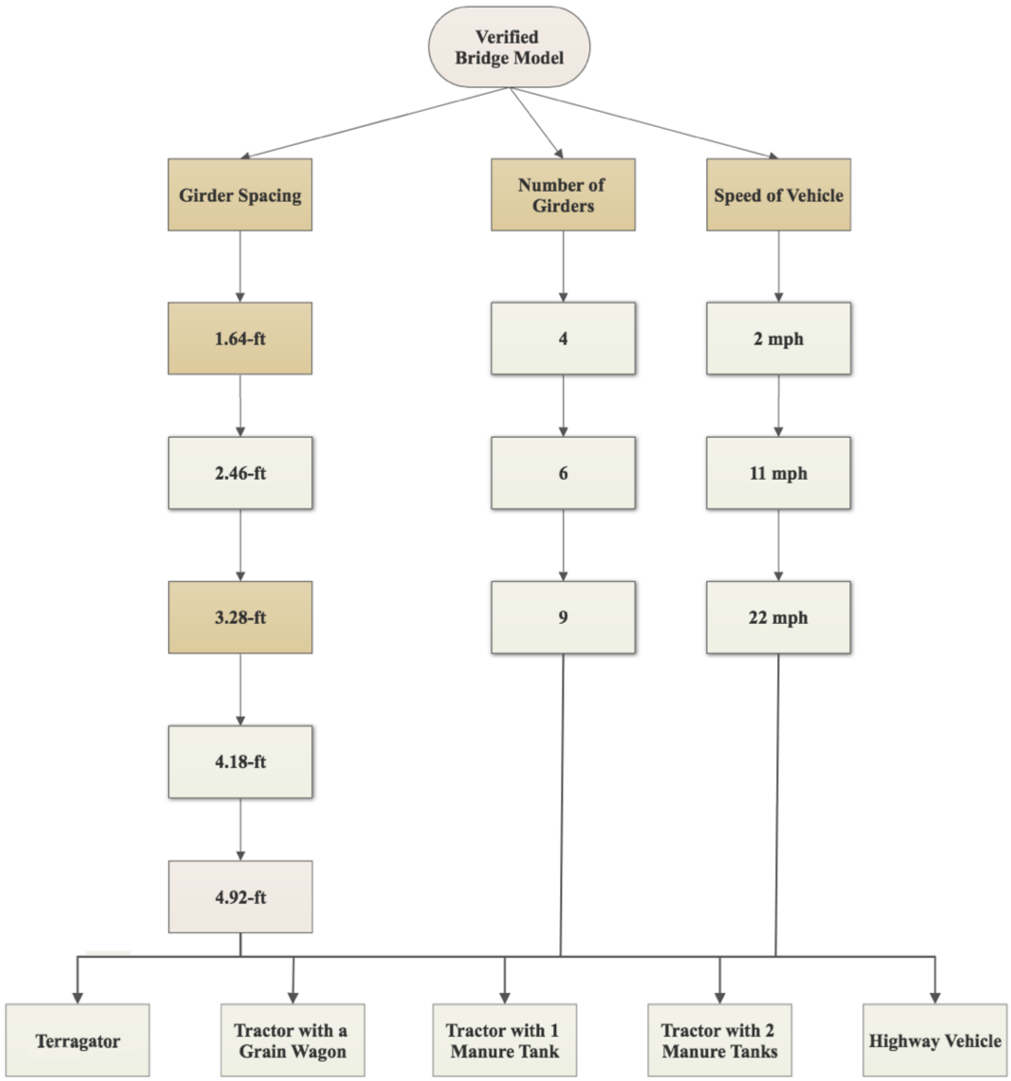
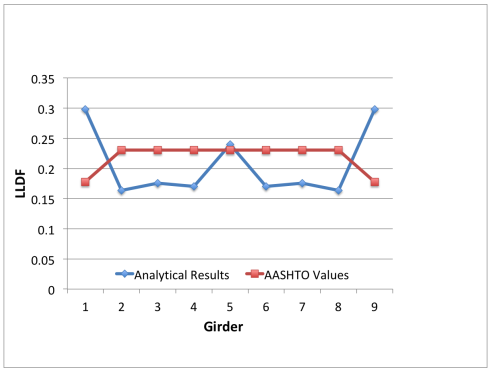


Figure 4.1: Once the model was verified, these different parameters were varied and analyzed under all five vehicles.

4.1.1.1 Bending Moment LLDFs

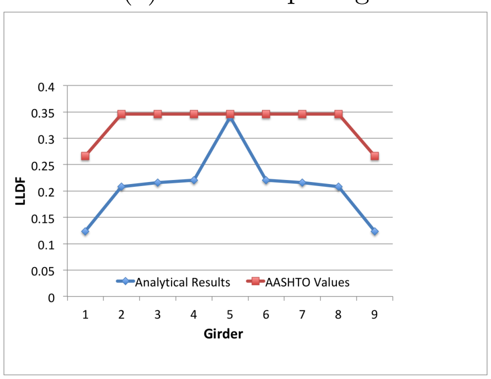
Figures 4.2 to 4.5 show the LLDFs under each vehicle for different spacing. For most of the girder spacings and vehicle types, the analytical LLDFs values were lower than the design values, however, the Terragator created a higher (4%) LLDF on the middle girder at smaller spacing than the values obtained from AASHTO design codes (See Fig. 4.2a). The LLDFs were much higher (67%) than the AASHTO values on the exterior girders when the girder spacing was 1.64-ft which is attributed to the higher girder stiffness. When the spacing between girders increases to 2.46-ft and 3.28-ft, the Terragator showed about the same LLDFs for the middle girder as the AASHTO values, and at spacing of 4.10-ft and 4.92-ft, the LLDFs were less than the AASHTO values by 57% and 56%, respectively. For all other vehicles, the LLDFs were less than the AASHTO values as shown in Figures 4.2 to 4.5.

Figure 4.7 shows a direct comparison of the maximum exterior and interior bending moment LLDFs created by the different vehicles. It can be seen from Figure 4.7a that the Terragator has a significant weight that produced a distribution factor of 0.30 for exterior girders, which exceeded the AASHTO design value of 0.18 at the smallest girder spacing. The other vehicles produced lower LLDFs compared to the Terragator. When the spacing between girders was increased to 2.64-ft, and 3.28-ft, the Terragator produced internal girder distribution factor of (0.29) that was equal to the AASHTO design value. The LLDFs for the exterior and interior girders due to Terragator at a girder spacing of 1.64-ft were higher than the semi truck by 88%, and 62%, respectively. The LLDFs for the interior girders due to the Terragator were larger than the semi truck by 70%. Other agricultural vehicles such as the tractor with a grain wagon produced 70% higher LLDFs for exterior girders compared to the semi truck when the girder spacing was 3.28-ft. For girder spacings of 4.10-ft and 4.92-ft, the LLDFs due to the semi truck were higher than the ones produced by tractor with one and two tanks, and it was noticed that the LLDFs for all exterior girders were almost zero.

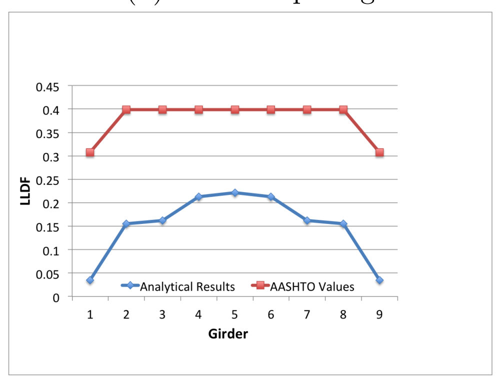


(a) 1.64-ft. Spacing

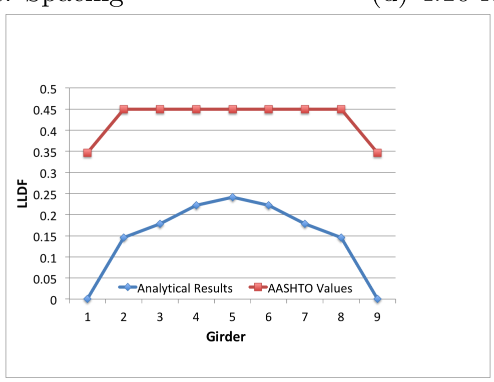
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing



(d) 4.10-ft. Spacing

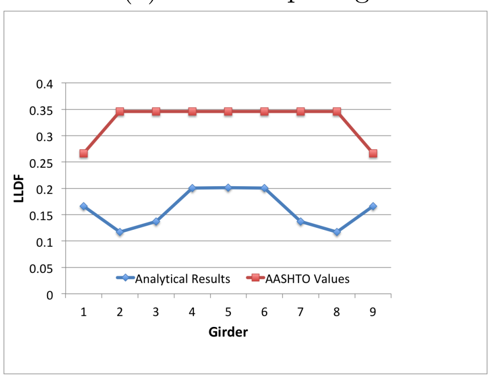


(e) 4.92-ft. Spacing

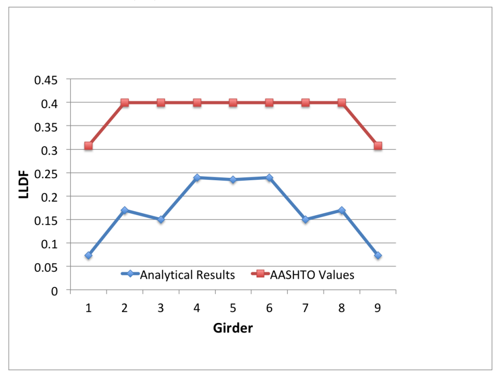
Figure 4.2: Bending moment load distribution factors due to a Terragator on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.

(a) 1.64-ft. Spacing

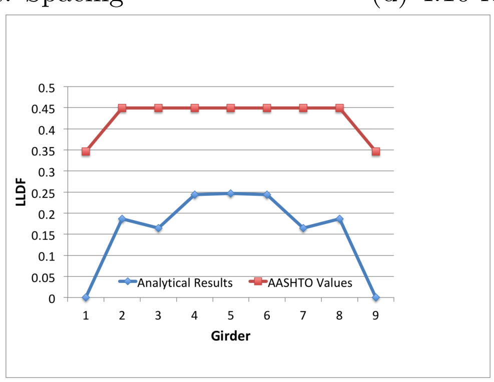
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing

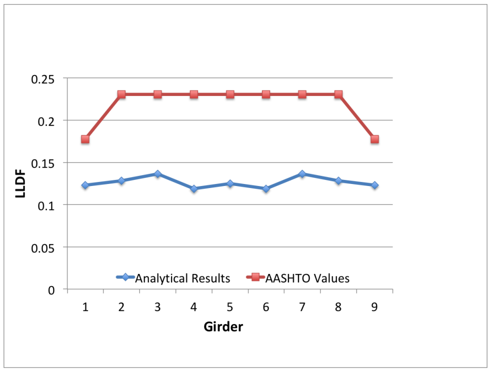


(d) 4.10-ft. Spacing



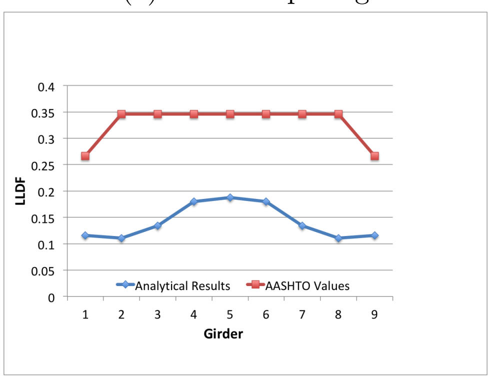
(e) 4.92-ft. Spacing

Figure 4.3: Bending moment load distribution factors due to a tractor with a grain wagon on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.

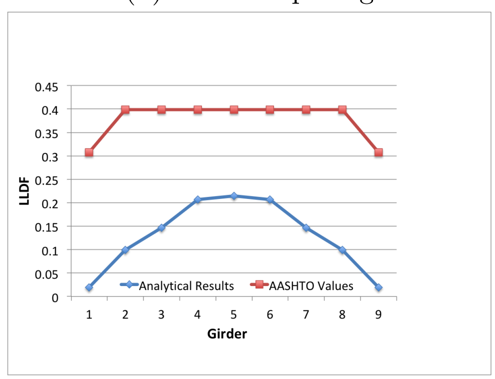


(a) 1.64-ft. Spacing

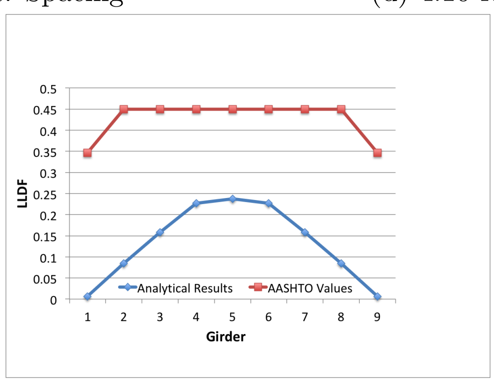
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing

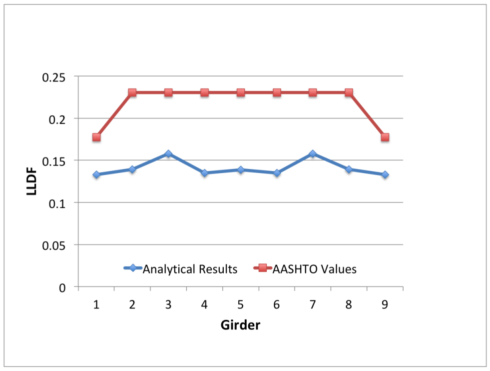


(d) 4.10-ft. Spacing

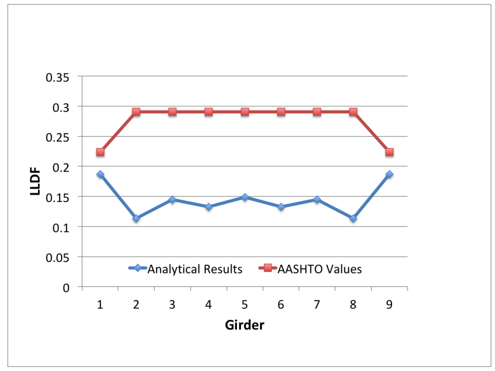


(e) 4.92-ft. Spacing

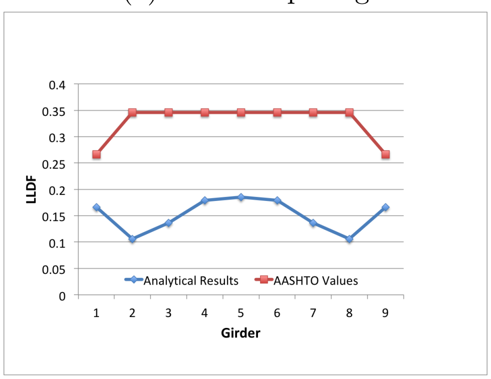
Figure 4.4: Bending moment load distribution factors due to a tractor with 1 tank on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.



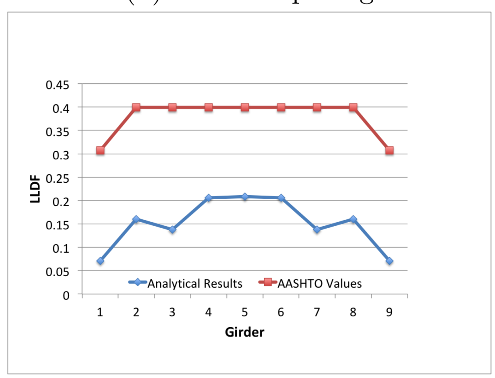
(a) 1.64-ft. Spacing



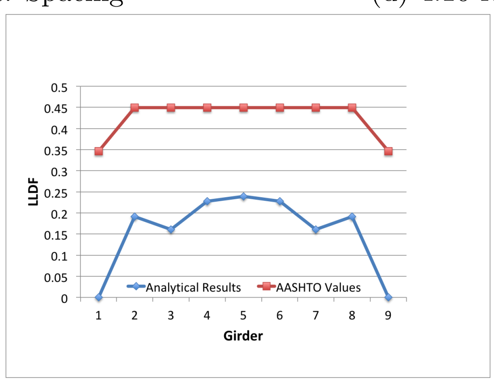
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing

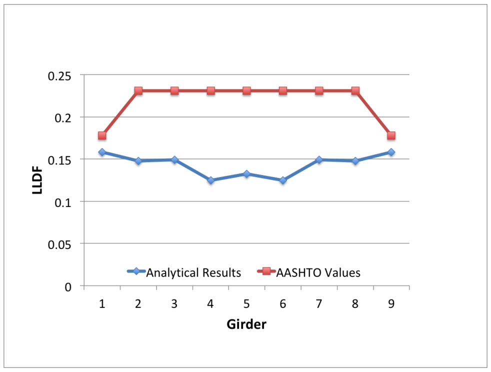


(d) 4.10-ft. Spacing

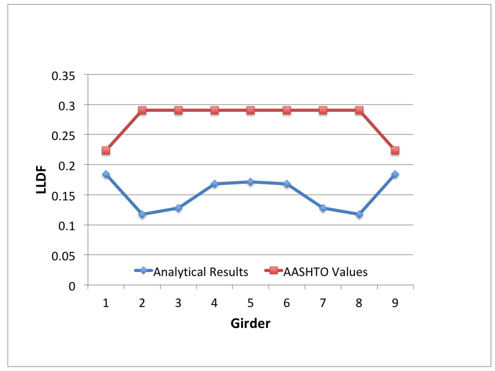


(e) 4.92-ft. Spacing

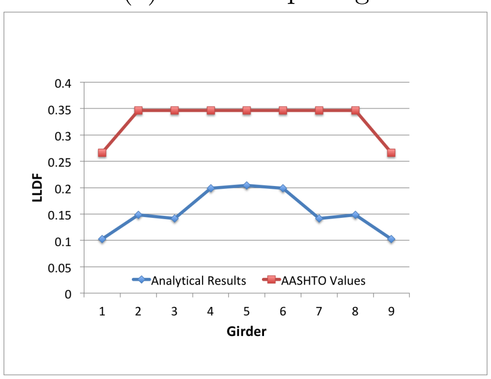
Figure 4.5: Bending moment load distribution factors due to a tractor with 2 tanks on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.



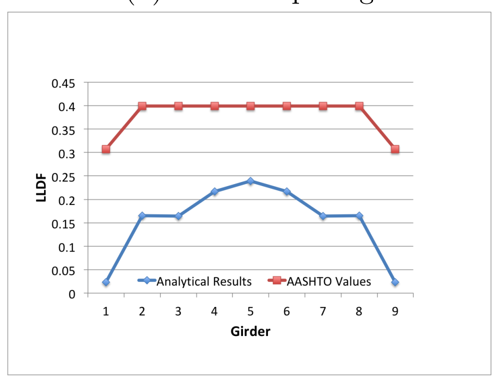
(a) 1.64-ft. Spacing



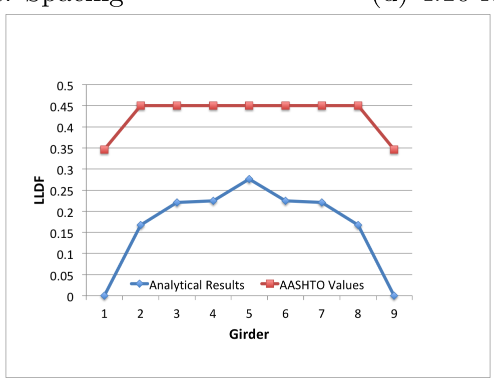
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing

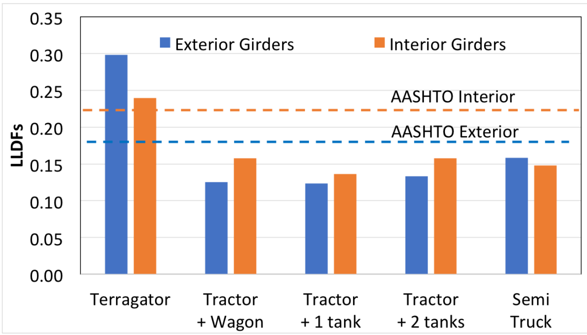


(d) 4.10-ft. Spacing

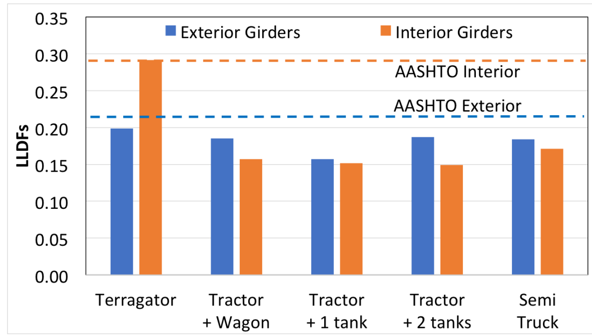


(e) 4.92-ft. Spacing

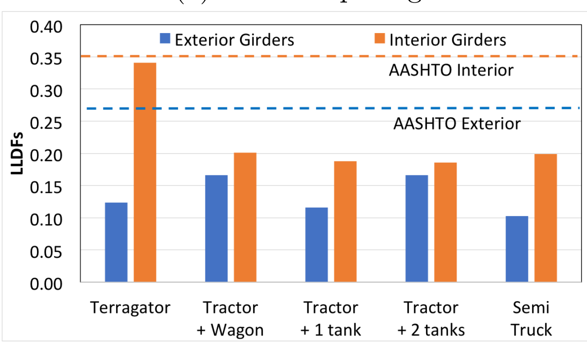
Figure 4.6: Bending moment load distribution factors due to a semi on a simply-supported, steel-concrete bridge with a constant span and with different girder spacings.



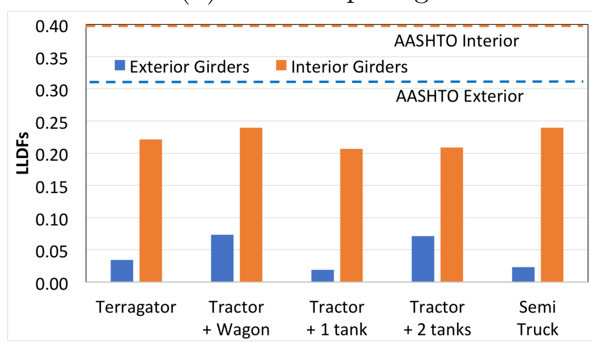
(a) 1.64-ft. Spacing



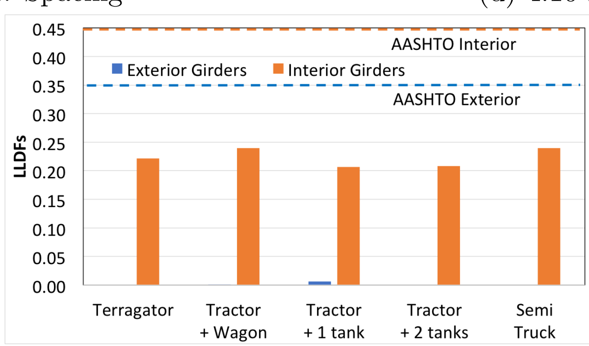
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing



(d) 4.10-ft. Spacing

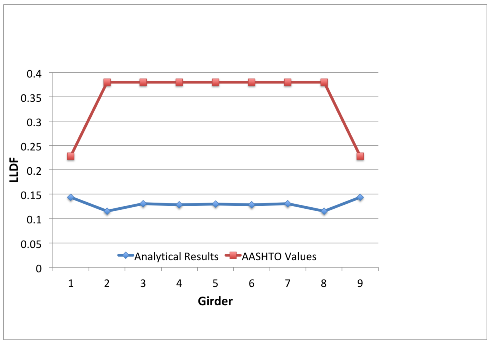


(e) 4.92-ft. Spacing

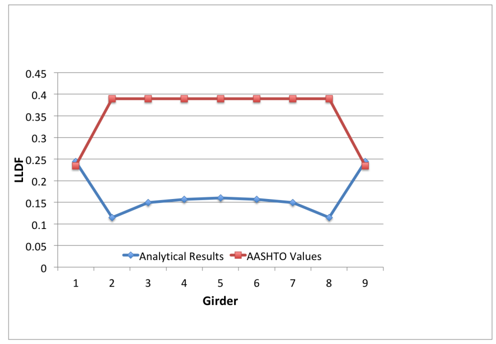
Figure 4.7: Comparison of the bending moment LLDFs from the model and AASHTO LRFD values for interior and exterior girders.

4.1.1.2 Shear LLDFs

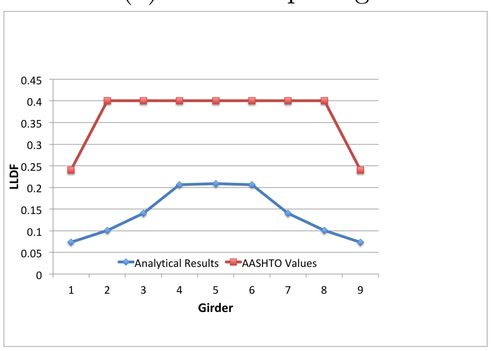
Figures 4.8 to 4.12 show the shear LLDFs for a single span, simply-supported, steel-concrete bridge with different girders spacings, and therefore different bridge widths. In almost all cases the analytical shear LLDFs are less than the AASHTO values. For a girder spacing of 2.46-ft, however, the LLDF for the exterior girders for the Terragator are 4% higher than the AASHTO value.



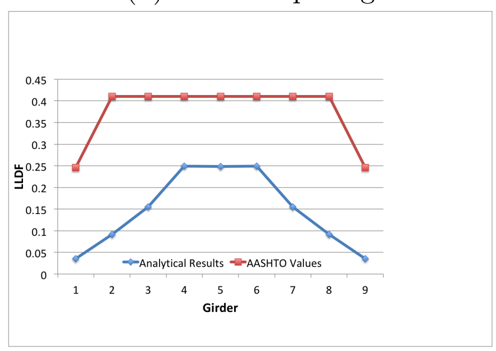
(a) 1.64-ft. Spacing



(b) 2.46-ft. Spacing



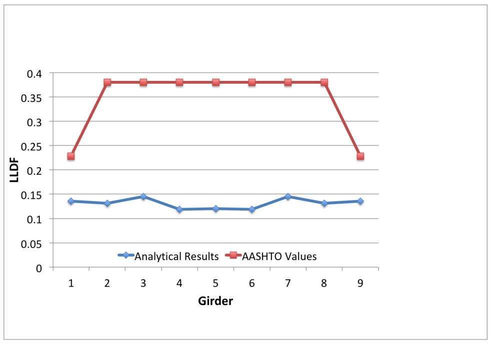
(c) 3.28-ft. Spacing



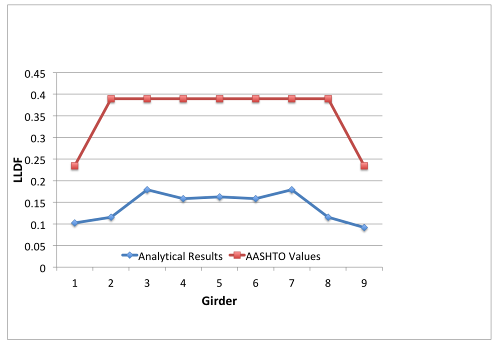
(d) 4.10-ft. Spacing

(e) 4.92-ft. Spacing

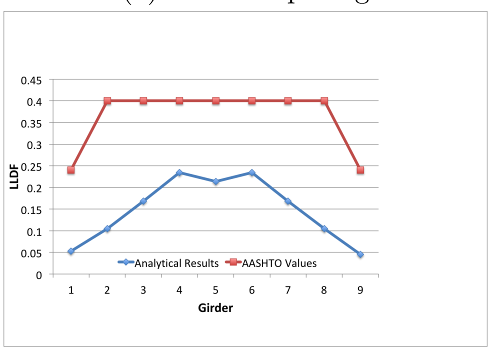
Figure 4.8: Shear distribution factors due to a Terragator on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.



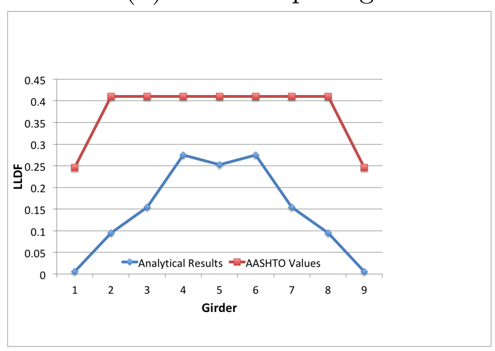
(a) 1.64-ft. Spacing



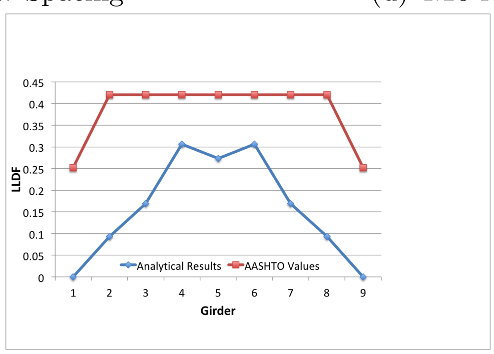
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing

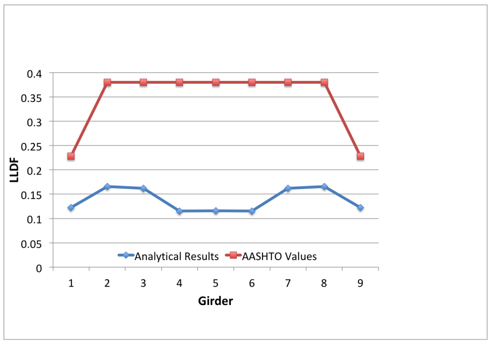


(d) 4.10-ft. Spacing

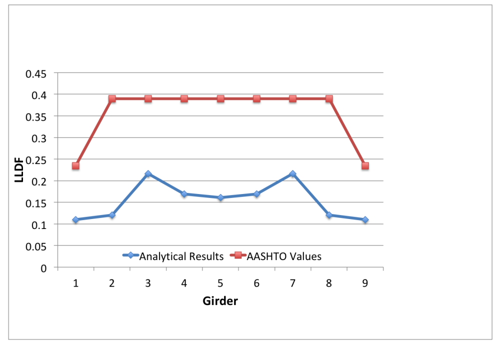


(e) 4.92-ft. Spacing

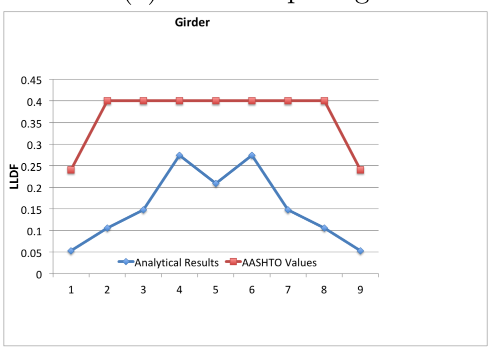
Figure 4.9: Shear distribution factors due to a tractor with a grain wagon on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.



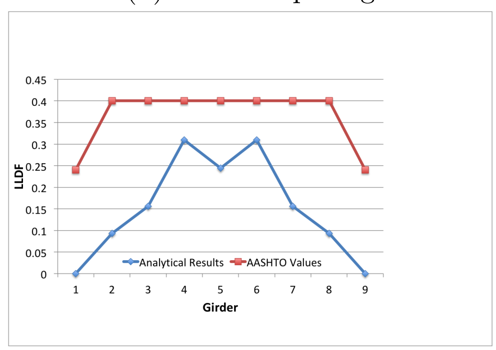
(a) 1.64-ft. Spacing



(b) 2.46-ft. Spacing



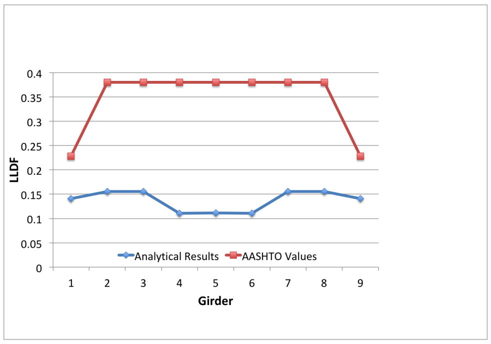
(c) 3.28-ft. Spacing



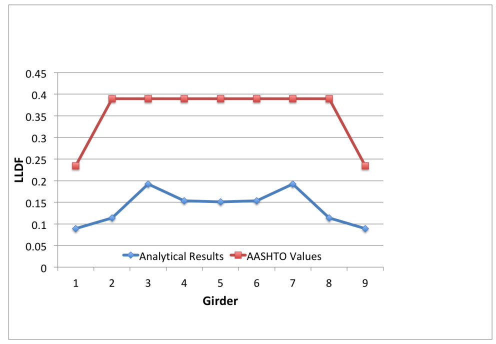
(d) 4.10-ft. Spacing

(e) 4.92-ft. Spacing

Figure 4.10: Shear distribution factors due to a tractor with 1 tank on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.

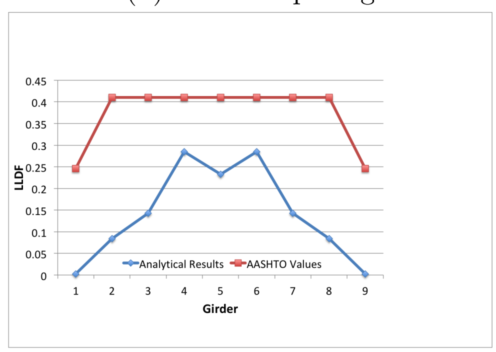


(a) 1.64-ft. Spacing

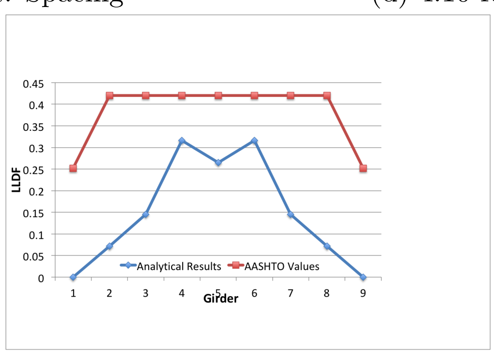


(b) 2.46-ft. Spacing

(c) 3.28-ft. Spacing

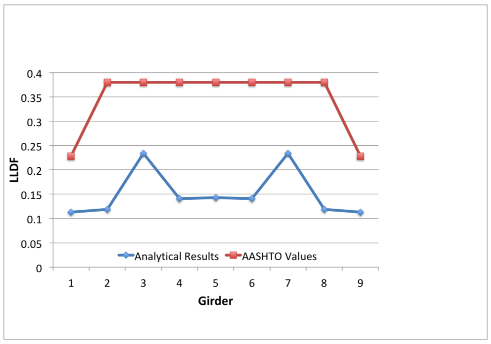


(d) 4.10-ft. Spacing

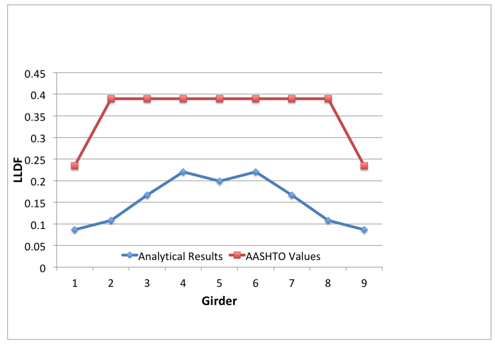


(e) 4.92-ft. Spacing

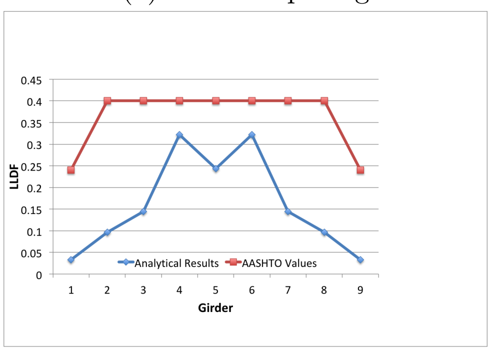
Figure 4.11: Shear distribution factors due to a tractor with 2 tanks on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.



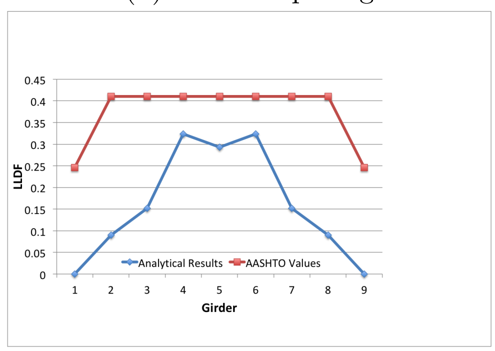
(a) 1.64-ft. Spacing



(b) 2.46-ft. Spacing



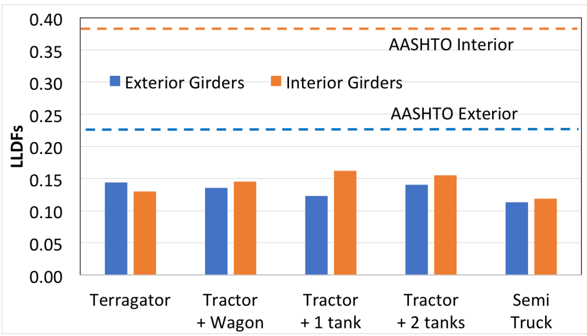
(c) 3.28-ft. Spacing



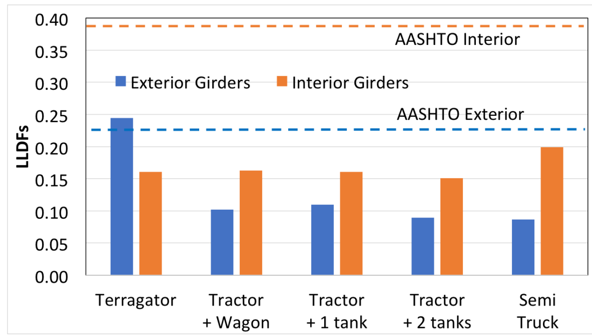
(d) 4.10-ft. Spacing

(e) 4.92-ft. Spacing

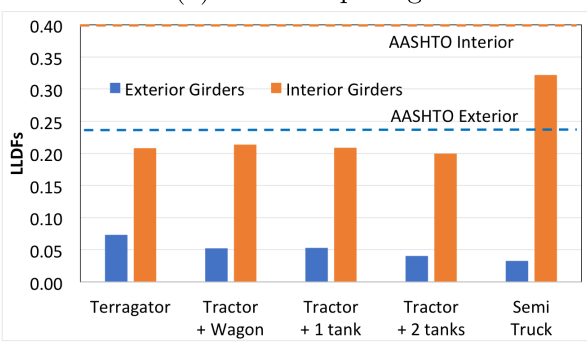
Figure 4.12: Shear distribution factors due to a semi truck on a simply-supported, steel-concrete bridge with a constant span and different girder spacings.



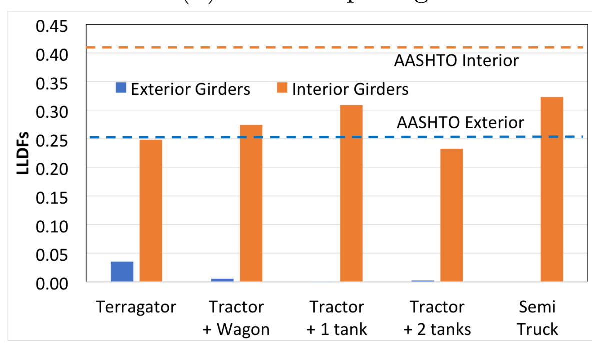
(a) 1.64-ft. Spacing



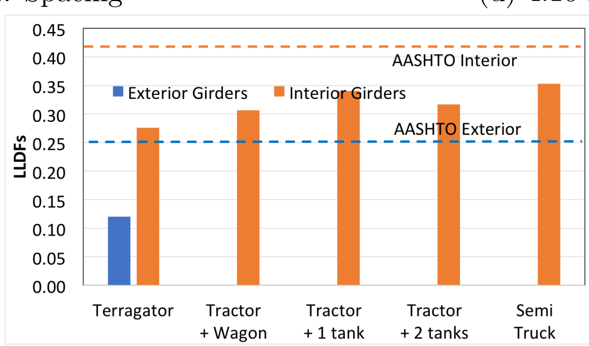
(b) 2.46-ft. Spacing



(c) 3.28-ft. Spacing



(d) 4.10-ft. Spacing



(e) 4.92-ft. Spacing

Figure 4.13: Comparison of the shear LLDFs from the model and AASHTO LRFD values for interior and exterior girders.

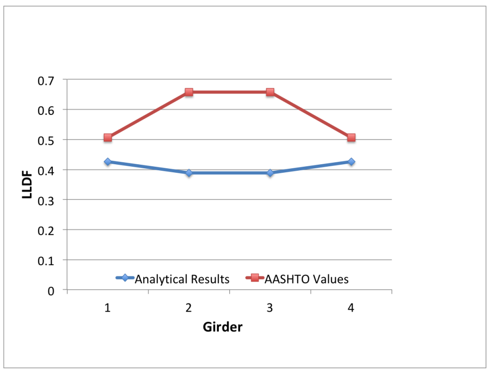
4.1.2 Effects of Number of Girders

The span and width of the simply-supported, steel-concrete bridge was kept constant at 42-ft and 26-ft respectively, while the number of girders was varied between 4, 6, and 9. The bridge with 4 girders had a girder spacing of 8.75-ft, the bridge with 6 girders a girder spacing of 5.25-ft, and the bridge with 9 girders a girder spacing of 3.28-ft. The five agricultural vehicles were tested on all bridge cases and the effect the different numbers of girders had on the LLDFs was observed.

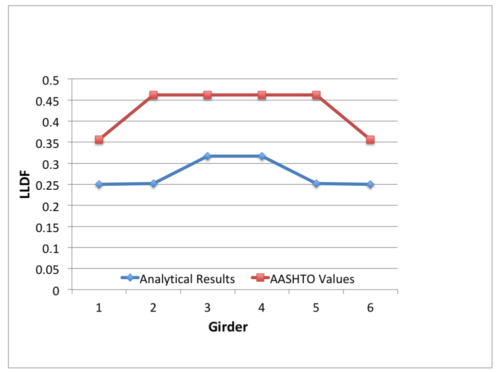
4.1.2.1 Bending Moment LLDFs

In general, it was found from Figures 4.14 to 4.18 that the analytical LLDFs were less than the AASHTO design values when there were fewer girders. For the case with the Terragator shown in Figure 4.14, the bridge with 4 girders had LLDFs less than the AASHTO values and, as expected, the loads were distributed almost evenly between the girders (LLDF=0.41 on average) as shown in Fig. 4.14a. For the bridge with 6 girders, the LLDFs were 30% lower than the AASHTO value for the interior and exterior girders. For example, the maximum LLDF of the bridge with 6 girders was 0.32 while for the bridge with 4 girders, it was 0.39. Once the number of girders increased to 9, the LLDF decreased to 0.29 on the middle girder. The tractor with a grain wagon, with one and two tanks generated lower LLDFs compared to the AASHTO LLDFs as shown in Figures 4.15 to 4.18.

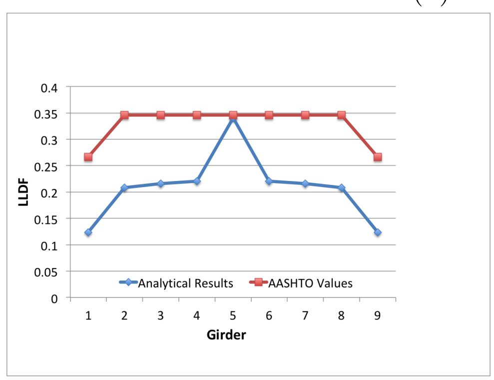
Figure 4.19 shows comparisons between the bending moment LLDFs resulting from the five different vehicles. It can be seen that none of the LLDFs are greater than the AASHTO LLDFs. For most of the different number of girders the LLDF values are comparable between vehicles, but the LLDFs for the interior girders due to the Terragator when there were 9 girders were larger than the semi truck by 70%.



(a) 4 Girders

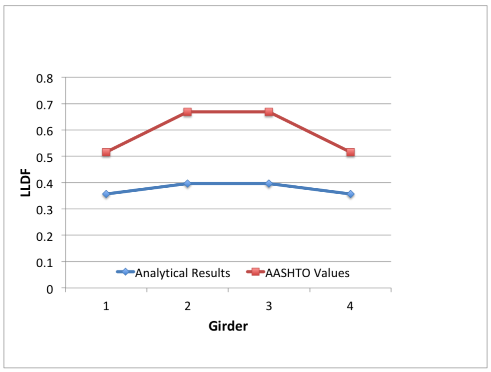


(b) 6 Girders



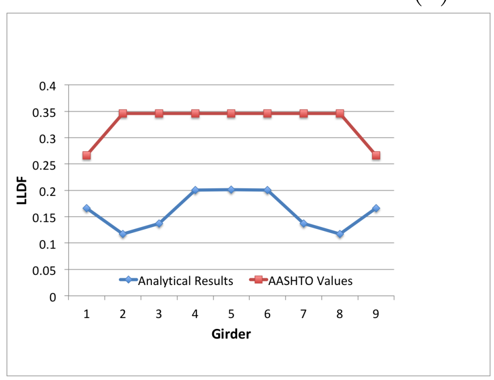
(c) 9 Girders

Figure 4.14: Bending moment load distribution factors due to a Terragator on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



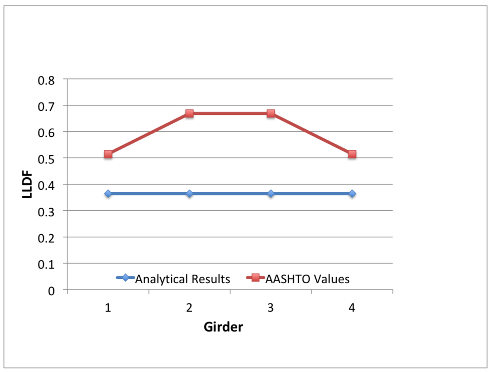
(a) 4 Girders

(b) 6 Girders



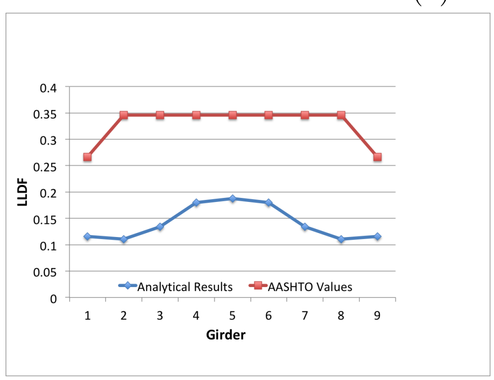
(c) 9 Girders

Figure 4.15: Bending moment load distribution factors due to a tractor with a grain wagon on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



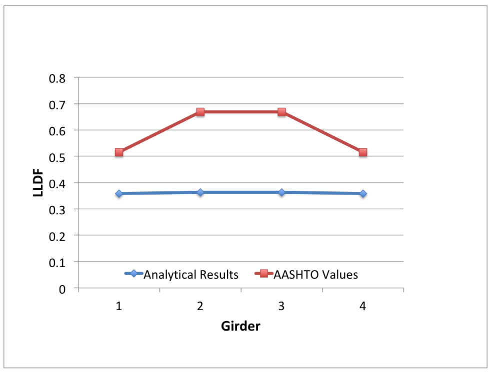
(a) 4 Girders

(b) 6 Girders

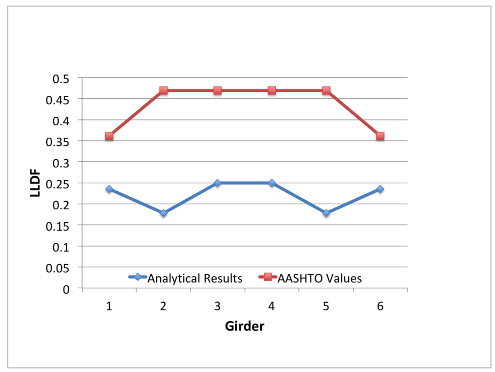


(c) 9 Girders

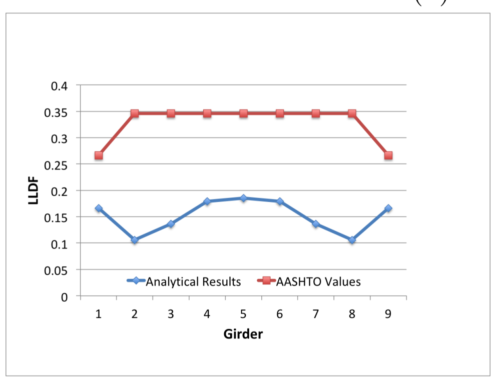
Figure 4.16: Bending moment load distribution factors due to a tractor with 1 tank on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



(a) 4 Girders

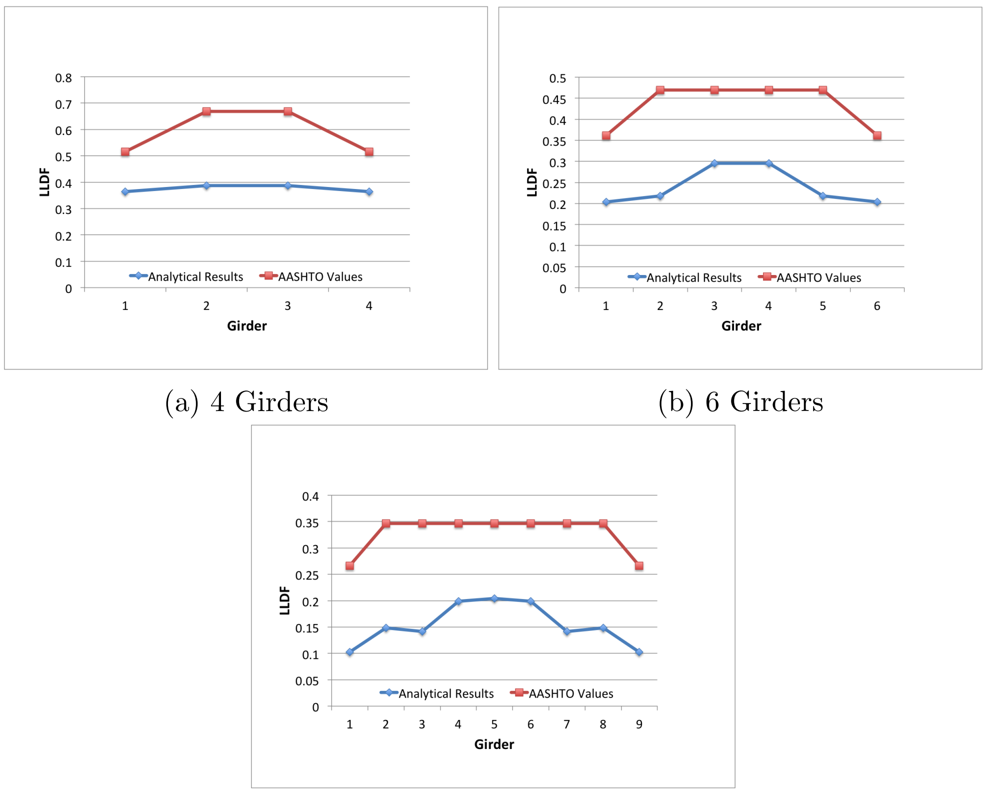


(b) 6 Girders



(c) 9 Girders

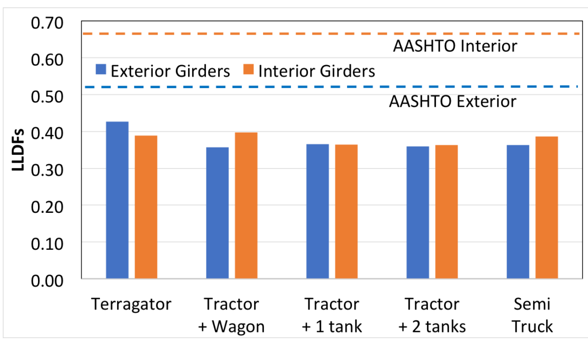
Figure 4.17: Bending moment load distribution factors due to a tractor with 2 tanks on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



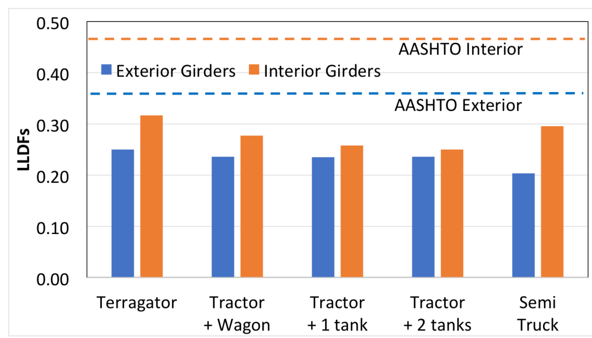
(a) 4 Girders (b) 6 Girders

(c) 9 Girders

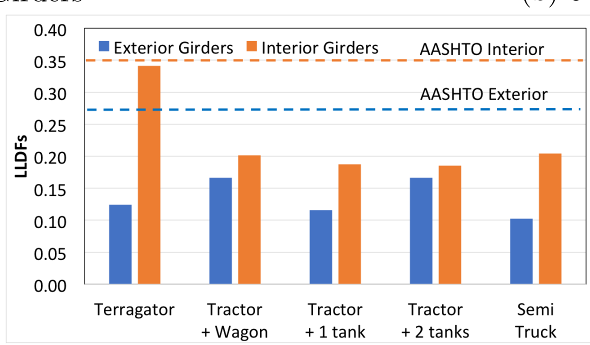
Figure 4.18: Bending moment load distribution factors due to a semi truck on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



(a) 4 Girders



(b) 6 Girders



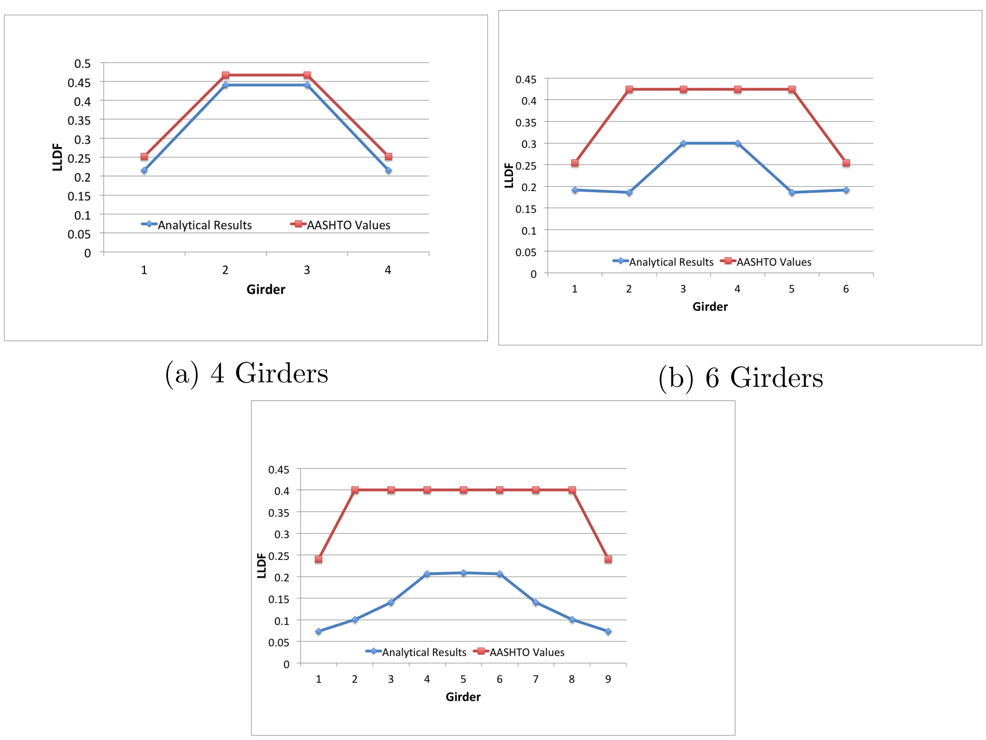
(c) 9 Girders

Figure 4.19: Comparison of the bending moment LLDFs from the model and AASHTO LRFD values for interior and exterior girders for bridges with different numbers of girders.

4.1.2.2 Shear LLDFs

Figures 4.20 to 4.24 show the shear LLDFs resulting from different numbers of girders in a 26-ft wide simply-supported, steel-concrete bridge. All the analytical interior girder results for the bridge with four girders are over or very close to the AASHTO values. The Terragator had lower interior LLDFs than the semi as shown in Figure 4.25. It had much higher exterior shear LLDFs however by 27%, 138%, and 167% for bridges with 4, 6, and 9 girders respectively.

Figure 4.25 shows comparisons between the shear LLDFs resulting from the five different vehicles. For the bridge with 4 girders, the exterior shear LLDFs are all lower than the AASHTO LLDFs. However, the interior LLDFs range from only 5% under the AASHTO LLDFs for the Terragator to 6% over the AASHTO LLDFs for the semi. For most of the different number of girders the LLDF values are comparable between vehicles.

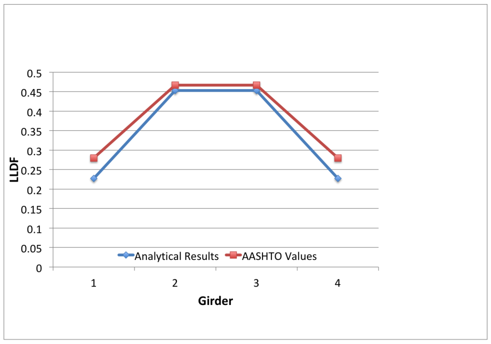


(a) 4 Girders

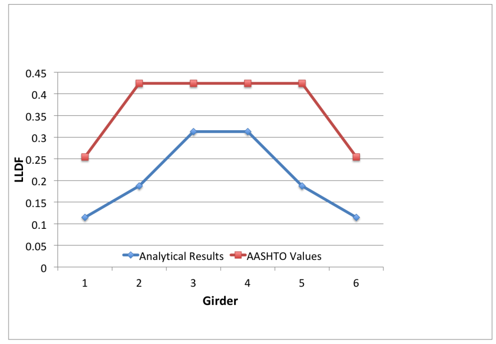
(b) 6 Girders

(c) 9 Girders

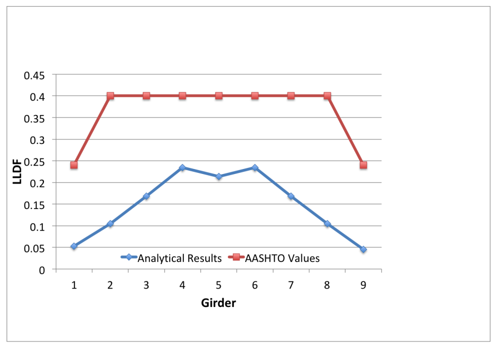
Figure 4.20: Shear distribution factors due to a Terragator on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



(a) 4 Girders

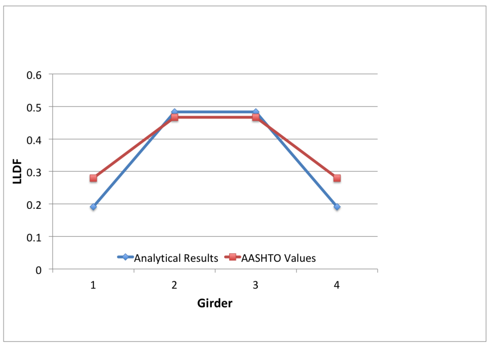


(b) 6 Girders

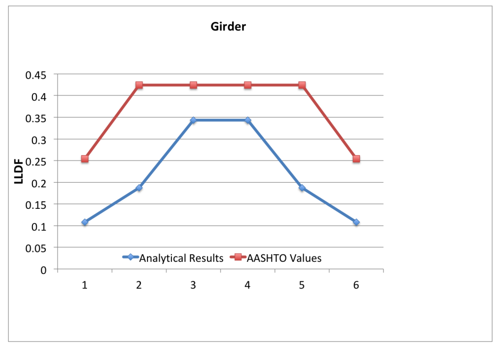


(c) 9 Girders

Figure 4.21: Shear distribution factors due to a tractor with a grain wagon on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



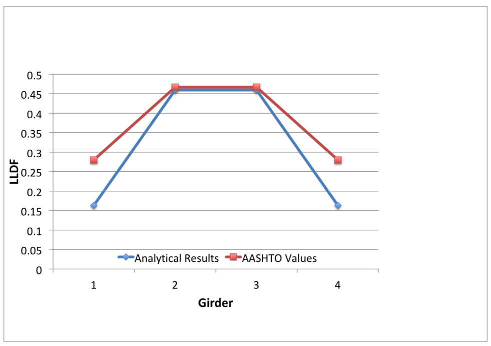
(a) 4 Girders



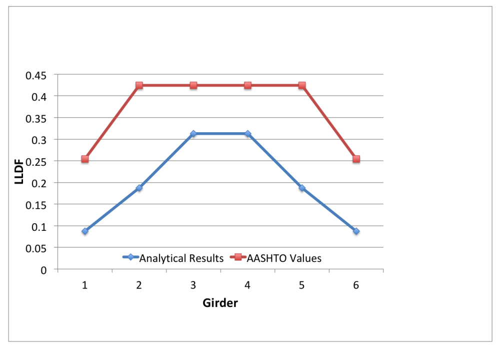
(b) 6 Girders

(c) 9 Girders

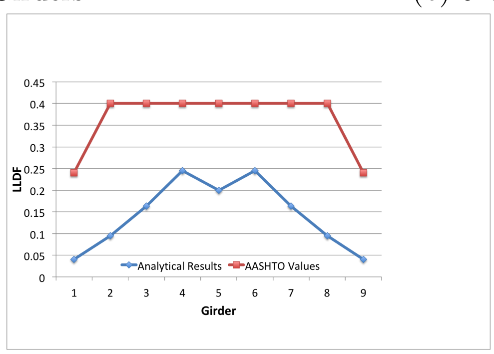
Figure 4.22: Shear distribution factors due to a tractor with 1 tank on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



(a) 4 Girders

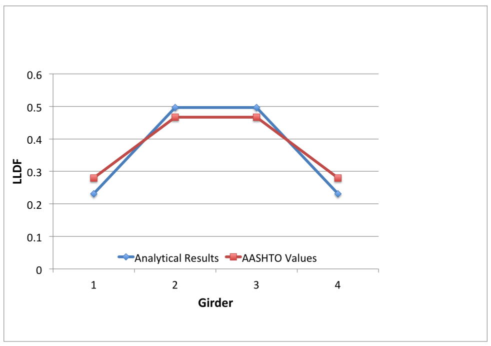


(b) 6 Girders

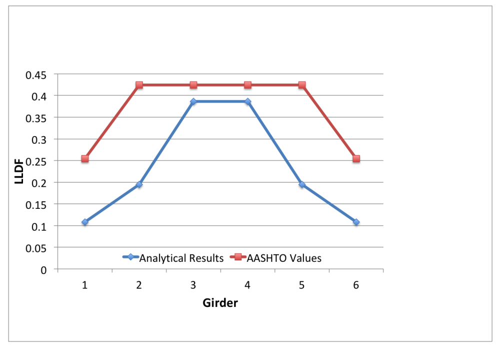


(c) 9 Girders

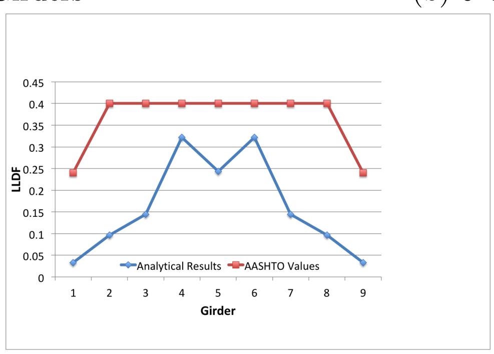
Figure 4.23: Shear distribution factors due to a tractor with 2 tanks on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



(a) 4 Girders

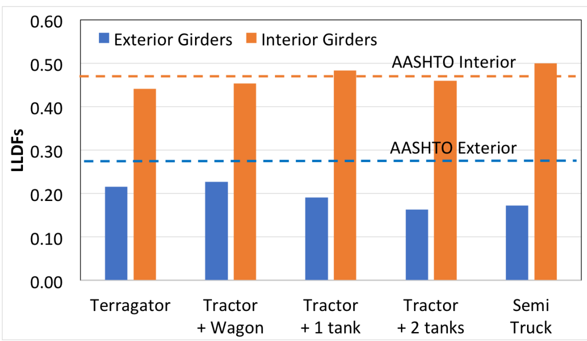


(b) 6 Girders

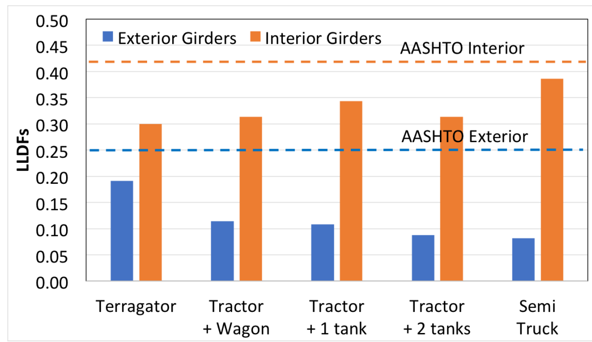


(c) 9 Girders

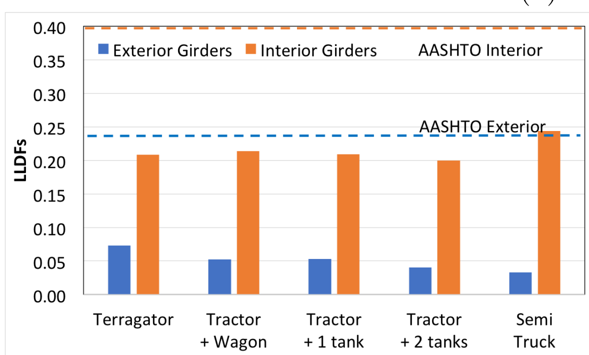
Figure 4.24: Shear distribution factors due to a semi truck on a simply-supported, steel-concrete bridge with a constant span, a constant width, and different numbers of girders.



(a) 4 Girders



(b) 6 Girders



(c) 9 Girders

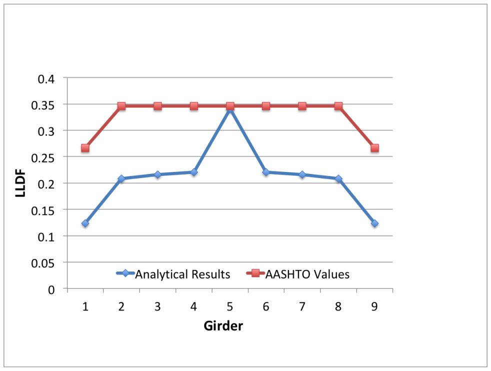
Figure 4.25: Comparison of the shear LLDFs from the model and AASHTO LRFD values for interior and exterior girders for bridges with different numbers of girders.

4.1.3 Effects of Vehicle Speed

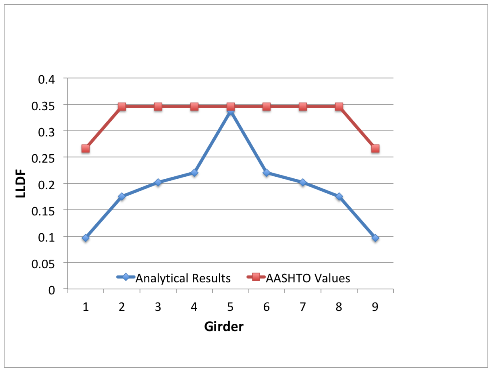
The speed of the vehicles was varied from 2 mph to 22 mph while the bridge itself was kept consistent in terms of width, number of girders, etc. The bridge had a 42-ft span and had 9 girders spaced 3.3-ft apart with a total width of 26-ft. The effect of dynamic impact was not taken into account.

4.1.3.1 Bending Moment LLDFs

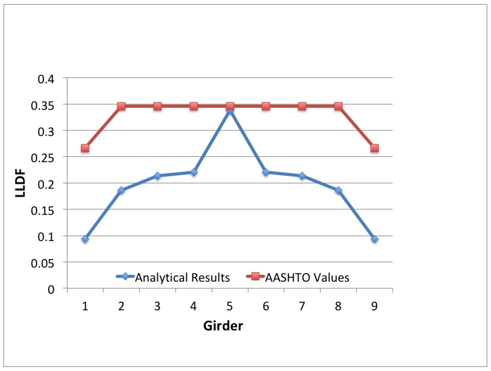
The speed of the vehicles did not drastically alter any of the values of the LLDFs due to the vehicles themselves. The AASHTO LRFD Specifications do not take into consideration vehicle speed as a factor for determining LLDFs.



(a) 2 mph

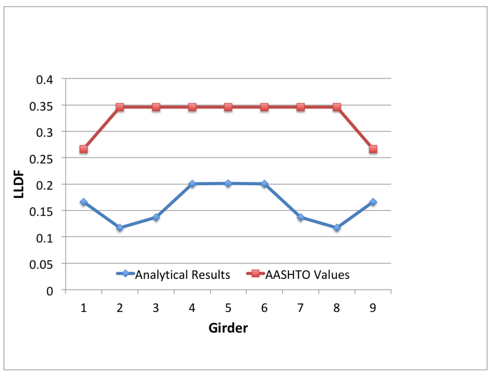


(b) 11 mph



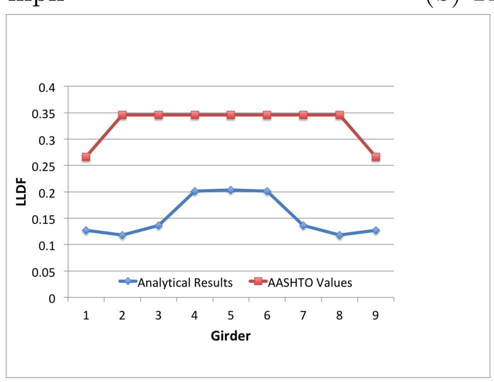
(c) 22 mph

Figure 4.26: Bending moment load distribution factors due to a Terragator on a simply-supported, steel-concrete bridge with different vehicle speeds.



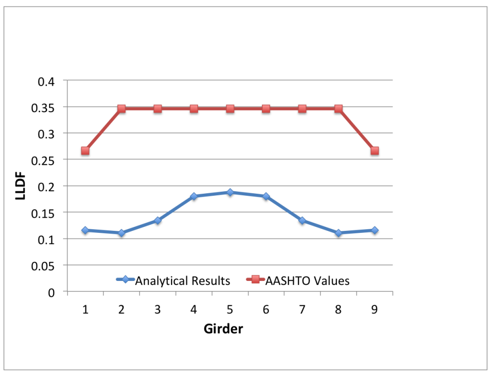
(a) 2 mph

(b) 11 mph

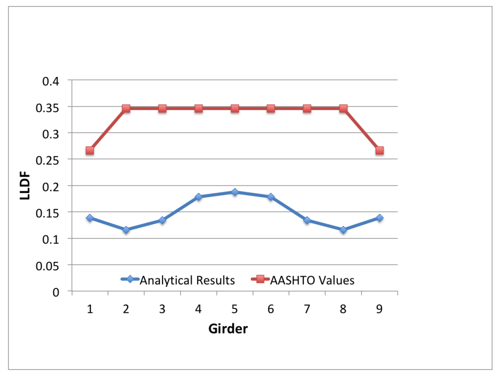


(c) 22 mph

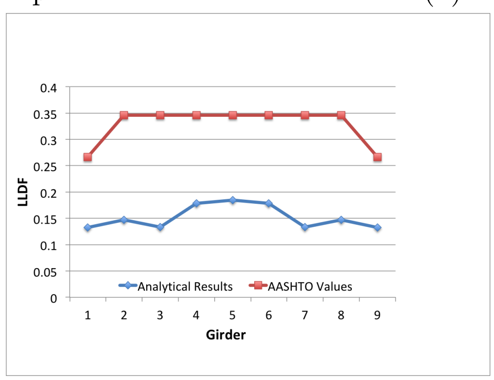
Figure 4.27: Bending moment load distribution factors due to a tractor with a grain wagon on a simply-supported, steel-concrete bridge with different vehicle speeds.



(a) 2 mph

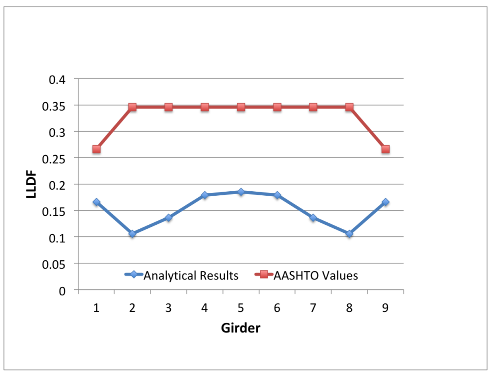


(b) 11 mph

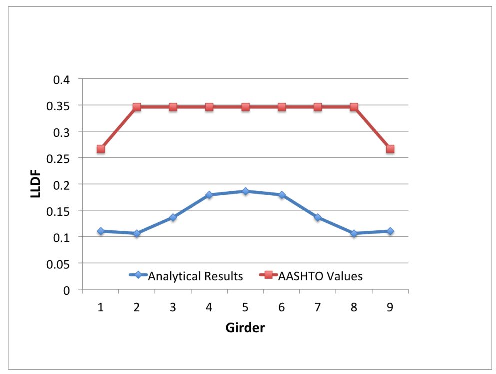


(c) 22 mph

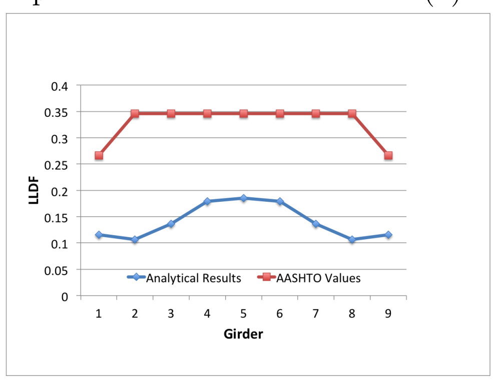
Figure 4.28: Bending moment load distribution factors due to a tractor with 1 tank on a simply-supported, steel-concrete bridge with different vehicle speeds.



(a) 2 mph

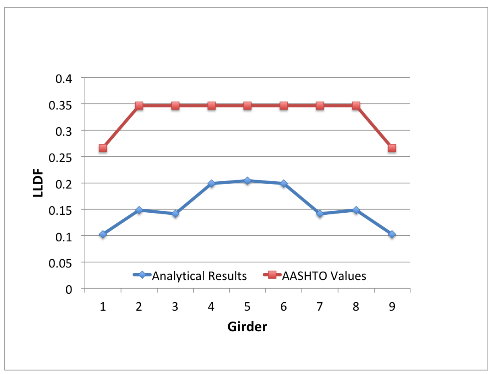


(b) 11 mph

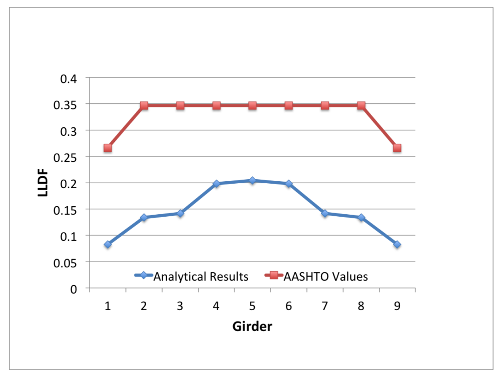


(c) 22 mph

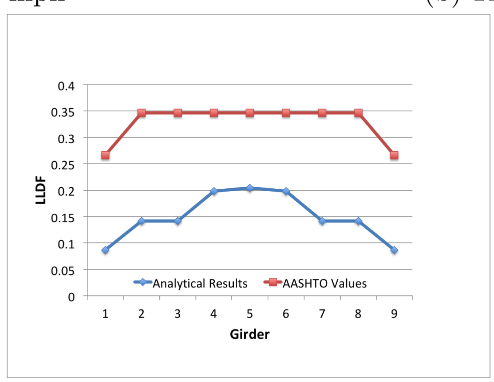
Figure 4.29: Bending moment load distribution factors due to a tractor with 2 tanks on a simply-supported, steel-concrete bridge with different vehicle speeds.



(a) 2 mph



(b) 11 mph

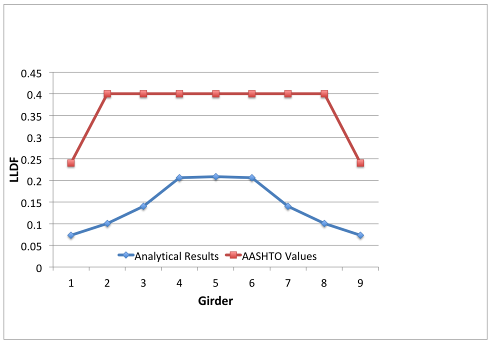


(c) 22 mph

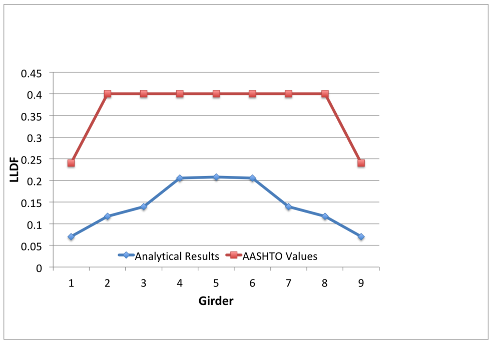
Figure 4.30: Bending moment load distribution factors due to a semi truck on a simply-supported, steel-concrete bridge with different vehicle speeds.

4.1.3.2 Shear LLDFs

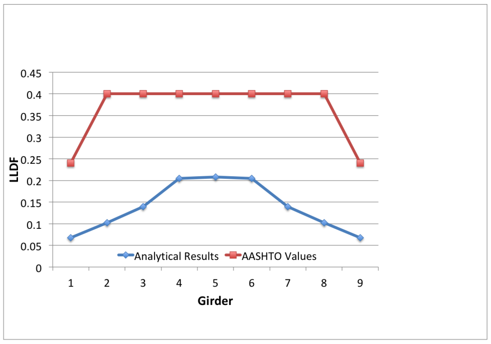
As with the bending moment LLDFs, the speed did not drastically alter shear LLDFs and all the LLDFs were below the AASHTO values as shown in Figures 4.31 to 4.35.



(a) 2 mph

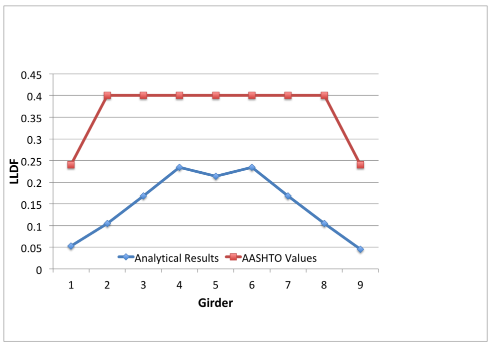


(b) 11 mph

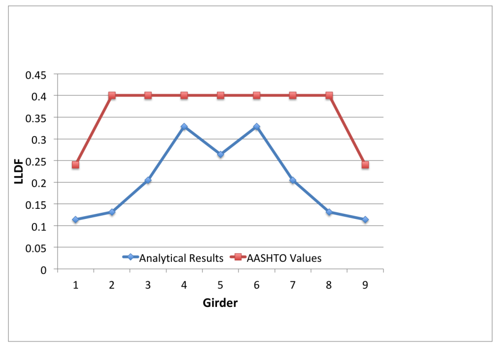


(c) 22 mph

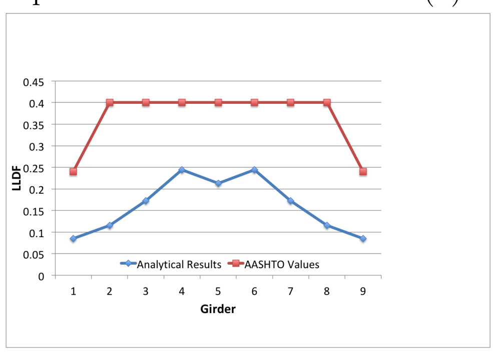
Figure 4.31: Shear distribution factors due to a Terragator on a simply-supported, steel-concrete bridge with different vehicle speeds.



(a) 2 mph

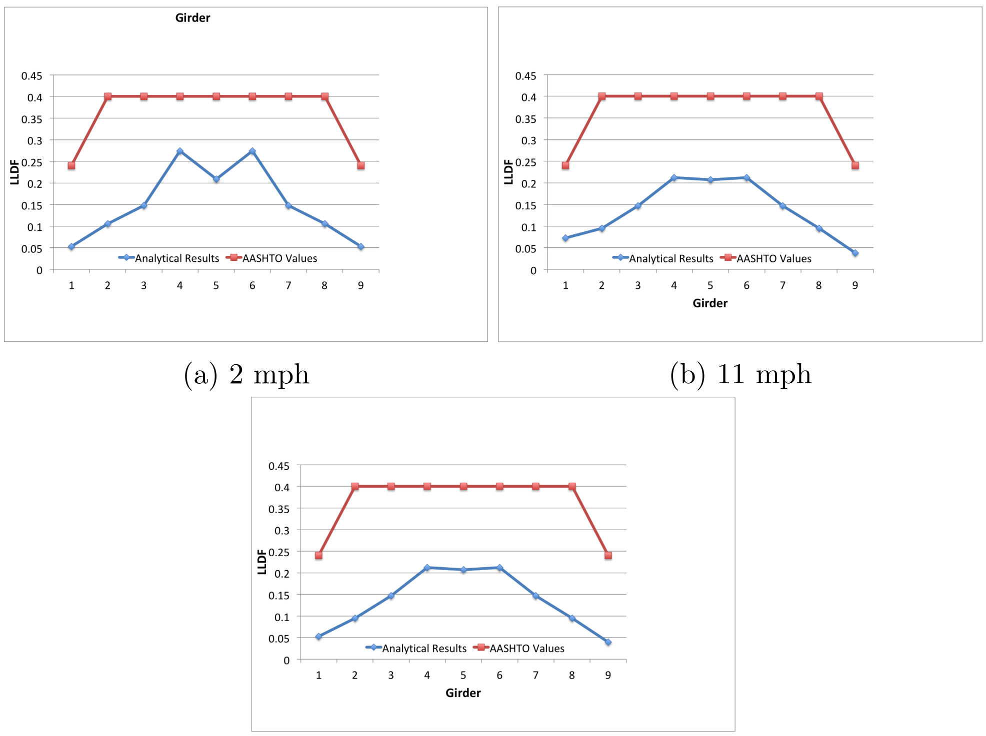


(b) 11 mph



(c) 22 mph

Figure 4.32: Shear distribution factors due to a tractor with a grain wagon on a simply-supported, steel-concrete bridge with different vehicle speeds.

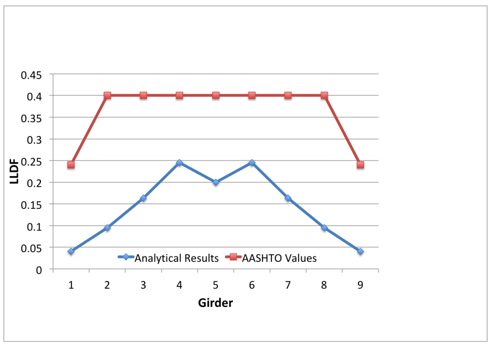


(a) 2 mph

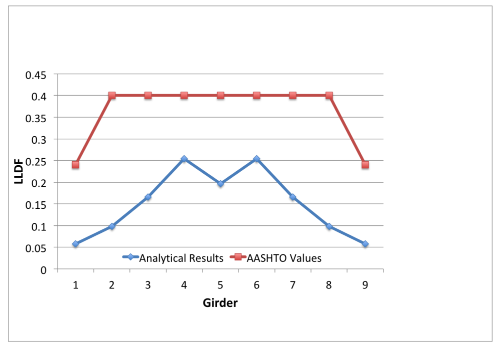
(b) 11 mph

(c) 22 mph

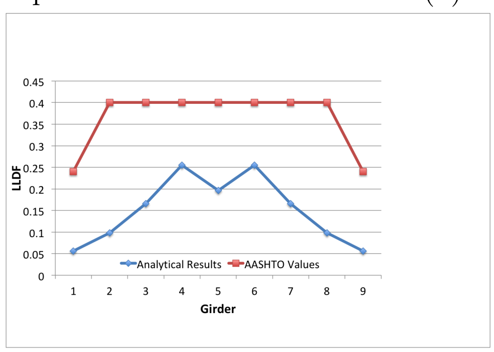
Figure 4.33: Shear distribution factors due to a tractor with 1 tank on a simply-supported, steel-concrete bridge with different vehicle speeds.



(a) 2 mph

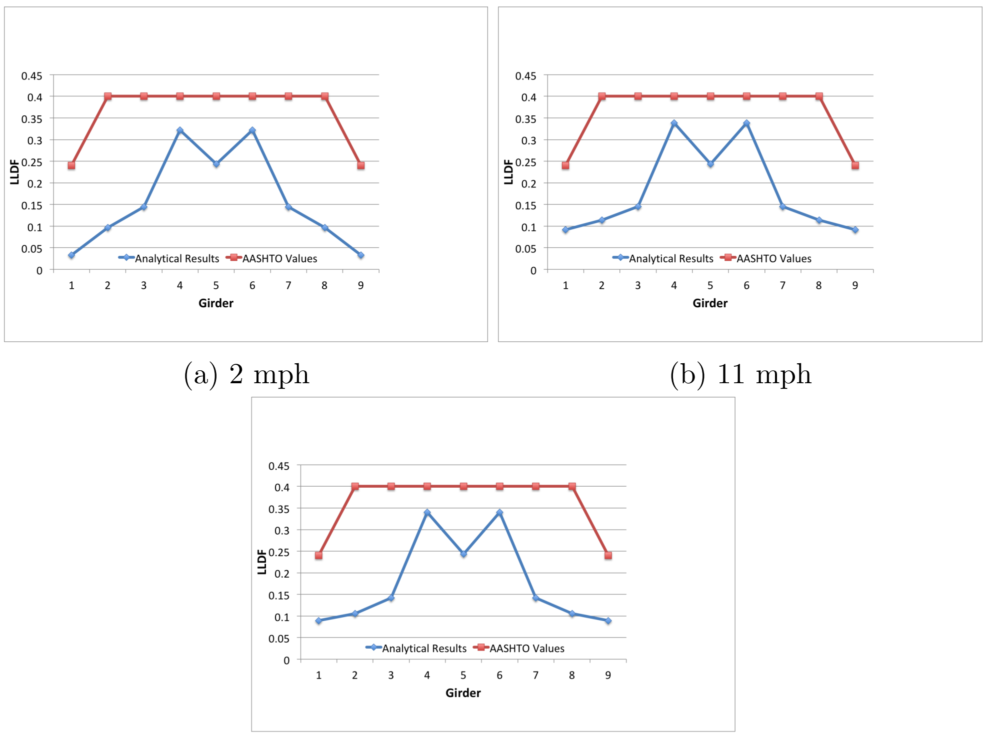


(b) 11 mph



(c) 22 mph

Figure 4.34: Shear distribution factors due to a tractor with 2 tanks on a simply-supported, steel-concrete bridge with different vehicle speeds.



(a) 2 mph (b) 11 mph

(c) 22 mph

Figure 4.35: Shear distribution factors due to a semi truck on a simply-supported, steel-concrete bridge with different vehicle speeds.

Chapter 5: Summary and Conclusions

Live Load Distribution Factors (LLDFs) for steel girder bridges loaded with different agricultural vehicles and a highway vehicle were investigated and determined based upon the methods to determine LLDF provided by the AASHTO LRFD specifications and Finite Element Analysis (FEA) model simulations. The vehicles used for the testing were four agricultural vehicles that are common in the state of Idaho and one five-axle semi truck representing a conventional highway truck. The finite element analysis results were verified by available field test results in the literature. Analytical models were created using commercially available FEA based software SAP2000. A parametric study was performed on a steel-concrete composite bridge. The girder spacing was varied from 1.64-ft to 4.96-ft, the number of girders from 4 to 9, and the speed of the vehicles from 2 mph to 22 mph. All resulting analytical bending moment and shear LLDFs were compared with those resulting from the AASHTO LRFD methods based on which the following conclusion were drawn.

- For most of the girder spacings and vehicle types, both the bending moment and shear analytical LLDFs values were lower than the design values, however, the Terragator created a higher (4%) bending moment LLDF on the middle girder at smaller spacings than the values obtained from AASHTO design code.

- When the spacing between girders increased, the Terragator showed the same LLDF for the middle girder, and at spacings of 4.10-ft and 4.92-ft, the LLDFs were less than the AASHTO values by 57% and 56% and, respectively. For all other vehicles, the LLDFs were less compared to the AASHTO values.

- It is also observed that the LLDFs for the exterior and interior girders due to Terragator with a very small girder spacing of 1.64-ft were higher than the semi truck by 88%, and 62%, respectively. Similar observations were obtained when

Table 5.1: Comparison of moment LLDFs induced by a Terragator for a steel-concrete bridge with 3.28-ft girder spacing.

	Analytical Results	AASHTO LRFD	AASHTO Standard	Literature (Seo et al.)
Interior Girder LLDFs	0.34	0.35	0.30	0.25
Exterior Girder LLDFs	0.12	0.27	0.30	0.15

Table 5.2: Comparison of moment LLDFs induced by a grain wagon for a steel-concrete bridge with 3.28-ft girder spacing.

	Analytical Results	AASHTO LRFD	AASHTO Standard	Literature (Seo et al.)
Interior Girder LLDFs	0.20	0.35	0.30	0.18
Exterior Girder LLDFs	0.17	0.27	0.30	0.16

girder spacing was increased to 2.64-ft and 3.28-ft The LLDFs for the interior girders due to the Terragator were larger than the semi truck by 70%.

- When there were only a few number of girders the exterior LLDFs resulting from all the vehicles were very close to the AASHTO LLDFs, ranging from just 5% below to 6% higher than the AASHTO LLDFs.
- The speed of the vehicles had no significant impact on the LLDFs of the bridges.
- It is recommended to perform field tests to investigate the effect of the agricultural vehicles on the various bridges in Idaho under multiple key parameters such as girder material types (timber, concrete, etc.), and girder spacing and configurations.

Table 5.3: Comparison of moment LLDFs induced by a semi truck for a steel-concrete bridge with 3.28-ft girder spacing.

	Analytical Results	AASHTO LRFD	AASHTO Standard	Literature (Seo et al.)
Interior Girder LLDFs	0.20	0.35	0.30	0.19
Exterior Girder LLDFs	0.10	0.27	0.30	0.16

Table 5.4: Comparison of shear LLDFs induced by a Terragator for a steel-concrete bridge with 3.28-ft girder spacing.

	Analytical Results	AASHTO LRFD
Interior Girder LLDFs	0.21	0.40
Exterior Girder LLDFs	0.07	0.24

Table 5.5: Comparison of shear LLDFs induced by a tractor with a grain wagon for a steel-concrete bridge with 3.28-ft girder spacing.

	Analytical Results	AASHTO LRFD
Interior Girder LLDFs	0.23	0.40
Exterior Girder LLDFs	0.05	0.24

Table 5.6: Comparison of shear LLDFs induced by a semi truck for a steel-concrete bridge with 3.28-ft girder spacing.

	Analytical Results	AASHTO LRFD
Interior Girder LLDFs	0.32	0.40
Exterior Girder LLDFs	0.03	0.24

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