RURAL BRIDGE SAFETY: EVALUATION OF ATYPICALLY LARGE FARM VEHICLES

FINAL PROJECT REPORT

by

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16. Abstract

The Pacific Northwest region has no data on the assessment of and recommendations for the safety design of rural bridges subjected to farm vehicle (FV) loading. The study determined how different types of FVs with different characteristics distribute their loads on bridge superstructures. The study was conducted through computer simulation using the finite element method. The selected bridges were representative of rural bridges subject to FV traffic in the region. The live load distribution factors (LLDFs) due to shear and moments for interior and exterior girders under critical loading conditions were determined. The computer models were verified using field data to explore a broad number of bridge cases under various FV loads and key parameters. is the authors concluded that some of the FVs, such as the Terragator, resulted in more loads on the exterior and interior girders. For example, the Terragator produced LLDFs higher than the design load distribution factors obtained from the AASHTO LRFD, and from the standard highway truck being used for bridge design. It is recommended that farming states pay attention to increases in FV loads and bridge weight limits, especially under such loading or to generate specific farming vehicles' signage, to ensure the safety of rural bridges. It is also recommended that the effects of FVs on the live load distribution factors for rural bridges be addressed by AASHTO. The authors also suggest that DOTs and local jurisdictions consider posting special signage for rural bridges that carry farm vehicles.

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Acronyms and Abbreviations

AASHTO: American Association of State Highway and Transportation Officials
FEM: Finite element method
FFA: Finite element analysis
FV: Farm vehicle
LLDF: Live load distribution factors
LRFD: Load and resistance factor design
ITD: Idaho Department of Transportation
PacTrans: Pacific Northwest Transportation Consortium
SCF: Skew correction factors

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Executive Summary

The Pacific Northwest region has no data on the safety design of rural bridges subjected to farm vehicle (FV) loading. This study determined how different types of FVs with different characteristics distribute their loads on rural steel-concrete bridge superstructures. The study was conducted through computer simulation using the finite element method. The selected bridges were representative of rural bridges subject to FV traffic in the region. Load distribution factors due to shear and moments for interior and exterior girders under critical loading conditions were determined. The computer models were verified with field data to explore a broad number of bridges under various FV loads and key parameters.

There were 614,387 bridges in the United States as of 2017 (ASCE 2017). A large portion of these bridges are rural bridges. Rural transportation systems are a key factor in food supply chains; however, approximately 13 percent of rural bridges are considered structurally deficient, and 10 percent more are functionally obsolete (Orr 2012). Many vehicles that travel on these rural road systems are agricultural vehicles. These vehicles are designed for use on farms but also often travel on roadways. Agricultural vehicles can have vastly different wheel spacings, footprints, and axle weights than other vehicles. Because of this, they very likely cause different effects on bridges than vehicles on which the AASHTO Load and Resistance Factor Design (LRFD) specification are based. There are currently no standards to determine how to design for agricultural vehicles.

A finite element model of a steel-concrete girder bridge was generated and validated in order to determine the live load distribution factors produced by 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 standard

highway vehicle. The parametric study was performed to observe the differences and distributions of live loads that might affect a variety of bridges. The spacing of the girders, number of girders, and speed of the vehicles were considered key factors for the aforementioned vehicle types.

For most of the girder spacings and vehicle types, the analytical moment live load distribution factor (LLDF) values were lower than the AASHTO design values. However, the Terragator created a higher (4 percent) moment LLDF on the interior girder for bridges with smaller girder spacing than the values recommended by AASHTO code. The moment LLDFs for exterior girders (spacing=1.64t.) was higher than the AASHTO values by 67 percent. When the spacing between girders increased to 3.26 ft., the Terragator showed the same moment LLDF for the middle girder. For bridges with girder spacings of 4.10 ft. and 4.92 ft., the moment LLDFs were less than the AASHTO values by 57 percent and 56 percent, respectively. For all other vehicles, the moment LLDFs were less than the AASHTO LRFD values.

We also observed that the moment LLDFs due to the Terragator for the exterior and interior girders (girder spacing= 1.64 ft.) were higher than the highway standard truck by 88 percent and 62 percent, respectively. Similar observations were obtained when girder spacing was increased to 2.64 ft. and 3.28 ft., for which the LLDFs due to the Terragator were larger for the interior girders than the those due to a standard highway truck by 70 percent on average.

The Terragator produced significant increases in LLDFs for the exterior girders for bridges with four (17 percent), six (24.7 percent), and nine (93.6 percent) girders. However, for the interior girders, for the bridge with four girders there was no significant difference between the numerical analysis LLDFs and the AASHTO values. However, for bridges with six and nine girders, the Terragator produced higher LLDFs (5 percent and 43 percent, respectively) than the standard truck case.

The shear LLDFs due to the Terragator for the exterior and interior girders (girder spacing= 1.64 ft.) were higher than those produced by the highway standard truck by 27 percent, and 9 pecent, respectively. The Terragator produced higher LLDFs for the exterior girders for bridges with four (27 percent), six (237 percent), and nine 267 percent) girders. The researchers recommend field tests to investigate the effects of agricultural vehicles on various bridges in Idaho under multiple key parameters, such as girder material type (timber, concrete, etc.), girder spacing, and other configurations. Overall, the speed of the vehicles had no significant impact on the shear of the moment LLFDs of the bridges

In conclusion, some of the FVs, such as the Terragator, produced more loads on the exterior and interior girders of steel-concrete bridges. State departments of transportation and local highway jurisdictions should pay attention to rural bridges that are exposed to frequent farming vehicle traffic by posting FV weight limit signs.

Introduction

Bridges are usually designed and evaluated with live load distribution factors (LLDFs). These LLDFs are generally defined as the ratio of the effect of maximum live load in a bridge girder to the effect of the maximum live load in all the bridge girders when the truck is located at a certain location along the bridge. The American Association of State Highway and Transportation Officials (AASHTO) has provided methods to determine LLDFs for different types of bridges. The LLDFs are based on the shear and moments that a typical highway vehicle places on a bridge. LLDFs quantify how much live load a girder must be able to hold. If the LLDFs are estimated too high, the bridge is considered overdesigned, and if they are too low, then the bridge may not be able to carry the weight required (Eom and Nowak 2006). Although values obtained from the AASHTO specifications tend to be conservative for typical highway vehicles, there is not much 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 loadings than typical standard highway vehicles.

1.1 Problem Statement

There were 614,387 bridges in the United States as of 2017 (ASCE 2017). A large portion of those bridges are rural bridges. The rural transportation system is a key factor in food supply chains; however, approximately 13 percent of rural bridges are considered structurally deficient, and 10 percent more are functionally obsolete (Orr 2012).

Many vehicles that travel on rural road systems are agricultural vehicles. These vehicles are designed for use on farms but also often travel on some roadways. Agricultural vehicles can have vastly different wheel spacings, footprints, and axle weights than other vehicles. Because of this, they very likely cause different effects on bridges than the vehicles on which the AASHTO

Load and Resistance Factor Design (LRFD) specifications are based. There are currently no standards or recommendations to determine how to design for agricultural vehicles.

1.2 Objectives

The overall objective of the study presented herein was to evaluate the live load distribution factor provisions in the AASHTO LRFD manual for steel bridge girders under farm agricultural vehicle loadings. The goal of this study was to perform an analysis using the finite element method (FEM). A review of provisions for LLDFs in the AASHTO LRFD bridge design manual for steel–concrete girder bridges was conducted, and the LLDF factors obtained from using the FEM were compared.

1.3 Methodology

A finite element model for a steel-concrete girder bridge was created and validated to determine the live load distribution factors for 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 standard highway vehicle. The parametric study was performed to observe the differences and distributions of live loads that might affect a variety of bridges. The spacing of girders, number of girders, and speed of vehicles were considered key factors in combination with the aforementioned vehicle types.

1.3 Organization of the Report

This report examines the LLDFs of steel girder bridges under different types of agricultural vehicle loading. The report is divided into five chapters. Chapter 2 summarizes previous work performed and 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 for the vehicles and bridges used are detailed in

Chapter 3, along with the FEM model used. Chapter 4 describes the results obtained from the finite element simulation. The analytical values obtained are compared to the values recommended by using AASHTO specifications. Lastly, Chapter 5 summarizes the results and conclusions.

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 farming vehicles (FVs). The FVs have various 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/standard design" vehicle, generally a standard 80,000-lbs. truck. Farm vehicles, such as farm equipment and trucks carrying different agriculture 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 for farm vehicles. Severe damage and failure of rural bridges as a result of FV loading have been reported in the literature, as shown in figure 2.1.

Figure 0.1 Bridge failures initiated by farm vehicles (Phares et al. 2005)

The current American Association of State Highway and Transportation Officials (AASHTO) code of practice does not specifically address FVs as a separate category of vehicles and does not consider the effects of their heavy loads on fewer axles or their operational characteristics in design codes. Weigh-in-motion live load data from millions of trucks indicate that live load is strongly site-specific. Therefore, the AASHTO code provides an option to choose live load factors that are different than those listed in the code. As a consequence, the study of the influence of FV loads on rural bridges is a local phenomenon and warranted for the Pacific Northwest region. Truck weigh-in-motion data indicate that Pacific Northwest farm vehicles are getting larger, causing unanticipated loads on local rural and off-road bridges. However, recommendations for the size and weight of FVs to ensure the safety of off-road bridges are limited. One of the major problems with FV loading is that the gross load is distributed over a relatively few number of axels, with gross weight that might be over 100,000 lbs., well over the 80,000-lbs average design gross load of conventional trucks.

Currently, bridge load limits are based on semi-trucks, not farm vehicles, which have different axle configurations and wheel dimensions. “Their geometry is atypical; their length, widths are different; they have different suspension characteristics,” explained Brent Phares, director of the Bridge Engineering Center at Iowa State University. “The implements of husbandry will help limit the confusion of current load posting signs for farmers,” said Minnesota Department of Transportation bridge load rating engineer Moises Dimaculangan.

The farming industry has grown since 1993, which has led to use of larger FVs. Furthermore, when harvest season starts, grain wagons are typically used to transport crops. These vehicles were exempted from size, weight, and load provisions on all roads except interstates in a law passed 14 years ago. Wood and Wipf (1999) tested four timber bridges to examine the influence of FV loading on rural bridges (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 the tire of a grain cart. The study ignored the effects of impact (dynamic) and multiple lane loads and assumed that the lateral load distribution for FVs and standard trucks were the same. This work indicated that FVs caused demands greater than those considered during design and increased the likelihood of damage or failure.

In Minnesota, FVs have punched through the deck slab of a bridge, and most bridge failures have been related to two failure modes: bending and punching, as shown in figure 2.2, (Rholl, 2004). Rholl (2004) 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 FVs and the standard design vehicle could be compared, as shown in figure 2.2. Several FV configurations produced punching shear conditions exceeding the values obtained from the design vehicles. Seo, et al. (2013) investigated the effects of FVs 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 by using strain gages mounted on the bottom flanges of the girders. The FVs were driven across all bridges at a very slow speed while the response of the girders was recorded. The study indicated that the distribution factors for a Terragator were higher than the AASHTO design values.

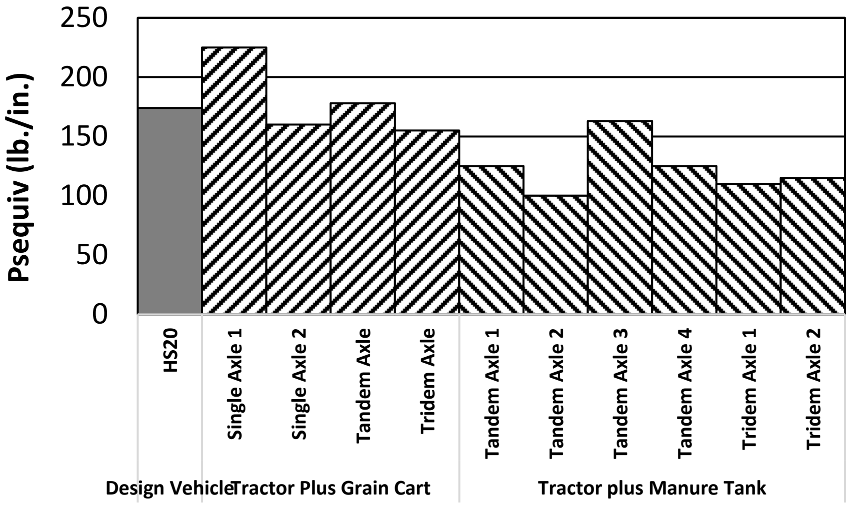


Figure 0.2 Bridge deck punching condition: design vehicles, grain carts, and manure tank implements. (Phares et al. 2005)

Collapses of rural bridges have been observed in conjunction with agricultural loads (Stachura 2007, Nixon 2012). A report published by Iowa DOT observed that 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 loads and gross weights. However, vehicles that carry heavy loads on fewer axles, such as grain carts and liquid manure tanks, create significantly more stress on bridges than commercial vehicles (see figure 2.3), which can shorten the service life of a bridge and can cause visible and hidden damages (Iowa DOT 2015).

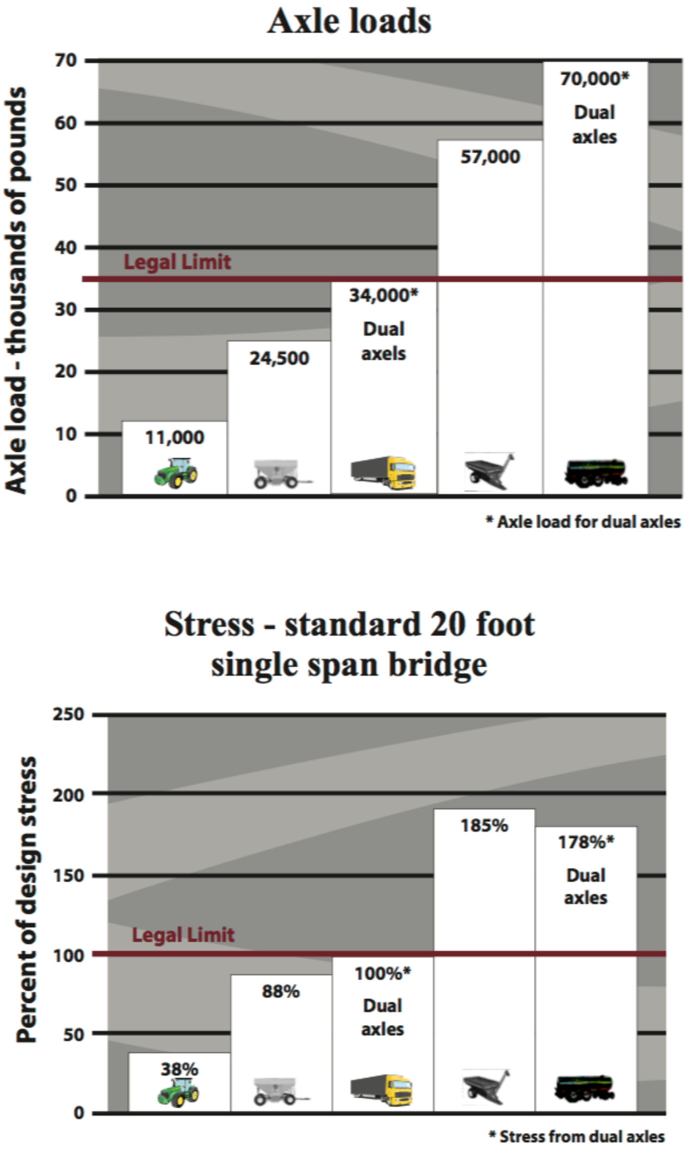


Figure 0.3 The axle loads and stress on a bridge due to certain types of agricultural vehicles can be many times t due to a typical highway vehicle (Iowa DOT 2015)**.**

Seo et al. (2014) 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 highway truck, as well as analytically tested with over 120 agricultural vehicles, to determine the effects on the live load distribution factors (LLDFs). The results indicated that the LLDFs were sensitive to different farm 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 (Seo et al. 2014).

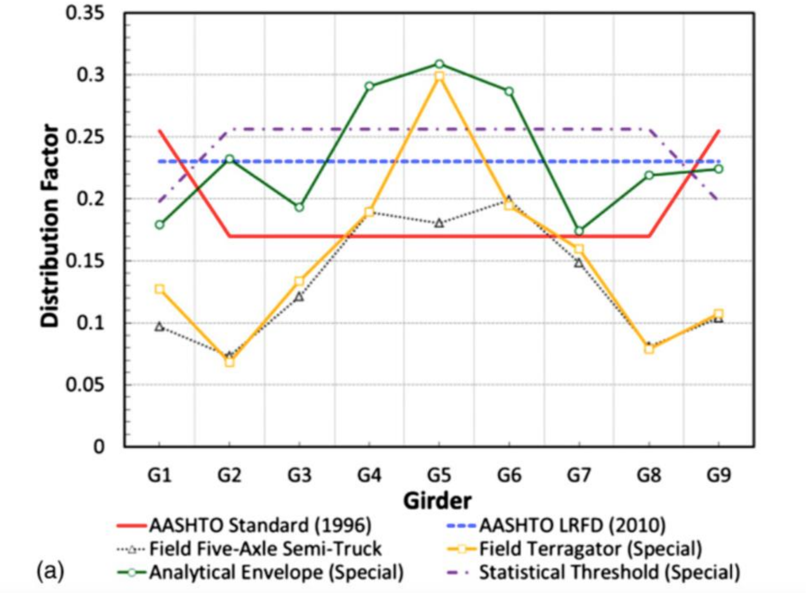


Figure 0.4 Envelope functions of special farm vehicle-induced distribution factors for a steel-concrete bridge (Seo et al. 2014)

Seo et al. (2015) 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 (Seo et al. 2015).

Bending moment distribution factors for steel girder bridges were developed by Tarhini et al. (1992), and the study concluded that the live load distribution factors for agriculture vehicles were lower than those obtained from the AASHTO specifications.

2.2 Pavements and Roads

It is widely believed that agricultural vehicles play a significant role in the degradation of rural roads for three reasons: vehicles exceed the 20,000-lb single-axle weight limit; wide tire spacing places heavy loads on pavement edges; and vehicles move slowly, increasing the load duration and creating rutting (Oman et al. 2001).

In 1999 Wood and Wipf studied the effects of a heavily loaded grain cart on a section of 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 there were a few instances in which the tension stress level exceeded the concrete rupture strength (Wood and Wipf 1999).

A study conducted by Sebaaly (2003) observed the impacts of various agricultural vehicles on pavements in comparison to those of an 18,000-lb single-axle truck. They found that one trip of an empty Terragator, a farm 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 worse than that of a standard truck, a legally loaded grain cart was 77 to 240 times worse, and an overloaded grain cart was 264 to 799 times worse(Sebaaly 2003).

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 the bridge is considered overdesigned, and if they are too low then the bridge may not be able to carry the weight required (Eom and Nowak 2006).

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 (1993) derived an equation to determine moment distribution factors using field data:

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

where g_i = flexure distribution factor of the ith girder

E = modulus of elasticity

$S_{t,i}$ = section modulus of the ith girder at time t

$\varepsilon_{t,i}$ = strain at time t at the ith girder

$M_{t,i}$ = bending moment at time t at the ith girder

j = number of girders

2.3.2 AASHTO Standard Specifications

AASHTO has provided specifications to determine LLDFs for bridges (AASHTO 1996, AASHTO 2010). The AASHTO standard code bases the calculations for LLDFs on a function of girder spacing, S, and bridge type (AASHTO 1996). These are easy to use but are often unnecessarily conservative (Eom and Nowak 2001). The AASHTO Standard Specifications for interior girders are given below.

For steel-concrete bridges:

$$LLDF_{single\ lane} = \frac{S}{7.0} \tag{2.1a}$$

$$LLDF_{multiple\ lane} = \frac{S}{5.5} \tag{2.1b}$$

where S = girder spacing (ft.)

For steel-timber bridges:

$$LLDF_{single\ lane} = \frac{S}{4.5} \tag{2.2a}$$

$$LLDF_{multiple\ lane} = \frac{S}{4.0} \tag{2.2b}$$

where S = girder spacing (ft.).

For timber-timber bridges:

$$LLDF_{single\ lane} = \frac{S}{4.0} \tag{2.3a}$$

$$LLDF_{multiple\ lane} = \frac{S}{3.75} \tag{2.3b}$$

where S = girder spacing (ft.).

The AASHTO Standard equations are based on axle loads and must therefore be divided by a factor of 2 in order to compare them with the LRFD specifications and analytical LLDFs (Eom and Nowak 2006).

2.3.3 AASHTO LRFD Specifications

The AASHTO LRFD specifications take into account bridge geometries and other factors and are more sophisticated than the standard specifications (AASHTO 1998). LLDFs are determined by using LRFD specifications and generally considered to be more consistent than those determined by using Standard Specifications, particularly for bridges with long spans (Eom and Nowak 2001). The AASHTO LRFD Specifications for the interior girders are given below.

For interior girders of steel-concrete bridges:

$$LLDF_{single\ lane} = 0.06 + \left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{12Lt_s^3}\right)^{0.1} \tag{2.4a}$$

$$LLDF_{multiple\ lane} = 0.075 + \left(\frac{S}{9.5}\right)^{0.6}\left(\frac{S}{L}\right)^{0.2}\left(\frac{K_g}{12Lt_s^3}\right)^{0.1} \tag{2.4b}$$

where S = girder spacing (ft.)

L = span length (ft.)

$K_g = n(I+Ae^2)$, longitudinal stiffness (in^4)

t_s = deck thickness (in)

n = modular ratio between steel and concrete

I = girder moment of inertia (in^4)

A = area of the girder cross-section (in^2)

E = eccentricity between the centroids of the girder and the deck slab (in).

For exterior girders of steel-concrete bridges:

$$LLDF_{multiple\ lane} = \left(0.77 + \frac{d_e}{9.1}\right) LLDF_{interior} \qquad (2.5)$$

where d_e = distance from the centerline of the web of the exterior girder to the interior edge of the curb (ft.)

$LLDF_{interior}$ = the distribution factor specified in equations 2.4b

For single lane bridges, exterior LLDFs can be determined on the basis of the lever rule specified in the AASHTO LRFD code (AASHTO 2010).

Skew correction factors (SCFs) are provided by the AASHTO LRFD specifications for steel-concrete bridges, which are then multiplied by the LLDFs of non-skewed bridges. The equation to determine SCFs is as follows:

$$SCF = 1 - 0.25\left(\frac{K_g}{12Lt_s^3}\right)^{0.25}\left(\frac{S}{L}\right)^{0.5}(tan\theta)^{1.5} \qquad (2.6)$$

where S = girder spacing (ft.)

L = span length (ft.)

K_g = longitudinal stiffness (in^4)

t_s = deck thickness (in)

θ = skew angle (degrees)

The LRFD specifications for steel-timber and timber-timber bridges are based on the *S*-over rule for interior girders.

For steel-timber bridges:

$$LLDF_{single\ lane} = \frac{S}{8.8} \qquad (2.7a)$$

$$LLDF_{multiple\ lane} = \frac{S}{9.0} \qquad (2.7b)$$

where S = girder spacing (ft.)

For timber-timber bridges:

$$LLDF_{single\ lane} = \frac{S}{6.7} \tag{2.7a}$$

$$LLDF_{multiple\ lane} = \frac{S}{7.5} \tag{2.7b}$$

where S = girder spacing (ft.).

The LLDFs of exterior girders for steel-timber and timber-timber bridges can be determined by the lever rule, as seen in the AASHTO LRFD specifications (AASHTO 2010). The details of the finite element analysis are presented in the following chapter.

Finite Element Analysis

3.1 General Description

Bridges in rural areas are usually designed under standard highway truck loads using the AASHTO specifications (2012). This study mainly focused on analyzing steel-concrete girder bridges with concrete decks subjected to agricultural vehicles. The effects of agricultural vehicles' loading on live load distribution factors were analyzed by using the finite element (FE) software SAP2000. The FE models considered the 3-D effects on the load distributions between girders under various agriculture vehicles. The code was validated by using field data gathered through a study done by Seo et al. (2014). This study included five different types of vehicles: four agricultural vehicles and one standard highway truck. In this chapter, the finite element analysis details of the studied bridges are introduced and discussed.

3.1.1 Bridge Description

The bridge under consideration was a simply supported, short-span, steel I-girder bridge with zero skew angle. The bridge had a span of 42.0 ft. and a 7.5-in-thick concrete deck. The steel girders had 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 had nine girders, with the interior girders spaced every 3.0 ft. and the exterior girders spaced 3.3 ft from the interior girders. The total bridge width was 24.3 ft. The moduli of elasticity used for the concrete was 3,200 ksi and for steel was 29,000 ksi. Figure 3.1 shows a local bridge that had steel girders supported with a concrete.

Figure 0.1 Representative steel girder bridge

3.1.2 Vehicles Description

Five vehicles were used in the testing of the bridges:

- a Terragator with a single-wheel front axle, and two closely rear axles
- A tractor with one honey wagon tank
- a tractor with two honey wagon tanks
- a tractor with a grain wagon
- a five-axle semi-truck.

The considered agriculture vehicles are shown in figure 3.2, and all the axle spacing and configurations are presented in table 3.1.

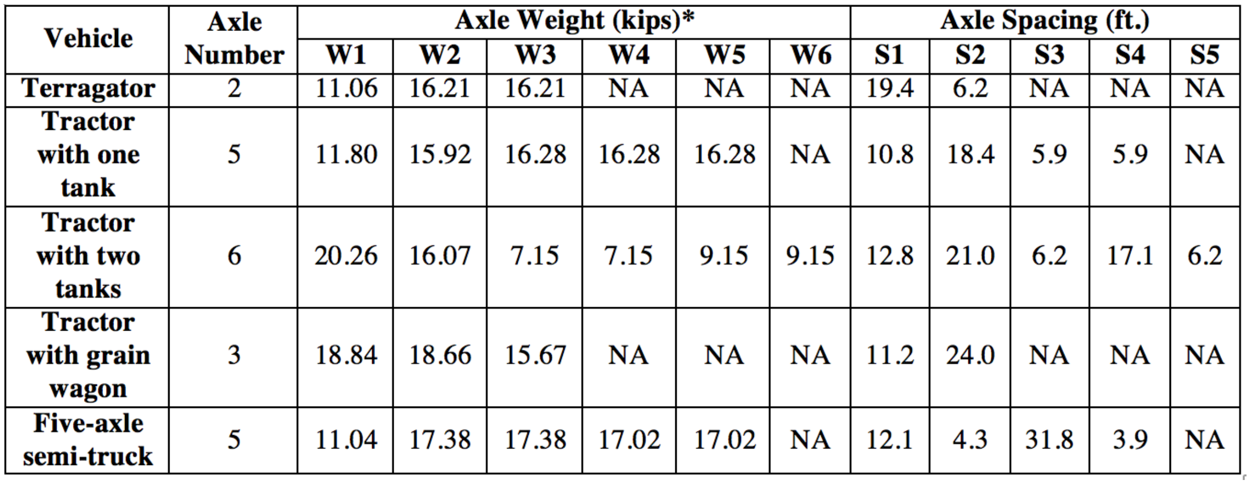
(a) Terragator (b) Tractor with one tank

(a) Tractor with two tanks (b) Tractor with grain wagon

(e) Semi-truck

Figure 0.2 Vehicles used in testing: (a) Terragator, (b) Tractor with one tank, (c) Tractor with two tanks, (d) Tractor with grain wagon, (e) Semi-truck

Table 0.1 Configurations of the vehicles



Vehicle	Axle Number	Axle Weight (kips)*						Axle Spacing (ft.)				
		W1	W2	W3	W4	W5	W6	S1	S2	S3	S4	S5
Terragator	2	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-truck	5	11.04	17.38	17.38	17.02	17.02	NA	12.1	4.3	31.8	3.9	NA

3.2 SAP2000

The finite element model was created with SAP2000. SAP 2000 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 abilities to extract data. The girders were modeled with frame elements, and the bridge deck was modeled with a quadrilateral shell element because of its uniform thickness and properties. Linear links were created between the frame elements (girders) and the shell elements (deck) to achieve full interaction between the girders and the concrete deck and to ensure that they behaved the same under the applied loads. The frames and shells were meshed to create a finite element model (see figure 3.3). The bridge supports were fixed to match the boundary conditions of the actual bridge tested in the field (Seo et al. 2014). A vehicle was moved across the center of the bridge at a crawl speed of 4.5 mph, simulating a static load, and at other speeds, as will be shown next.

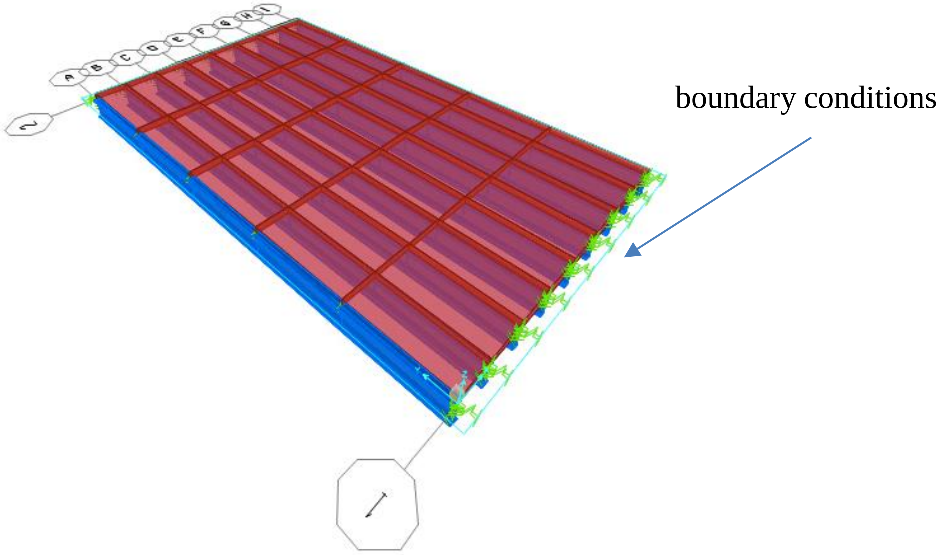


Figure 0.3 Snapshot of the bridge model developed in SAP2000

3.2.1 Element Types

Frame elements were used to model the girders of the bridge. According to the SAP2000 manual, the frame elements are “a general, three-dimensional, beam-column formulation which 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, described as “a two-joint connecting link composed of six separates ‘springs,’ one for each of the six deformational degrees of freedom” (SAP2000), were used to tie the bridge deck and girders together. The links were fixed in all six directions so that the bridge would act as a single entity.

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. (2014). The model of the bridge was built in SAP2000 according to the dimensions and boundary conditions taken from the engineering drawings they had used in their experiments, and a Terragator was run across the bridge. Figure 3.4 shows a 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. Because of the symmetrical shape of the bridge, the strains of girders 1 and 9 were similar, as were those of girders 2 and 8 and girders 3 and 7, while girder 5 was 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 a very slow speed of 4.5 mph. The strains obtained from the FE code compared very well with the field data, and the values of the maximum strain in girder 5 (middle girder) was 60 micorstrain, which was less than the yield strain of the structural steel used in the bridge (0.00207). On the basis of that result, the authors decided to use the linear analysis option to perform this study. Because of the very limited experimental data related to the behavior of bridges loaded with agricultural vehicles, this was the only validation testing that had been found.

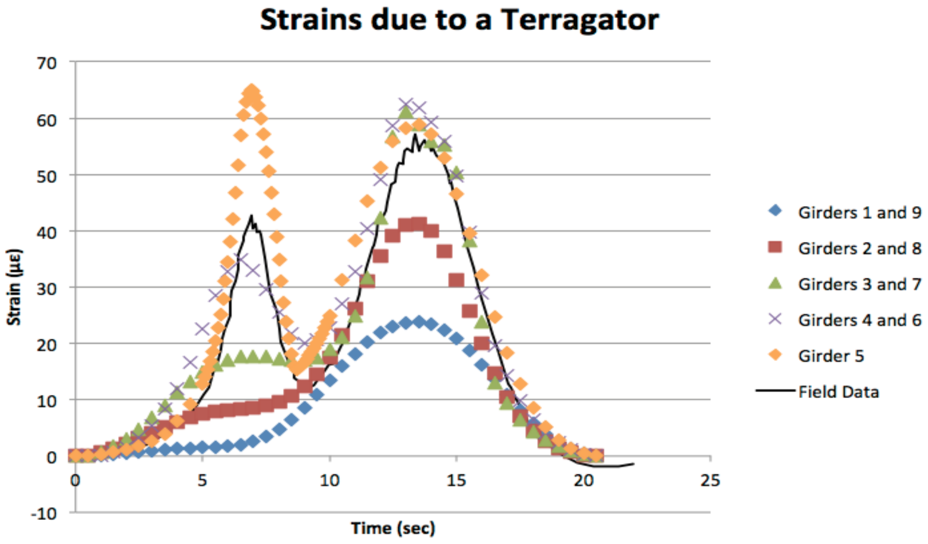


Figure 0.4 Strains in the bridge due to the loading of a Terragator over time

Results and Discussion

4.1 Parametric Study

This chapter presents the results from the FE analysis conducted on various cases of bridges under combinations of agricultural vehicles. The analytical LLDFs were determined from the resulting moments and shears and were compared to LLDFs derived by using the AASHTO manual. Figure 4.1 shows the various combinations of the FE models generated to predict the live load distribution factors.

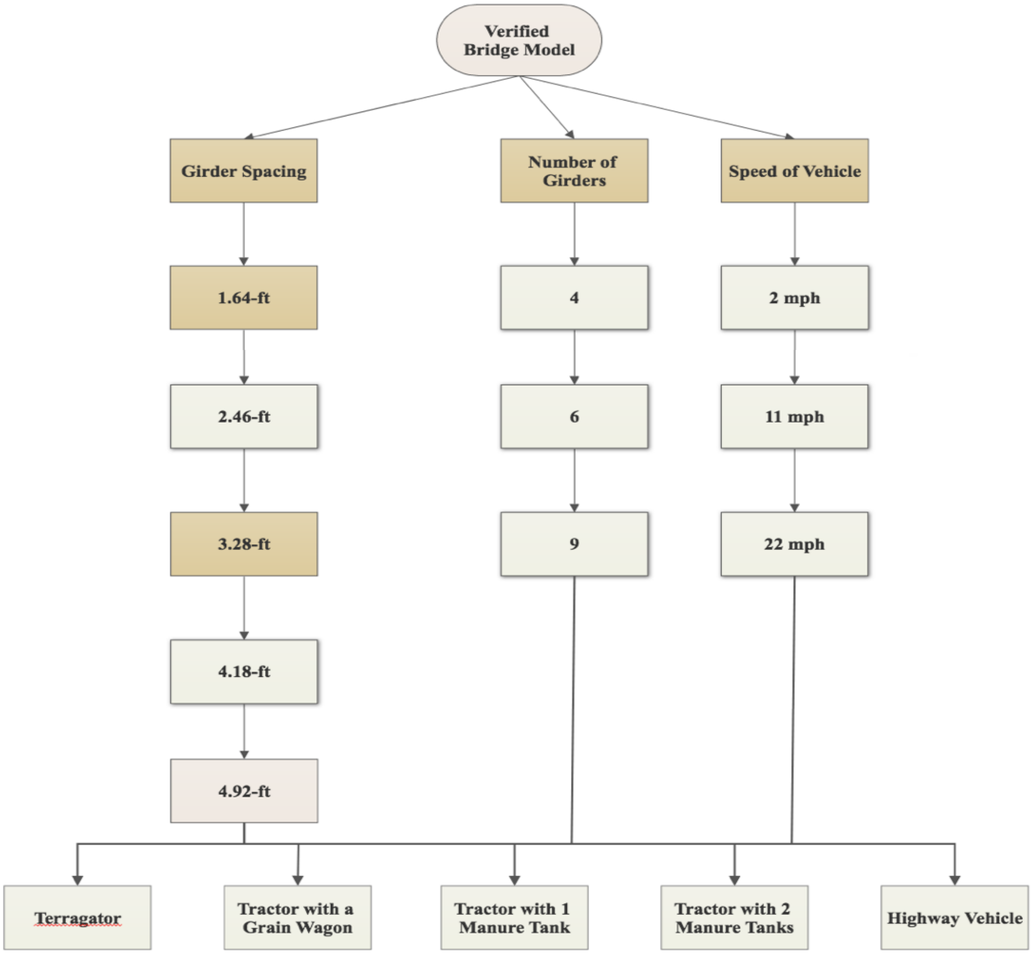


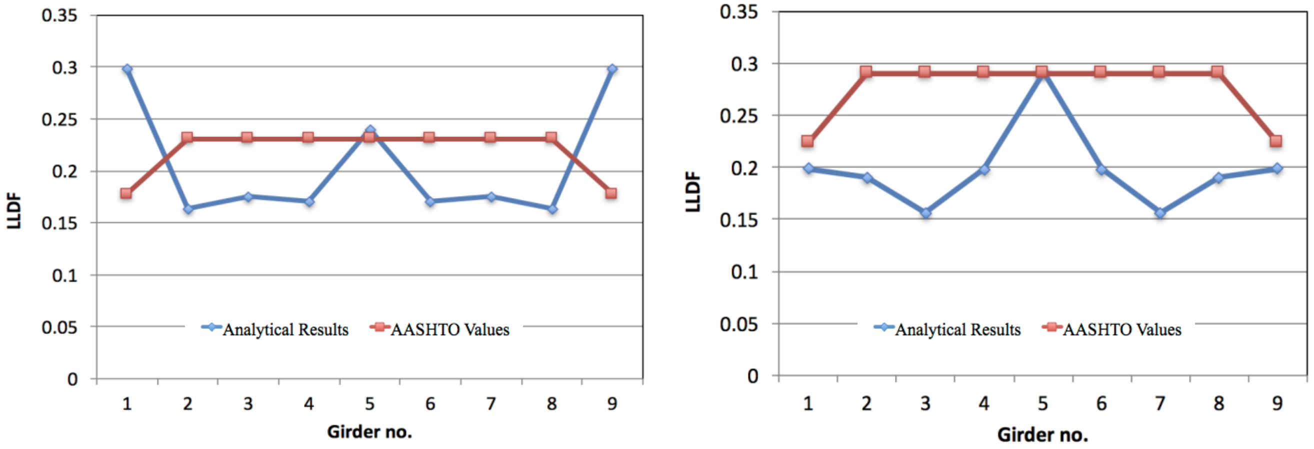
Figure 0.1 Flow chart showing the different loading scenarios

After the finite element model had been verified, a number of different parameters were varied, and the effects of those parameters on the LLDFs of the bridge girders were observed. The parameters that were changed were the spacing between girders while keeping a constant number of girders, and 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.

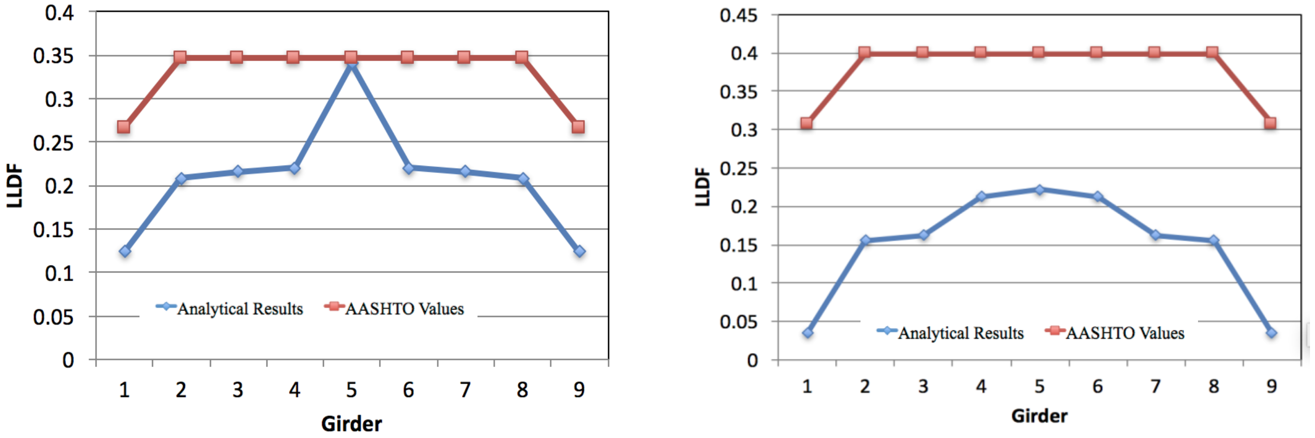
4.2 Moment Distribution Factors

4.2.1 Effects of Girder Spacing

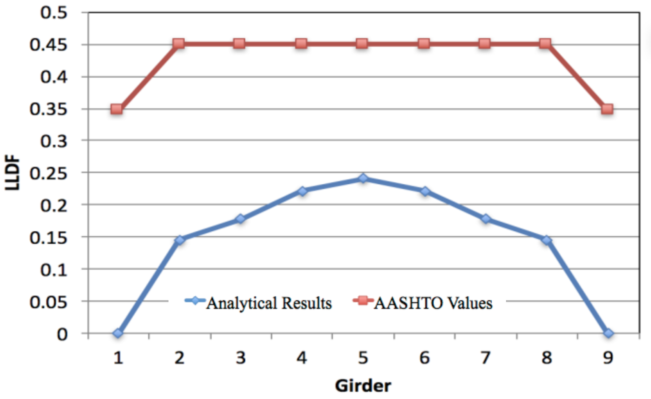
The effects of different girder spacing was investigated for various agricultural vehicles, and the span of the bridge and number of girders were kept constant at 42-ft. and nine girders, respectively. The spacing studied ranged from 1.64 ft. to 4.96 ft. between each girder centerline. The effects of five vehicle types were observed on how the spacing affected the load distribution factors between girders. 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 LLDF values were lower than the AASHTO design value. However, the Terragator created a higher (4 percent) LLDF on the middle girder for the bridge with smaller girder spacing than the values obtained from AASHTO design codes (see figure 4.1a). The LLDFs were much higher (67 percent) than the AASHTO values for the exterior girders when the girder spacing was 1.64 ft., and that was attributed to the higher girder stiffness. When the spacing between girders increased to 2.46 ft. and 3.28 ft., the Terragator showed same LLDFs for the middle girder, but at a spacing of 4.10 ft. the LLDFs were less than the AASHTO values by 57 percent and and at 4.92 ft. they were less by 56 percent. For all other vehicles, the anaytical LLDFs were less than the AASHTO values, as shown in figures 4.2 to 4.6.



(a) 1.64-ft Spacing (b) 2.46-ft Spacing

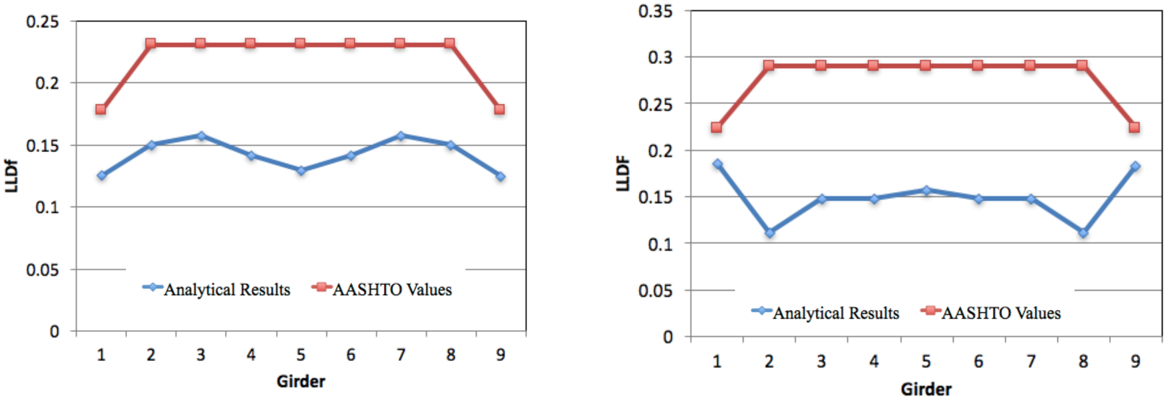


(c) 3.28-ft Spacing (d) 4.10-ft Spacing



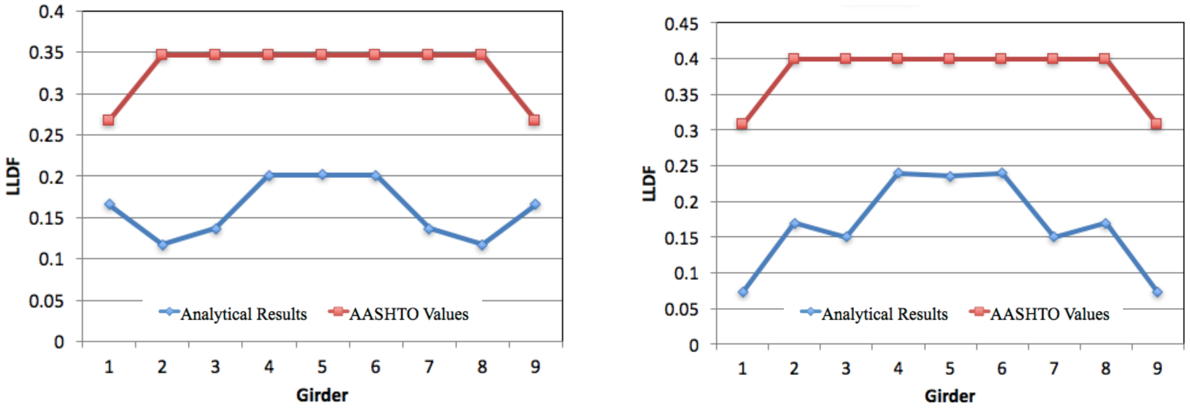
(e) 4.92-ft Spacing

Figure 0.2 Load distribution factors for a Terragator on a bridge with variable girder spacing



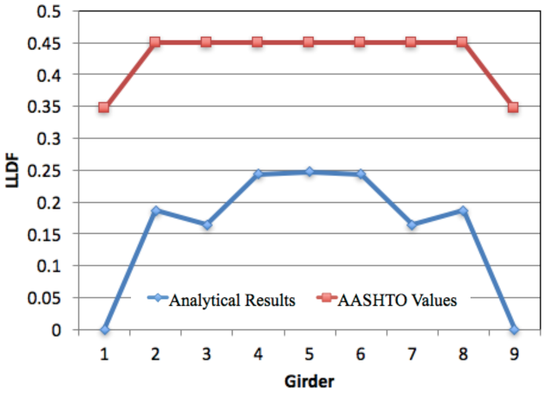
(a) 1.64-ft Spacing

(b) 2.46-ft Spacing



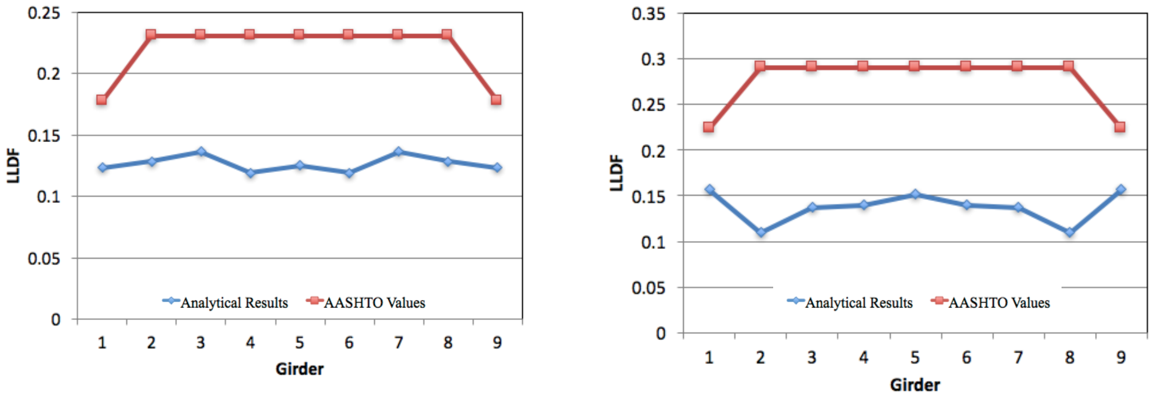
(c) 3.28-ft Spacing

(d) 4.10-ft

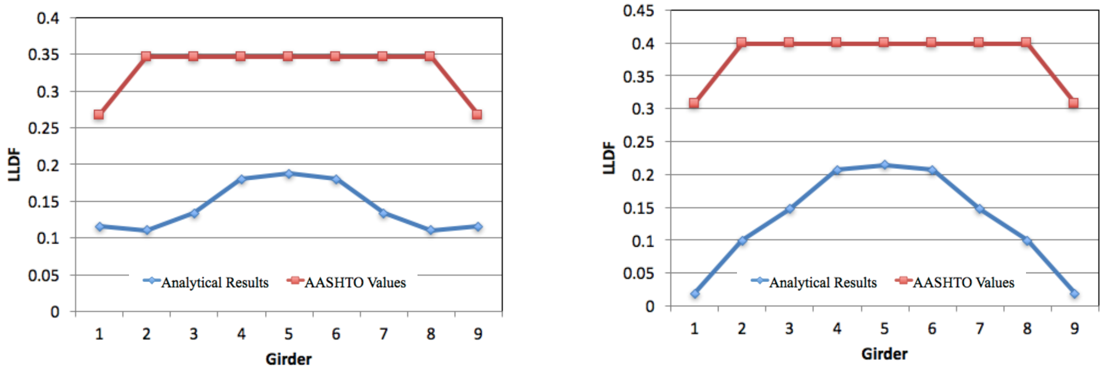


(e) 4.92-ft Spacing

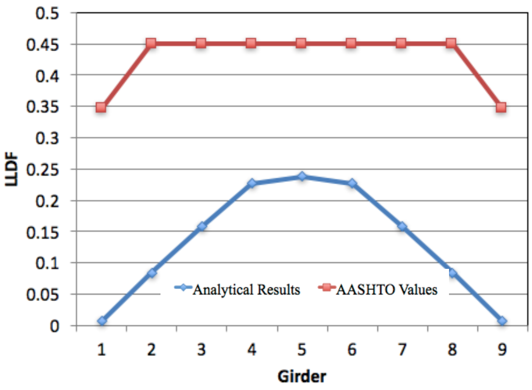
Figure 0.3 Load distribution factors for a tractor with a grain wagon on a bridge with variable girder spacing



(a) 1.64-ft Spacing (b) 2.46-ft

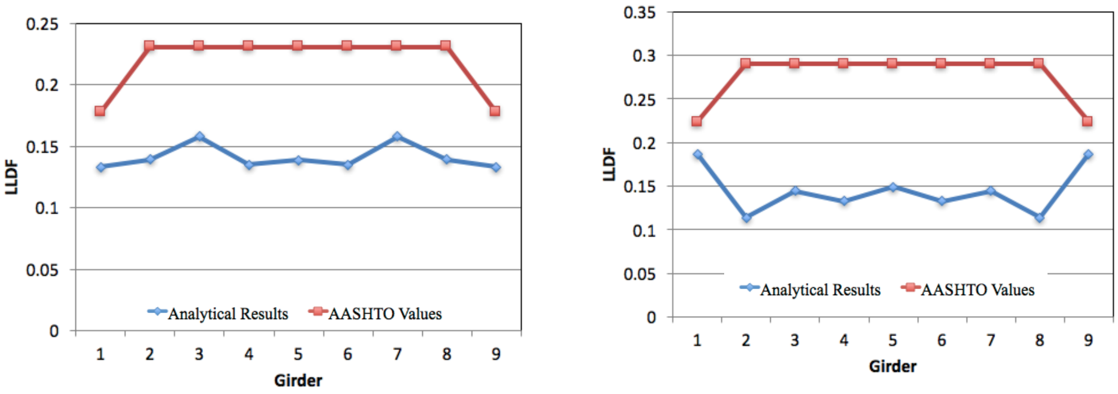


(c) 3.28-ft Spacing (d) 4.10-ft Spacing



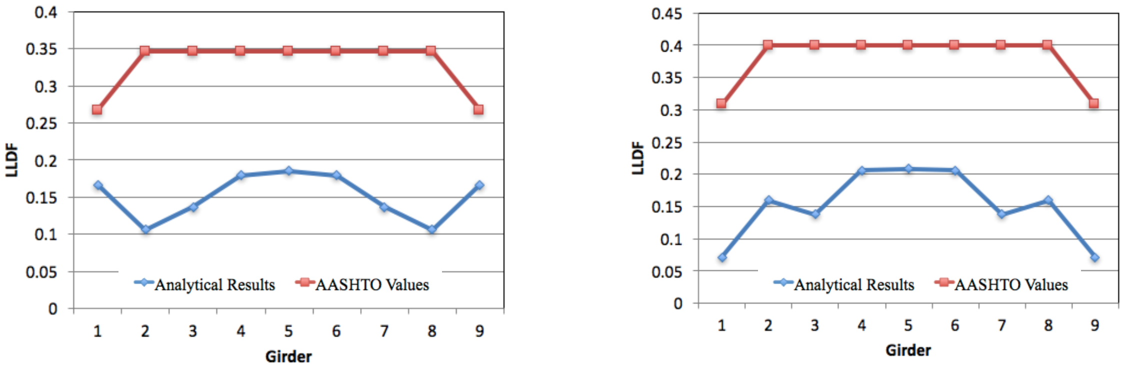
(e) 4.92-ft Spacing

Figure 0.4 Load distribution factors for a tractor with one tank on a bridge with variable girder spacing.



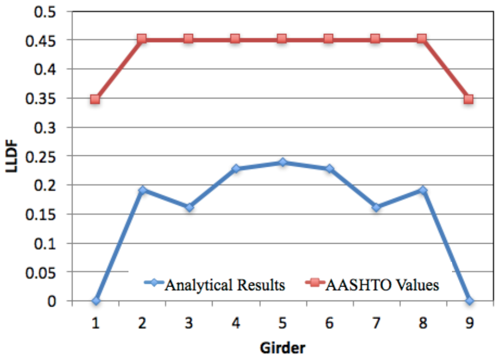
(a) 1.64-ft Spacing

(b) 2.46-ft



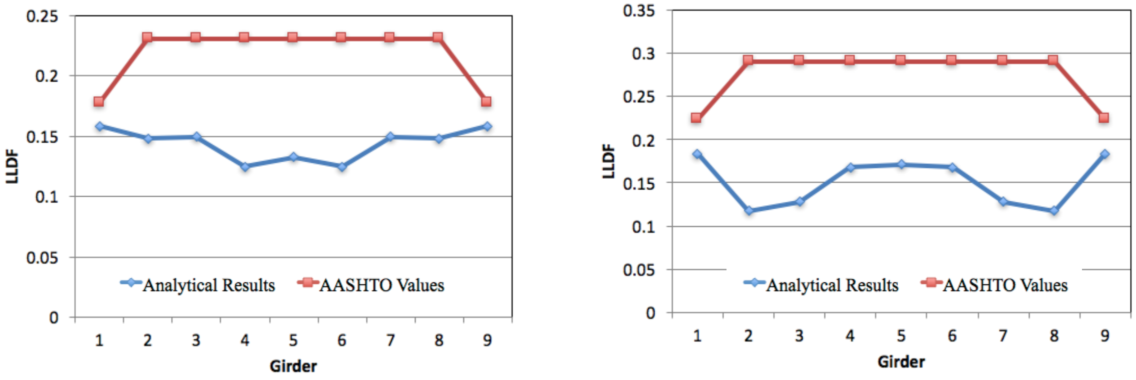
(c) 3.28-ft Spacing

(d) 4.10-ft Spacing



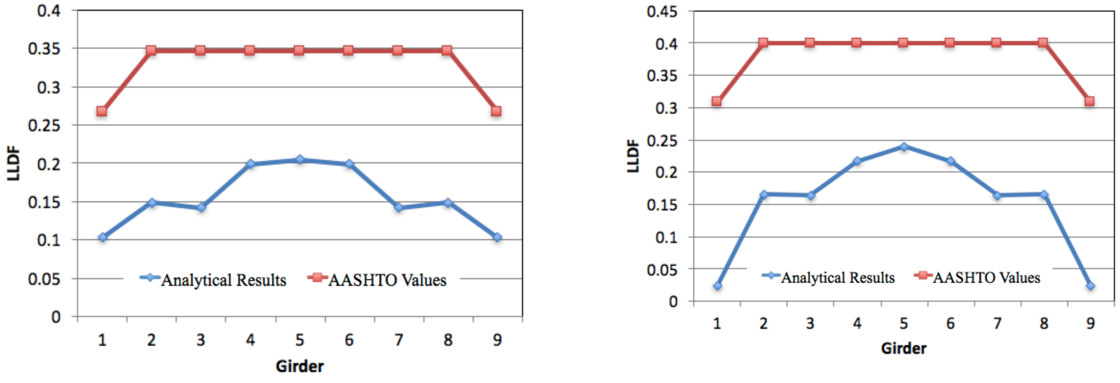
(e) 4.92-ft Spacing

Figure 0.5 Load distribution factors for a tractor with two tanks on a bridge with variable girder spacing



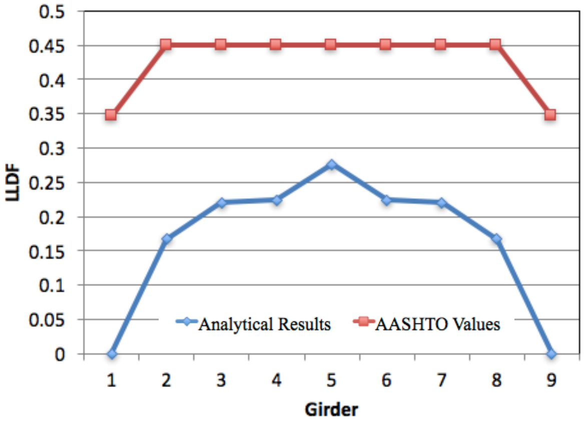
(a) 1.64-ft Spacing

(b) 2.46-ft



(c) 3.28-ft Spacing

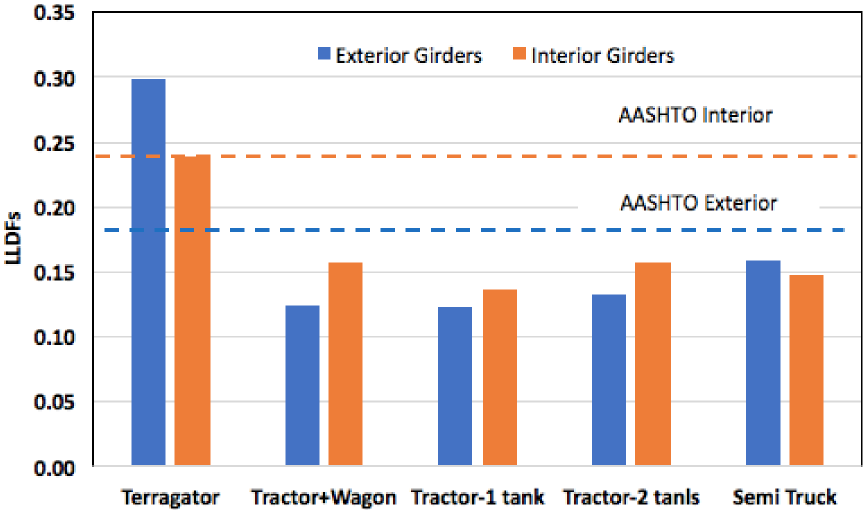
(d) 4.10-ft Spacing



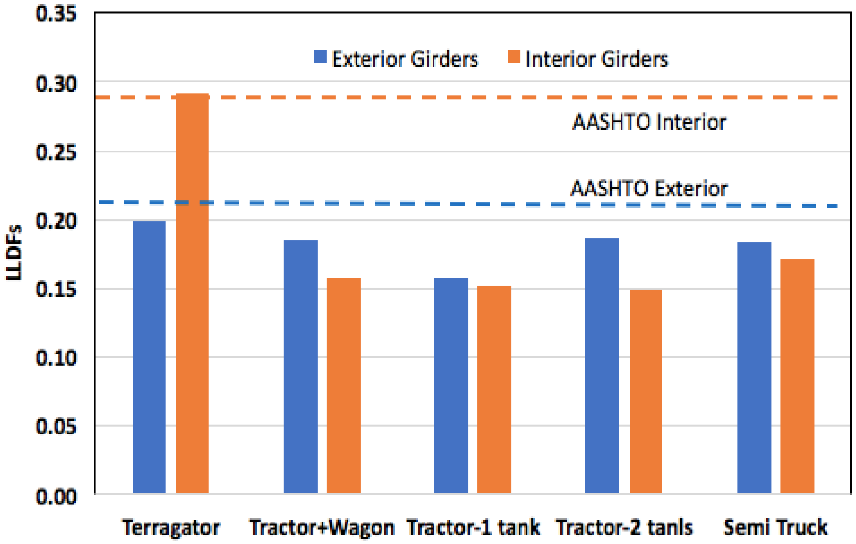
(e) 4.92-ft Spacing

Figure 0.6 Load distribution factors for a highway vehicle on a bridge with variable girder spacing

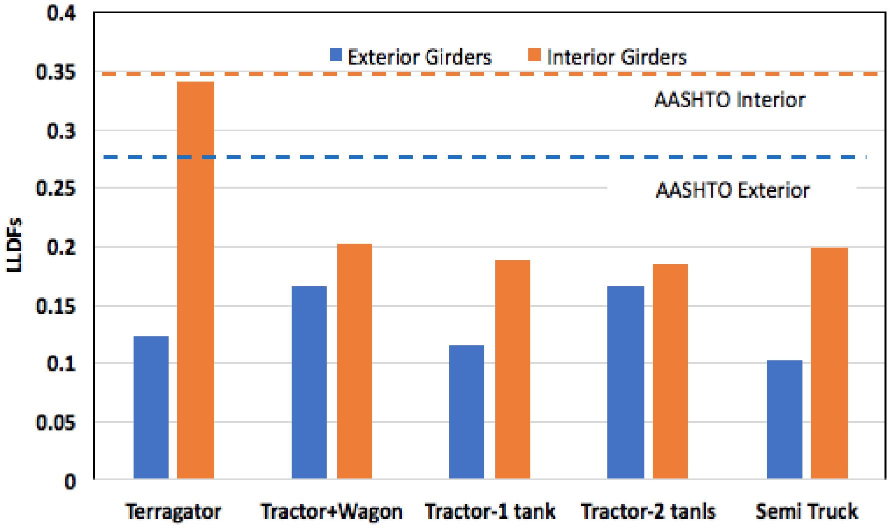
Figure 4.7 shows a better presentation of the LLDFs versus the agricultural vehicle types. The exterior girders' distribution factors were directly taken from the analysis, in which the distribution factors for the interior girders were assumed to be the maximum values obtained from the analytical results. It can be seen from figure 4.7 that the Terragator had a significant weight that produced a higher moment distribution factor of 0.30 for exterior girders, which exceeded the AASHTO design value of 0.18. That was noticed for bridges with small spacing between girders. The other vehicles produced lower LLDFs than the Terragator. When the spacing between girders was increased to 2.64 ft., and 3.28, the Terragator produced an internal girder distribution factor of 0.29, which was equal to the AASHTO design value. In addition, the LLDFs for the exterior and interior girders (girder spacing= 1.64 ft.) due to the Terragator were higher than those for the highway standard truck by 88 percent and 62 percent, respectively. Similar observations were obtained when the 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 those of a standard highway truck by 70 percent on average. The importance of this finding is that when any agricultural vehicle causes LLDFs that are larger than those of a highway semi-truck, the girders are under-sized because all bridges are designed on the basis of a standard highway truck. Other agricultural vehicles, such as the tractor with a grain wagon, produced a higher LLDF (70 percent) for the exterior girder than the semi-truck when girder spacing was 3.28 ft. For girder spacings of 4.10 and 4.92, the LLDFs due to the standard truck were higher than the ones produced by the tractor with one and two tanks, and the LLDFs for all exterior girders were almost zero.



a) Girder Spacing =1.64 ft.

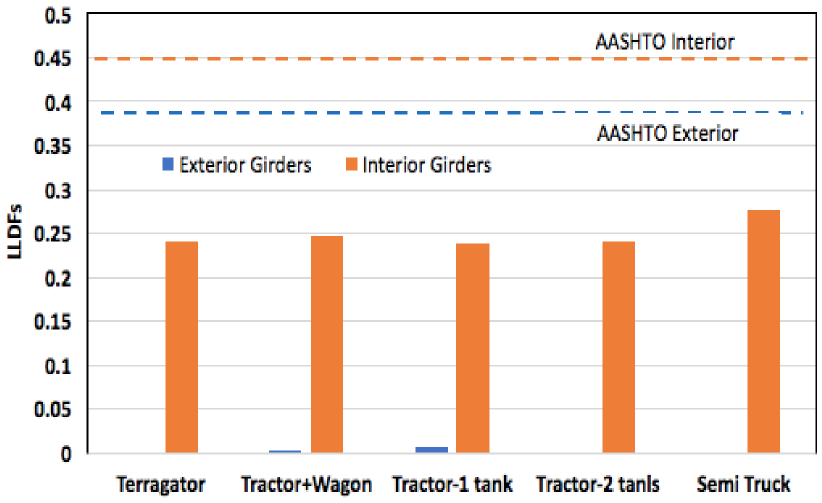


b) Girder Spacing = 2.64 ft.



c) Girder Spacing = 3.28 ft.

d) Girder Spacing = 4.10 ft.

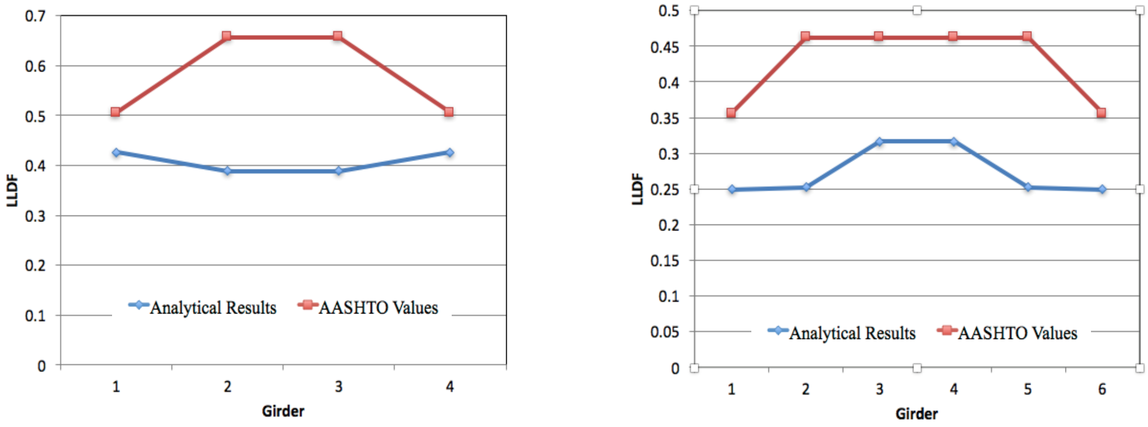


e) Girder Spacing = 4.92 ft.

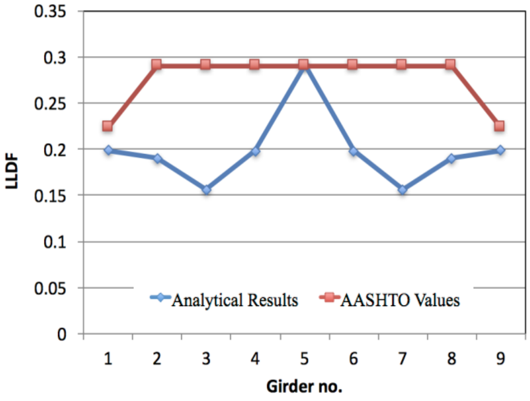
Figure 0.7 Load distribution factors due to a highway vehicle on a bridge with variable girder spacing

4.1.2 Effects of the Number of Girders

This section presents the effects of the number of girders on the live load distribution factors. The span and width of the bridge under investigation were kept constant at 42 ft. and 26 ft. respectively, while the number of girders was varied between four, six, and nine. The five agricultural vehicles were tested on all bridge cases. In general, as shown in figure 4.8, the analytical LLDFs were less than the AASHTO design values when there were fewer girders. The bridge with four girders had LLDFs that were less than the AASHTO values, and as expected, the Terragator load was distributed almost evenly between the girders (LLDF=0.41 on average), as shown in figure 4.8a. For the bridge with six girders, the LLDFs were lower (30 percent) than the AASHTO values for the interior and exterior girders. For example, the maximum LLDF of the bridge with six girders was 0.32, while for the bridge with four girders, it was 0.39. When the number of girders increased to nine, the LLDF decreased to 0.29 for the middle girder. The tractor with a grain wagon, with one and two tanks, generated lower LLDFs than the AASHTO equations, as shown in figures 4.8 to 4.12.

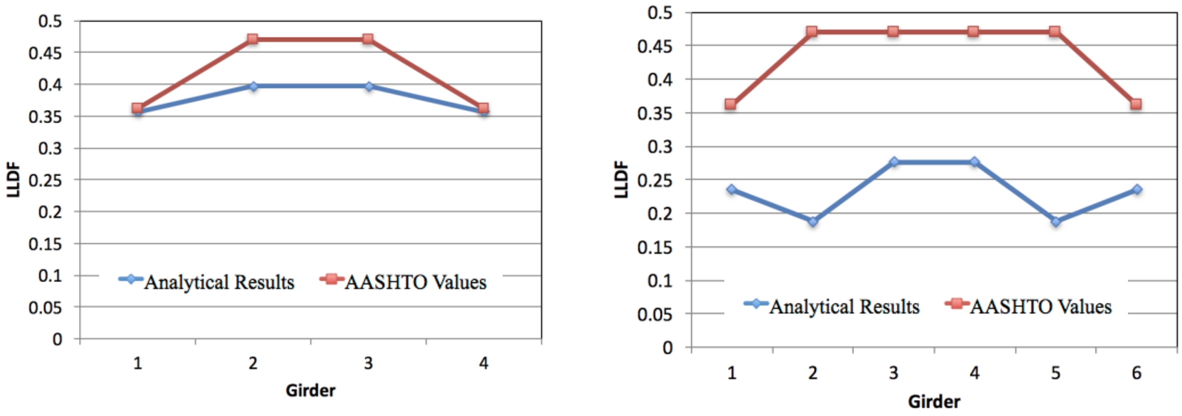


(a) 4-girgders (b) 6-gireders



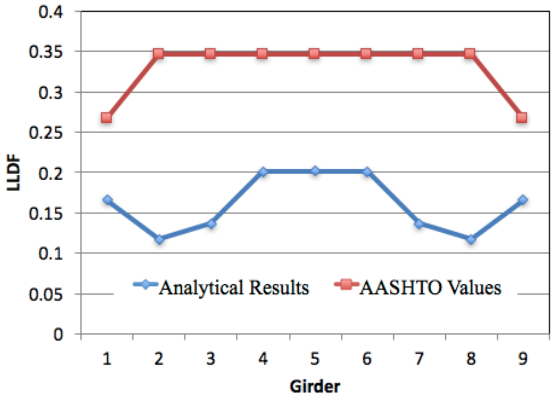
9-girders

Figure 0.8 Load distribution factors due to a Terragator on a bridge with a variable number of girders (spacing 3.28 ft.)



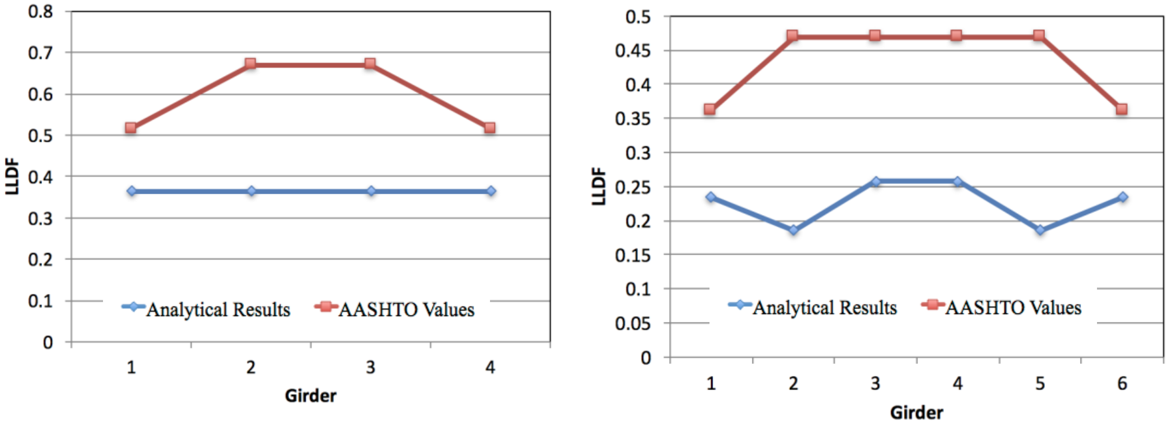
(a) 4-girgders

(b) 6-gireders

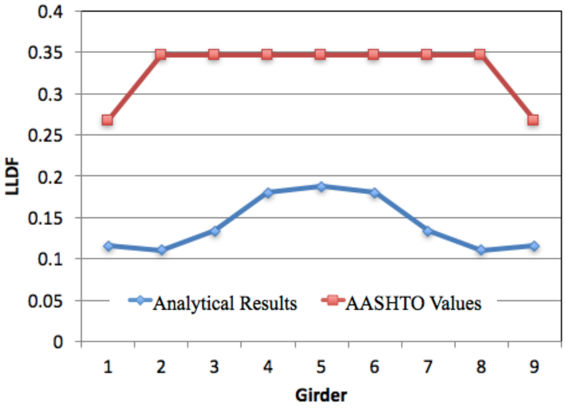


9-girders

Figure 0.9 Load distribution factors due to a tractor with a grain wagon on a bridge with a variable number of girders (spacing 3.28 ft.)

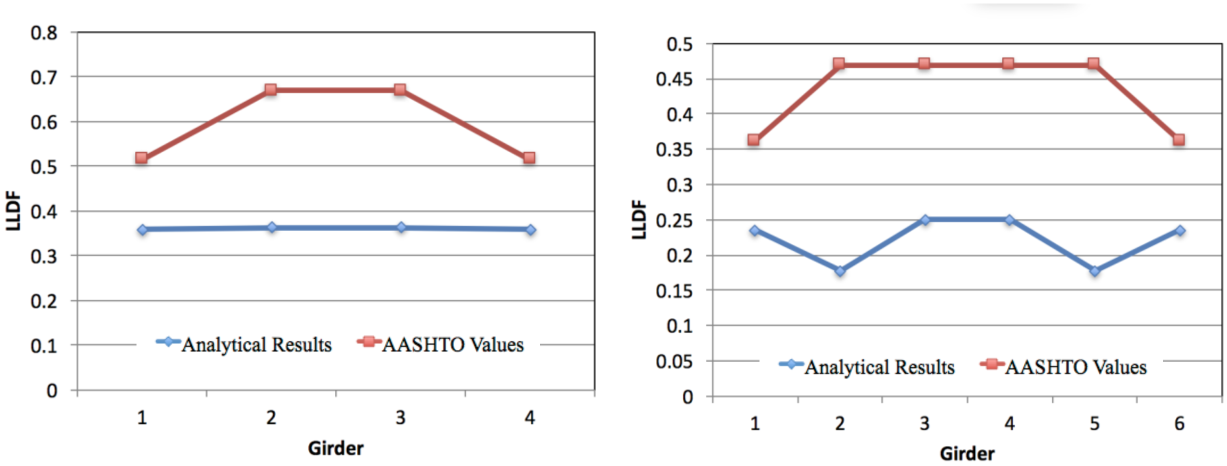


(a) 4-girgders (b) 6-gireders



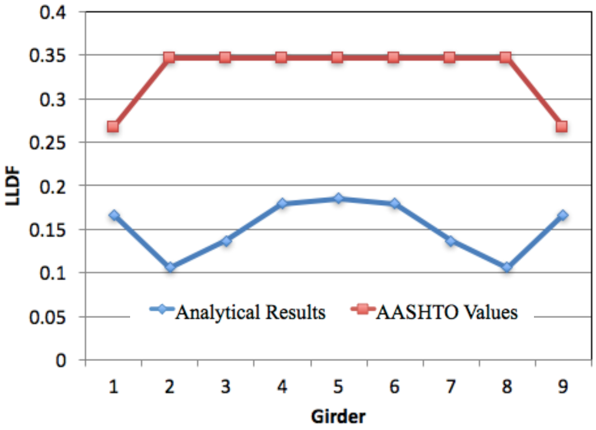
9-girders

Figure 0.10 Load distribution factors due to a tractor with one tank on a bridge with a variable number of girders (spacing 3.28 ft.)



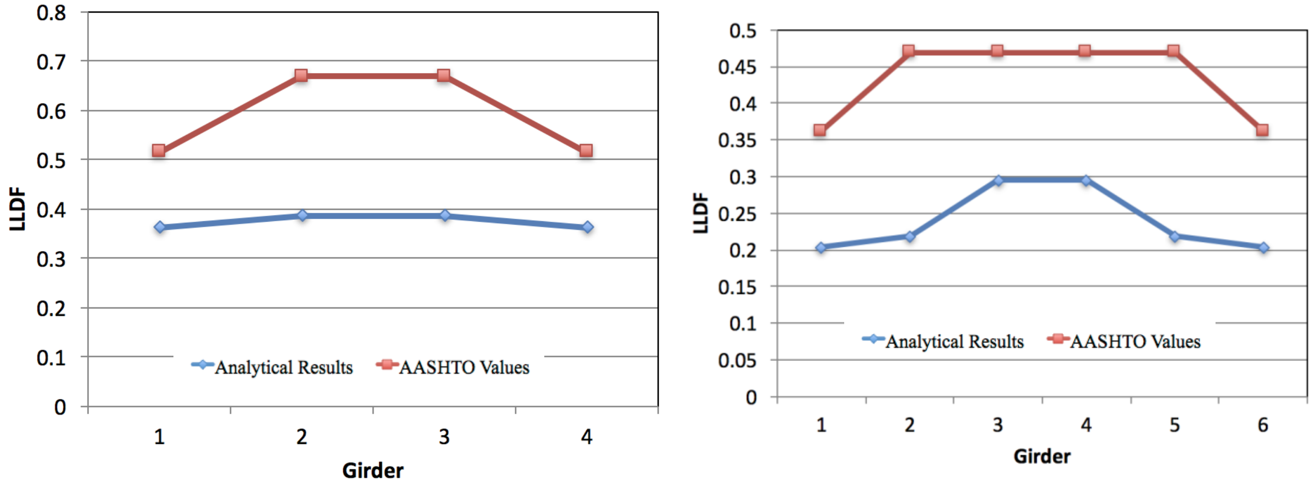
(a) 4-girgders

(b) 6-gireders



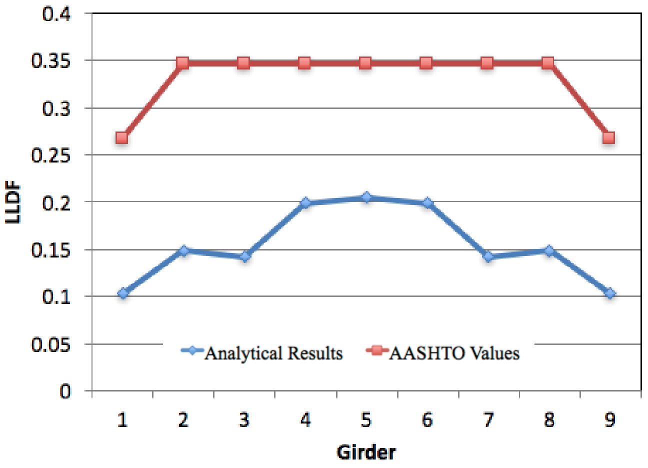
9-girders

Figure 0.11 Load distribution factors due to a tractor with two tanks on a bridge with a variable number of girders (spacing 3.28 ft.)



(a) 4-girgders

(b) 6-gireders



9-girders

Figure 0.12 Load distribution factors due to a highway vehicle on a bridge with a variable number of girders (spacing 3.28 ft.)

Figure 4.13a shows comparisons between the LLDFs resulteing from the Terragator and the standard truck. The Terragator produced significantly higher LLDFs for the exterior girders: 17 percent for bridges with four girders, 24.7 percent for six girders, and 93.6 percent for nine girders. The situation was different for the interior girders: for the bridge with four girders, there was no significant difference in the LLDFs. For bridges with six and nine girders, the Terragator produced LLDFs that were 5 percent and 43 percent higher, respectively, than those of the standard truck.

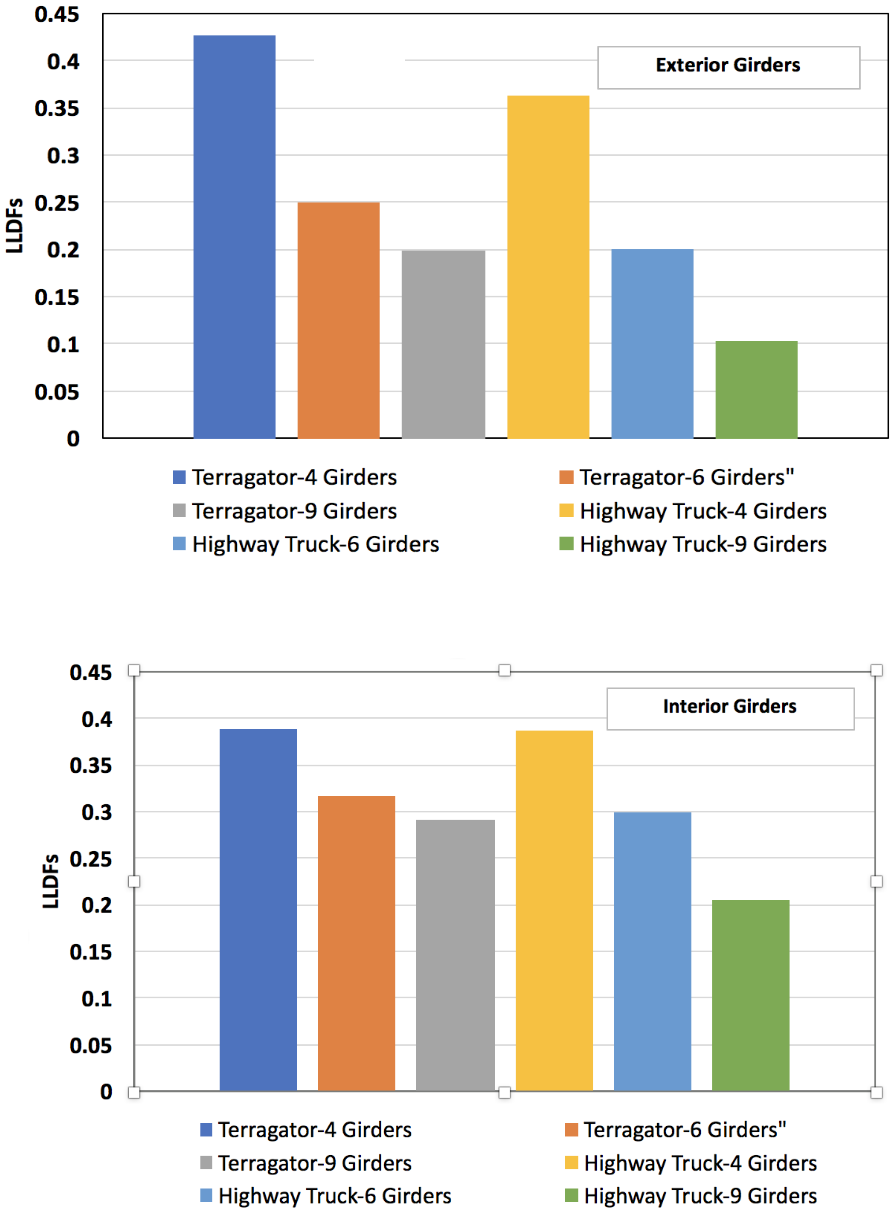
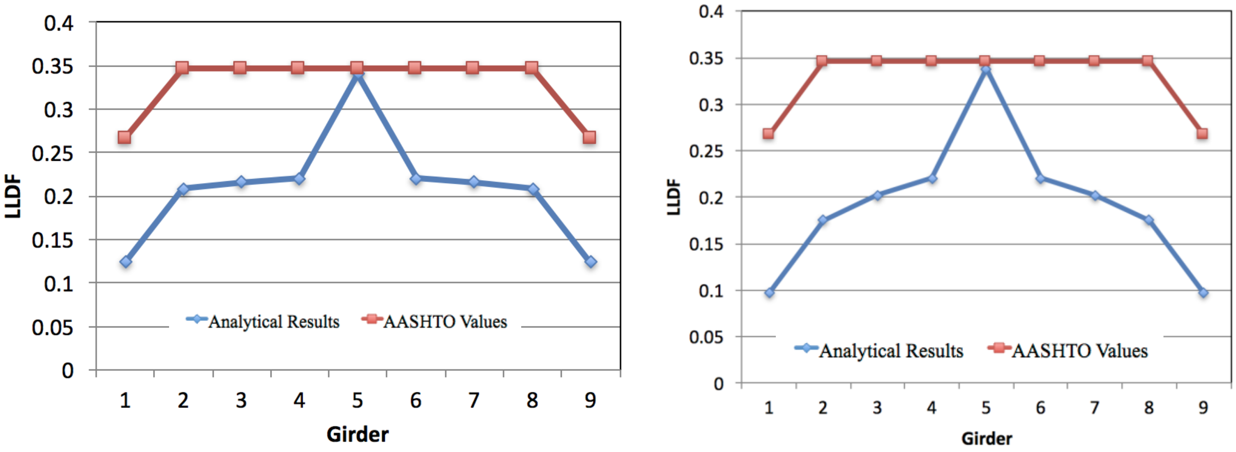


Figure 0.13 Comparison between LLDFs for the Terragator and the highway truck.

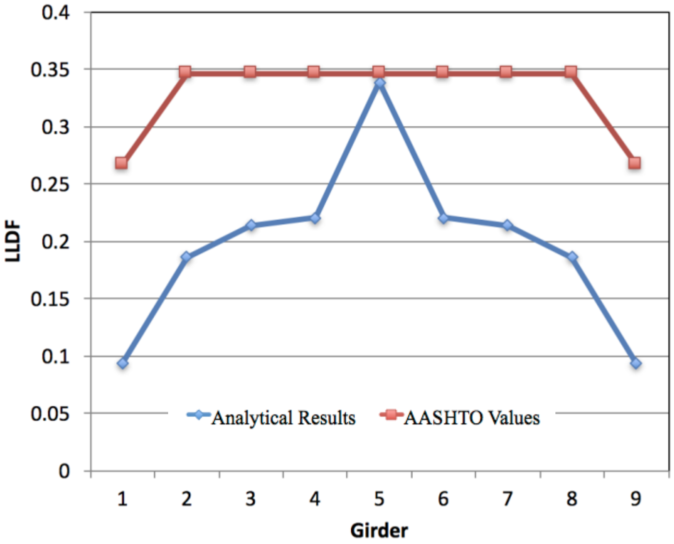
4.1.3 Effects of Vehicle Speeds

The speeds of the vehicles were varied from 2 mph to 22 mph while the bridge width and number of girders were kept consistent. The bridge had a 42-ft span and had nine girders spaced 3.3 ft. apart. The speed of the vehicles did not drastically alter the values of the LLDFs. The Terragator produced higher LLDFs than other vehicles and even the standard highway truck, as shown in figures 4.14 to 4.18.



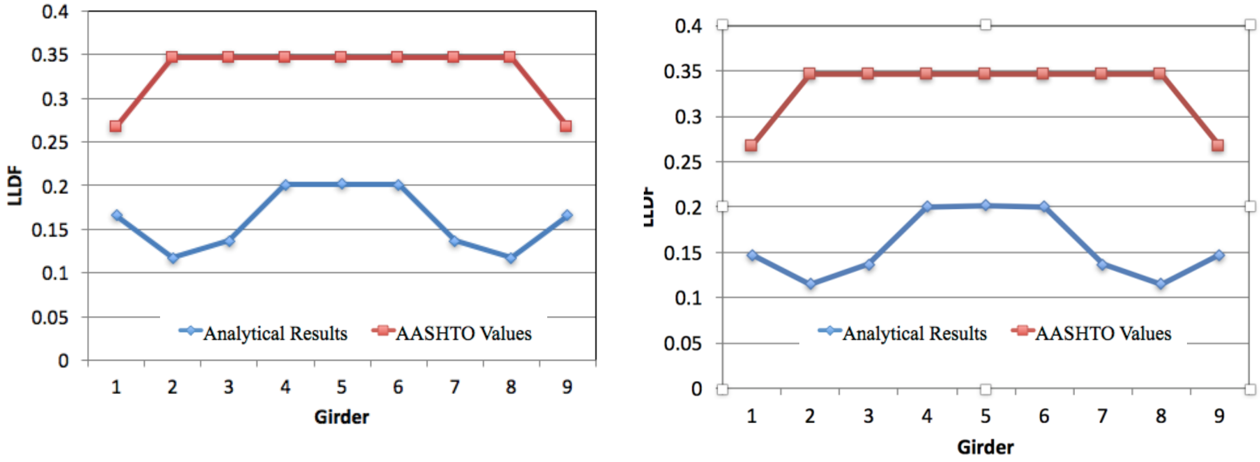
(a) 2 mph

(b) 11 mph



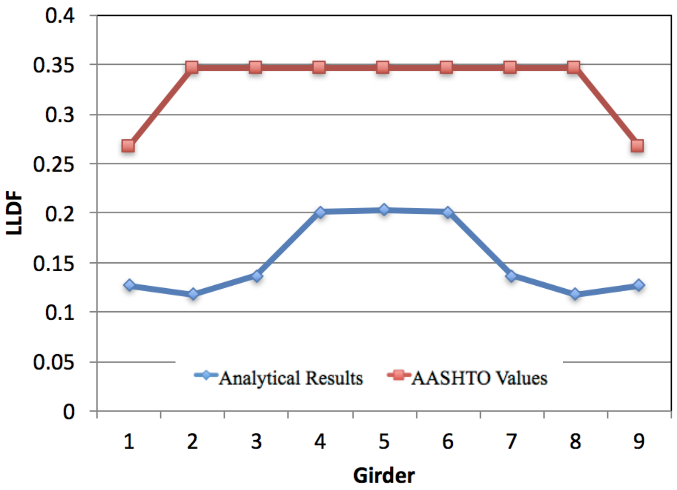
c) 22 mph

Figure 0.14 Load distribution factors due to a Terragator on a bridge with variable speed.



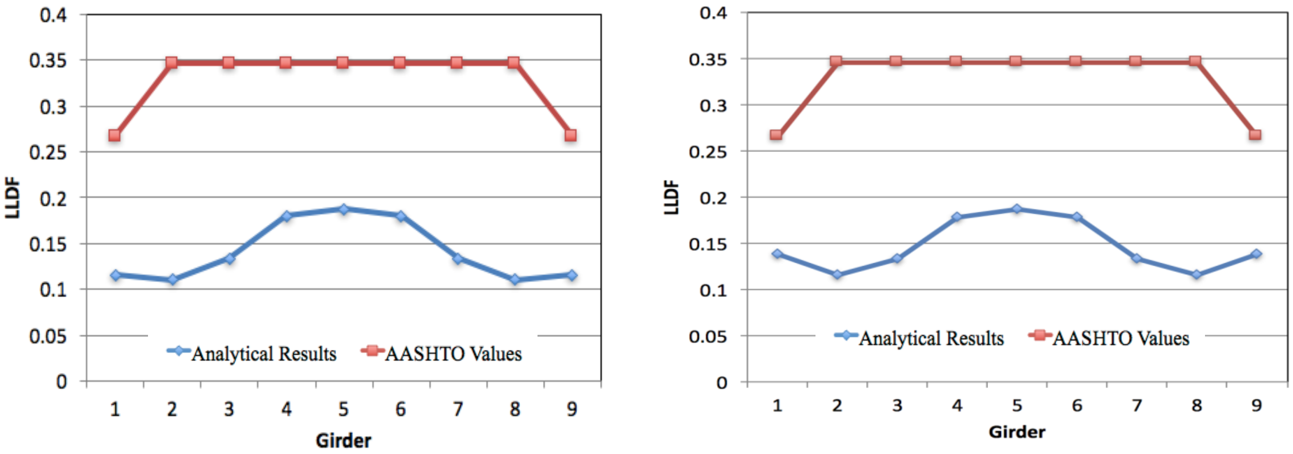
(a) 2 mph

(b) 11 mph

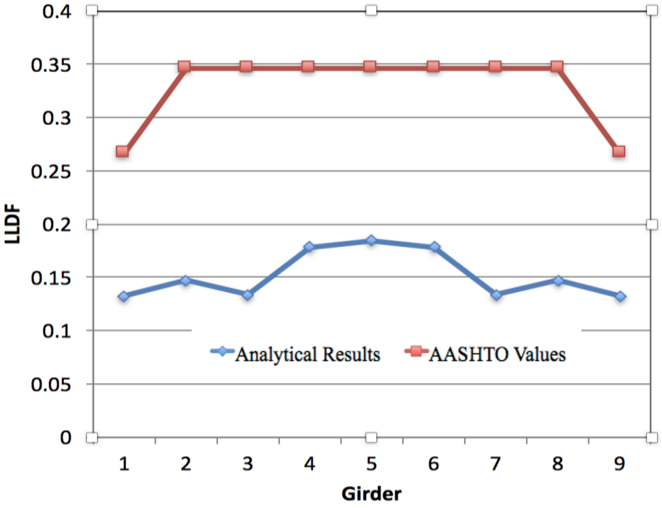


c) 22 mph

Figure 0.15 Load distribution factors due to a Terragator on a bridge with variable speed

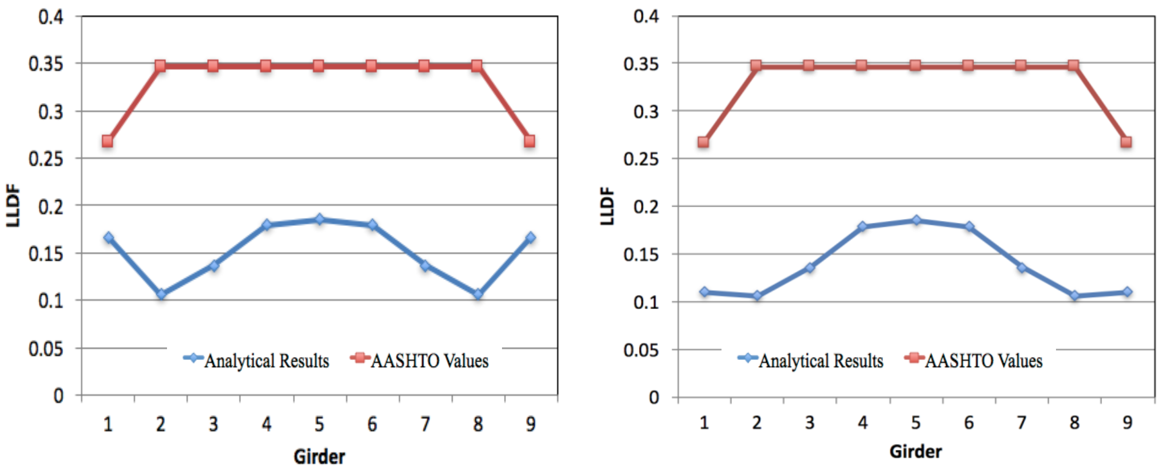


(a) 2 mph (b) 11 mph



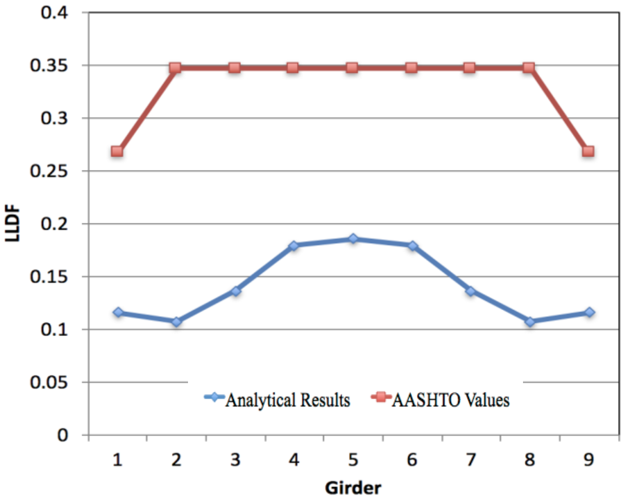
c) 22 mph

Figure 0.16 Load distribution factors due to a tractor with one tank on a bridge with variable speed



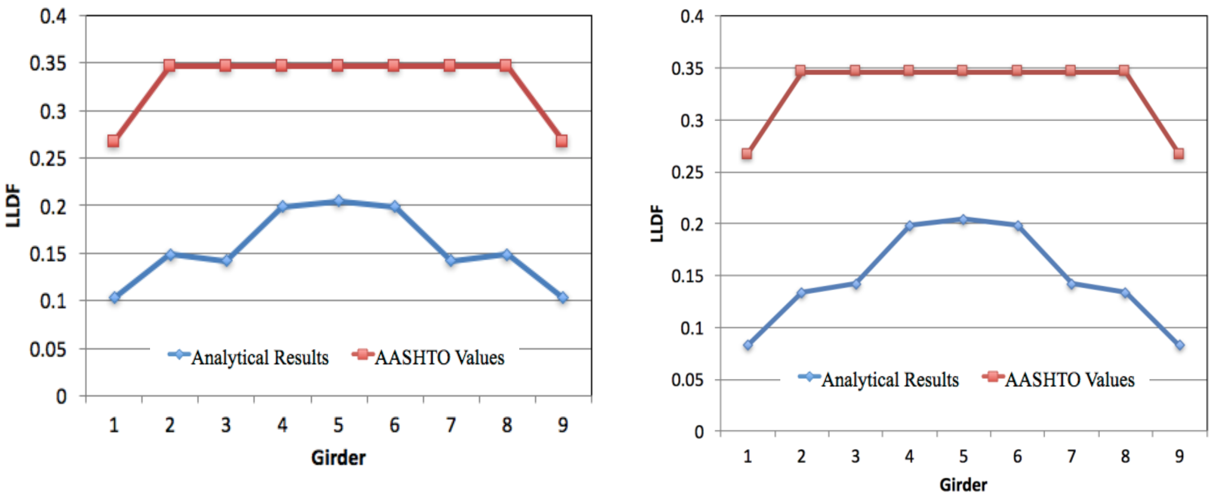
(a) 2 mph

(b) 11 mph



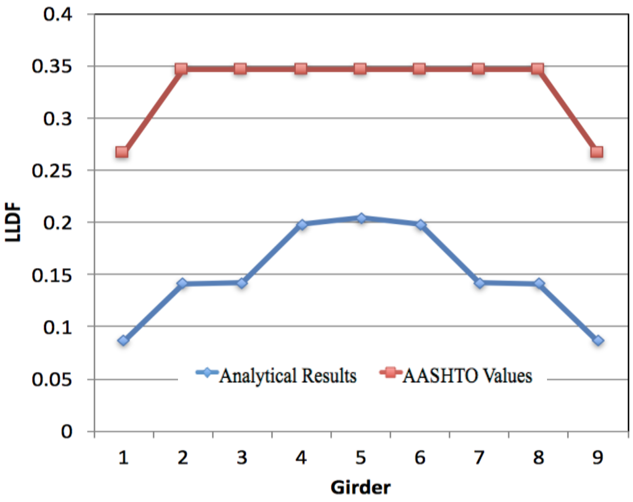
c) 22 mph

Figure 0.17 Load distribution factors due to a tractor with two tanks on a bridge with variable speed



(a) 2 mph

(b) 11 mph

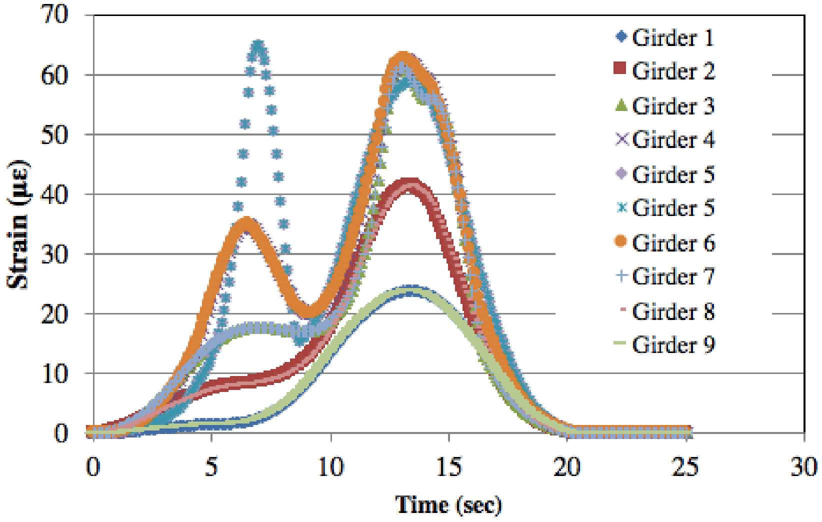


c) 22 mph

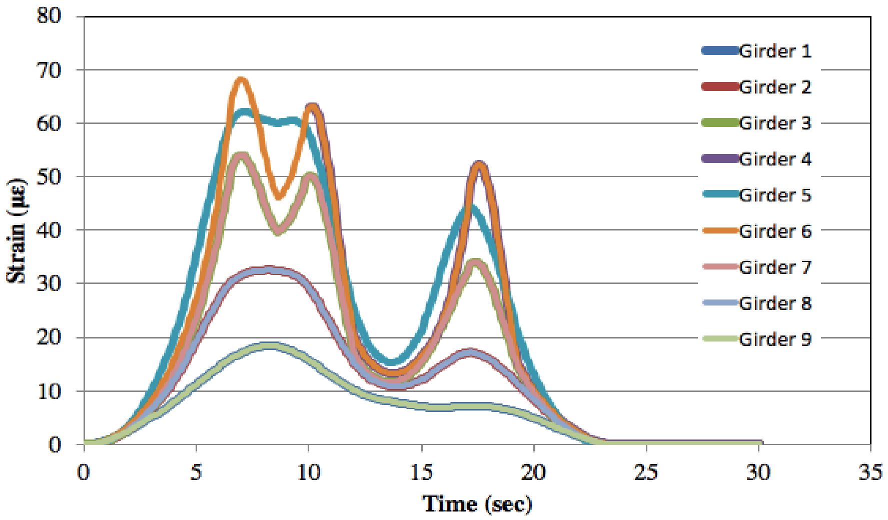
Figure 0.18 Load distribution factors due to a highway vehicle on a bridge with variable speed

4.3 Strain Time History

The strain time history under various cases was investigated. Figure 4.19a shows the strains at the mid-span of the bottom flange of the bridge under consideration. All vehicles were crossing the bridge at a speed of 2 mph. Figure 4.19a shows that the maximum strain of girder 5 due to the Terragator was 62.5 microstrains at a time of 3.1 seconds, while the tractor with the grain wagon induced a strain of 86.5 microstrains 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-truck generated a maximum strain of 86.6 at 10.2 seconds. The variability of strain was mainly due to the axle configurations, loads, and spacings of all the vehicles. Some of the farming vehicles, such as the tractor grain wagon and tractor with one tank, produced more tensile strain than the standard highway truck, which indicates that some types of the FVs might be considered in the future by AASHTO.

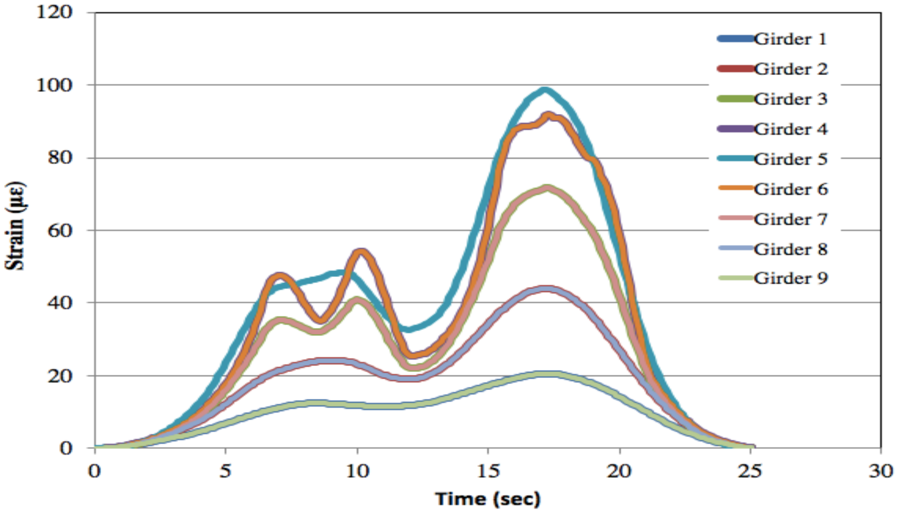


a)



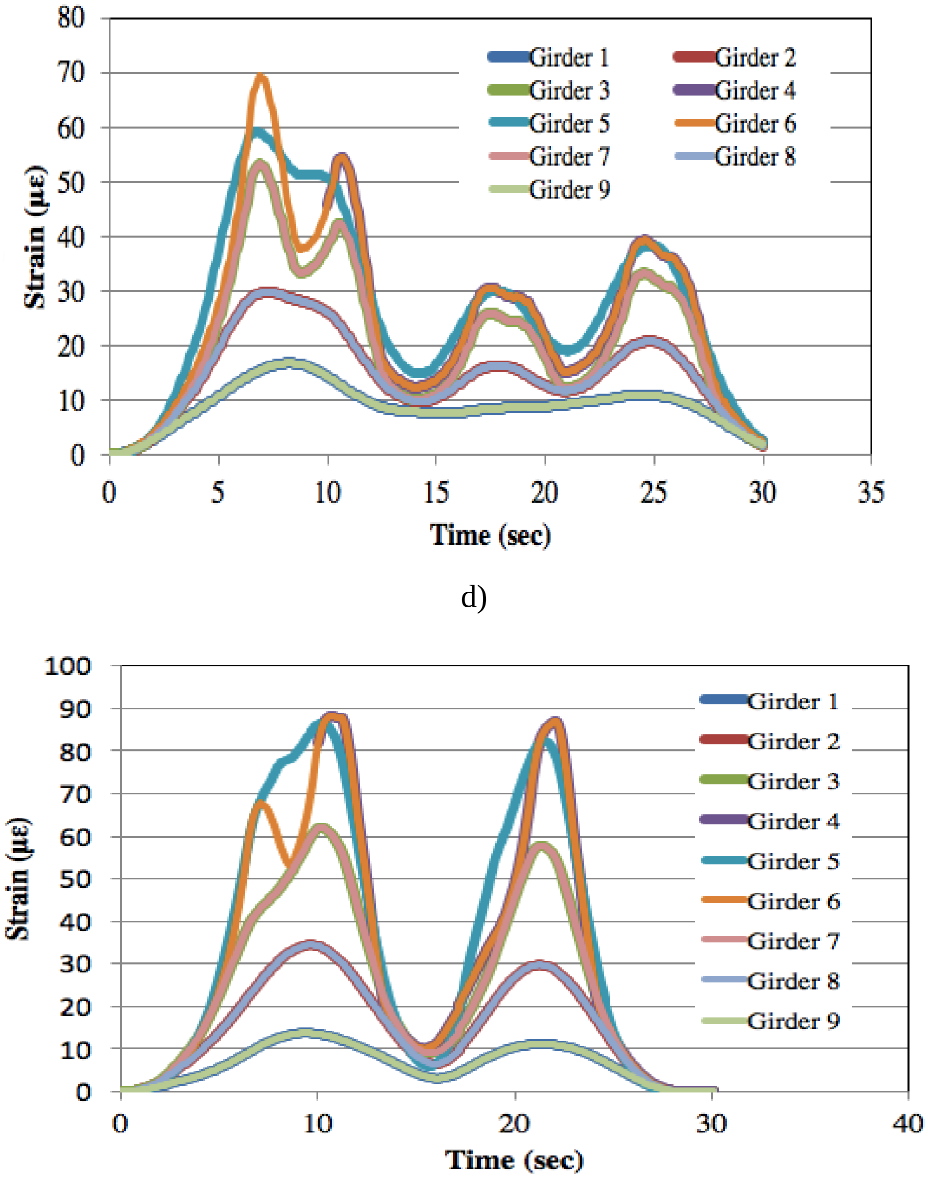
Strain (με)
Time (sec)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
Girder 1
Girder 2
Girder 3
Girder 4
Girder 5
Girder 6
Girder 7
Girder 8
Girder 9

b)



Strain (με)
Time (sec)
0
20
40
60
80
100
120
0
5
10
15
20
25
30
Girder 1
Girder 2
Girder 3
Girder 4
Girder 5
Girder 6
Girder 7
Girder 8
Girder 9

c)



d)

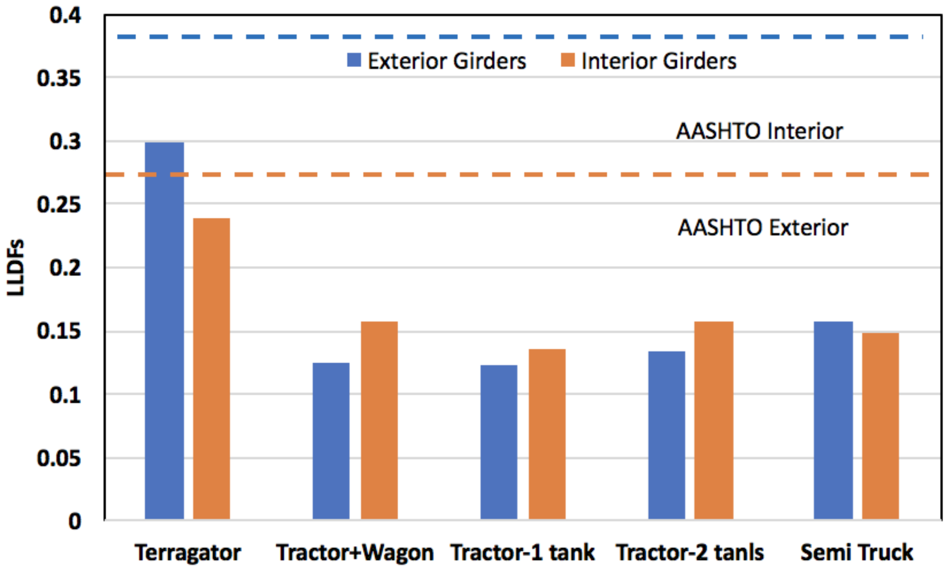
e)

Figure 0.19 Tensile strains due to a) a Terragator, b) a Tractor with grain wagon, c) Tractor with one tank, d) Tractor with two tanks, and e) Highway truck

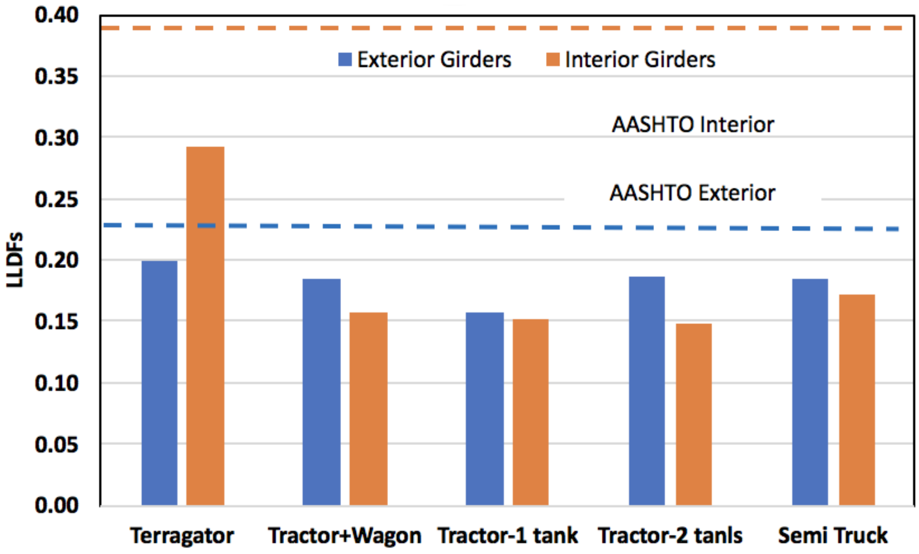
4.4 Shear Distribution Factors

The shear force distribution factors were calculated for the same cases presented in section 4.2. The key parameters were girder spacing, number of girders, and the speed of the farming vehicles over the studied bridges. Figure 4.20 shows the shear LLDFs versus the agricultural vehicle types. The Terragator produced a lower shear distribution factor of 0.14 for the exterior girders than the AASHTO design value of 0.23 for a girder spacing of 1.64 ft. For a girder spacing of 2.46 ft., the Terragator produced a higher shear LLDF of 0.24 than the AASHTO design value of 0.23. For the interior girders, none of the shear distribution factors for any of the farming vehicles exceedsx the AASHTO values. The other vehicles produced lower LLDFs compared than the Terragator.

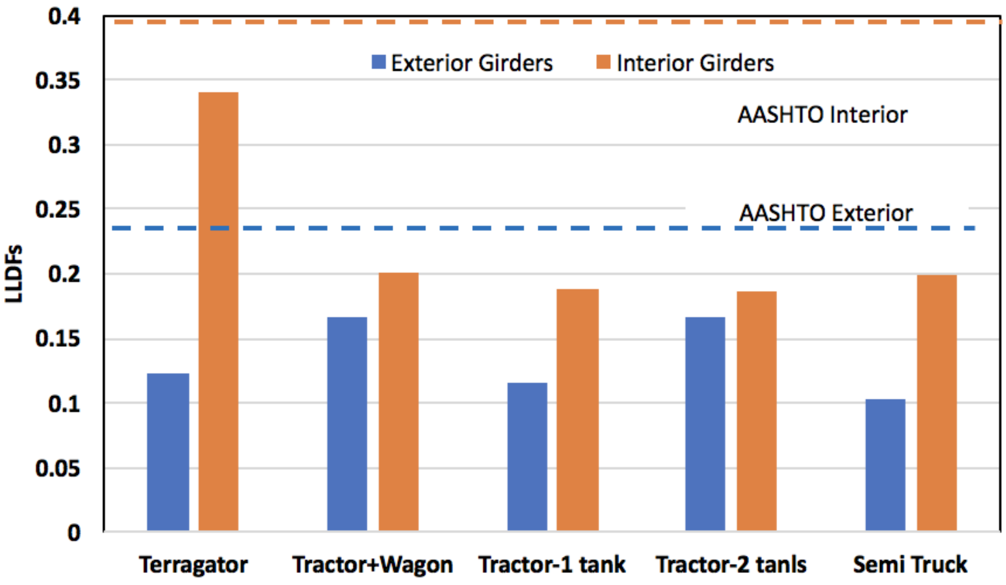
The LLDFs for the exterior and interior girders (girder spacing= 1.64 ft.) due to the Terragator were higher than the highway standard truck by 27 percent, and 9 percent, respectively. Similar observations were obtained when the girder spacing was increased to 3.28 ft., as the shear distribution factors were higher than the standard truck by 200.8 percent for the exterior girder and lower than the standard truck by 20 percent for the interior girders. At a girder spacing of 1.64 ft., the tractor with a grain wagon produced LLDFs for the exterior girder that were higher than those of the semi-truck by 27 percent, and the tractor with two tanks produced LLDFs that were 8 percent higher. For girder spacings of 4.10 and 4.92, the LLDFs for the standard truck were higher than the ones produced by the tractor with one and two tanks. Finally, the LLDFs for all exterior girders were almost zero.



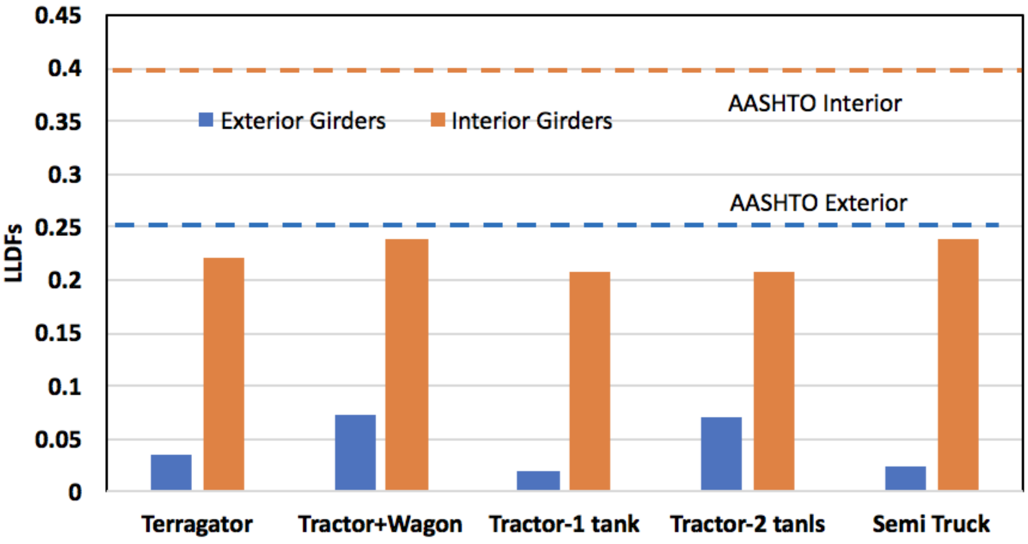
a) Girder Spacing 1.64 ft.



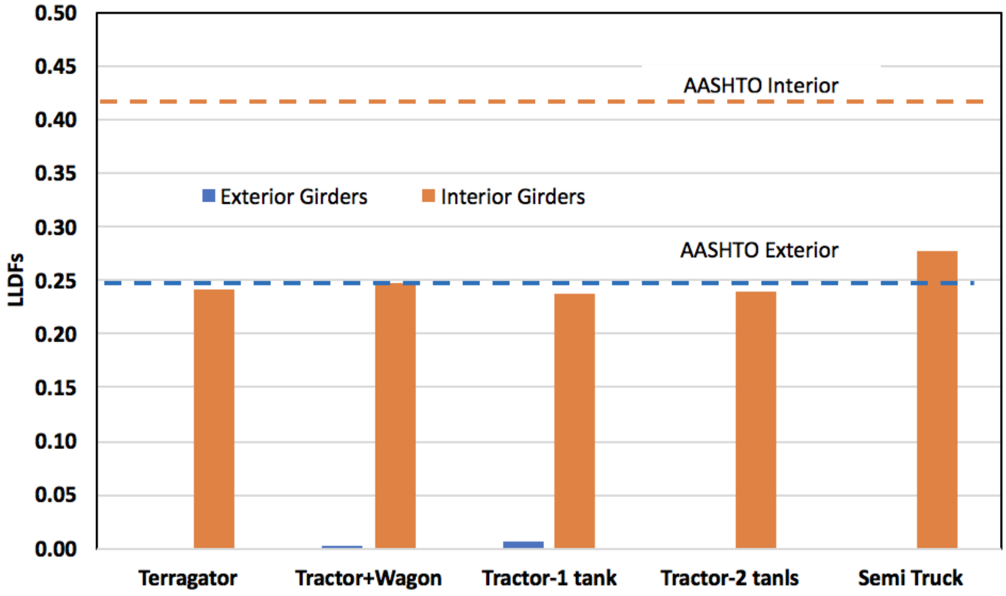
b) Girder Spacing 2.46 ft.



c) Girder Spacing 3.28 ft.



d) Girder Spacing 4.10 ft.



e) Girder Spacing 4.92 ft.

Figure 0.20 Shear force distribution factors due to a highway vehicle on a bridge with variable girder spacing

Figure 4.21a shows comparisons between the shear LLDFs resulting from the Terragator and the standard truck. The Terragator showed higher LLDFs for the exterior girders: 27 percent, 237 percent, and 267 percent for bridges with four, six, and nine girders, respectively. For the interior girders, the shear force distribution factors were 20 percent, 28 percent, and 10percent less than the standard truck for the bridge with four, six, and nine girders, respectively.

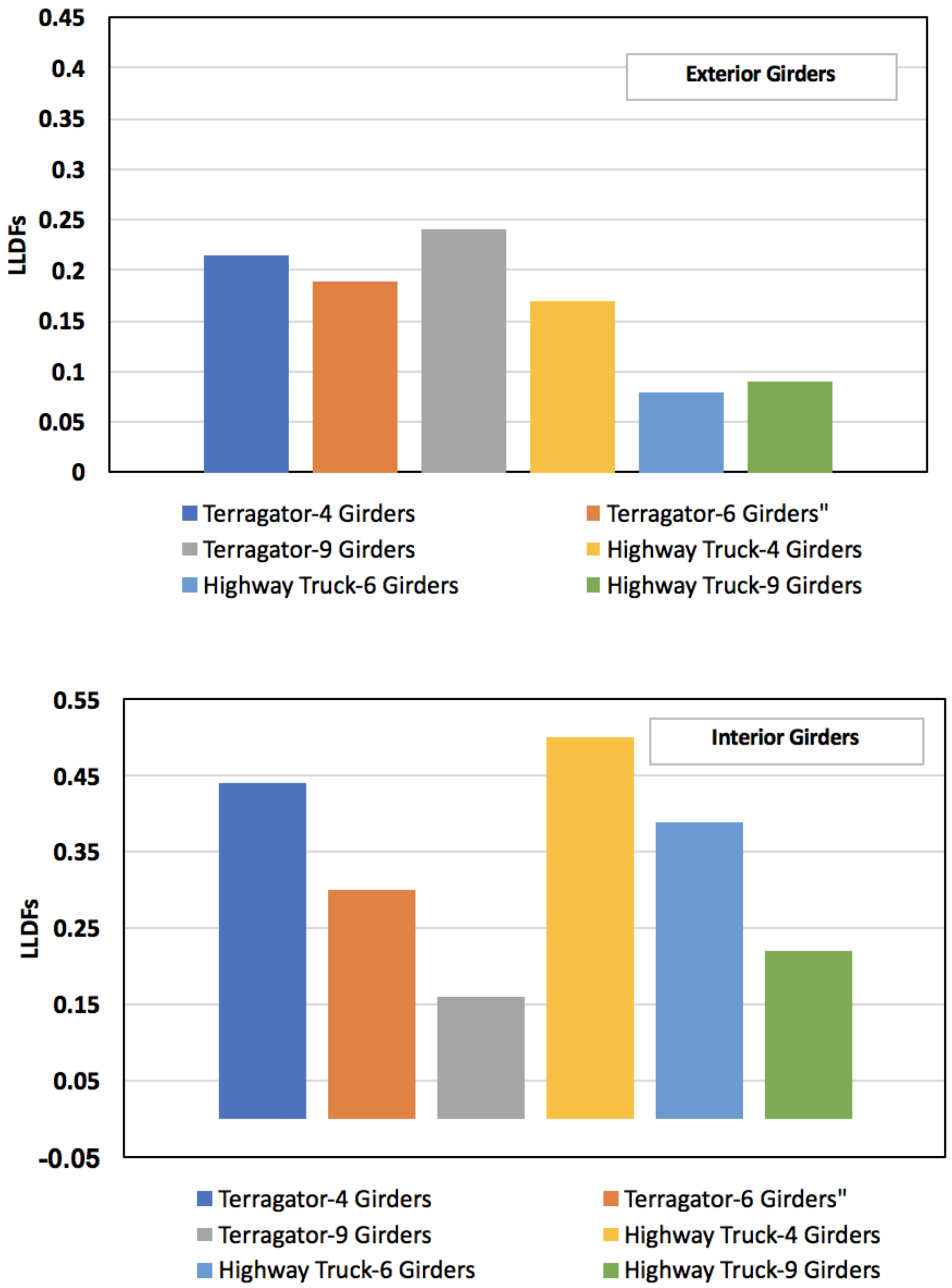
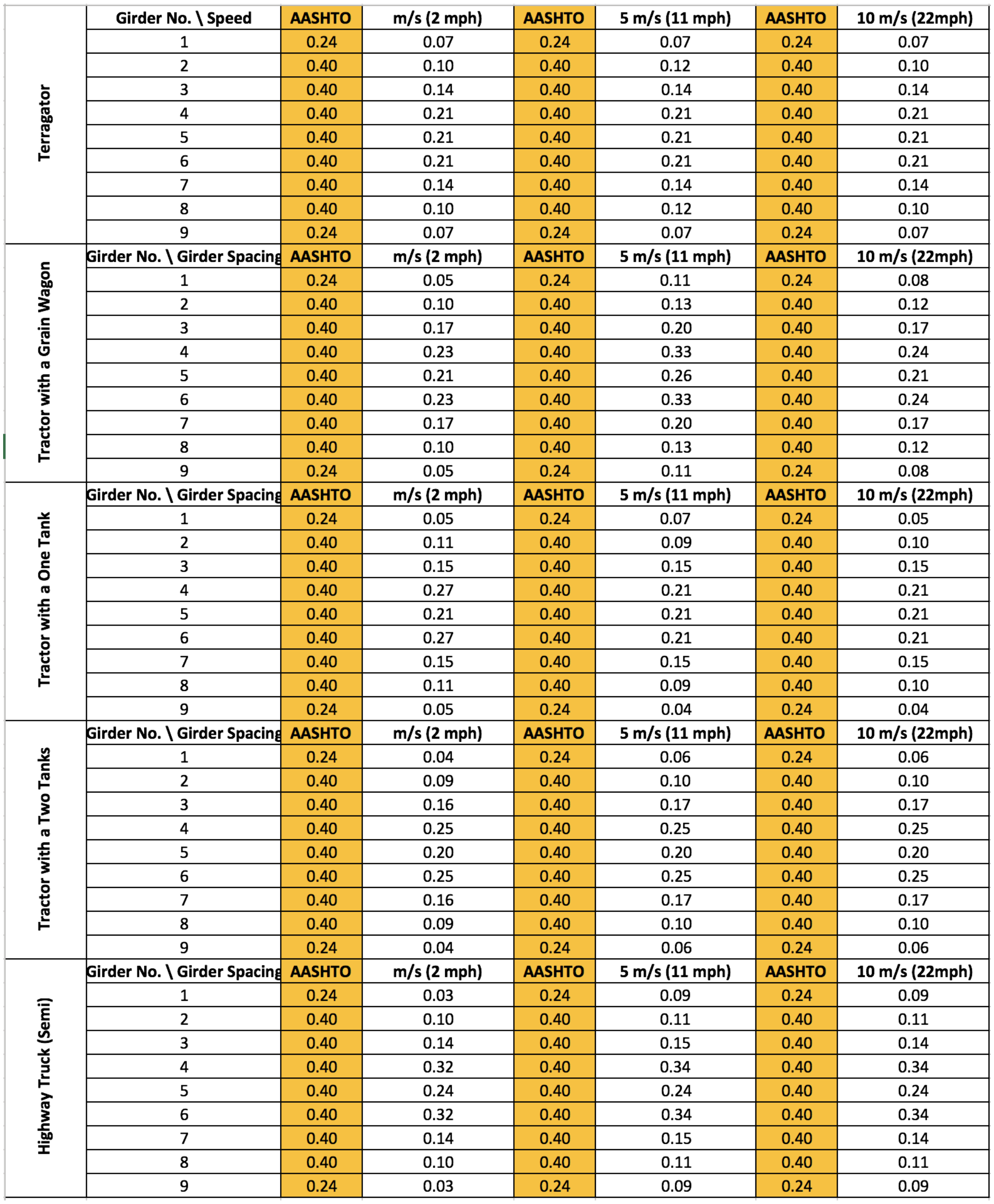


Figure 0.21 Comparison between LLDFs for the Terragator and the highway truck.

Finally, the speeds of the farming vehicles were varied from 2 mph to 22 mph while other bridge characteristics such as width and number of girders were kept constant. The speed of the vehicles did not drastically change the values of the LLDFs, as shown in table 4.1.

Table 0.1 Shear force distribution factors under various truck speeds



	Girder No. \ Speed	AASHTO	m/s (2 mph)	AASHTO	5 m/s (11 mph)	AASHTO	10 m/s (22mph)
Terragator	1	0.24	0.07	0.24	0.07	0.24	0.07
	2	0.40	0.10	0.40	0.12	0.40	0.10
	3	0.40	0.14	0.40	0.14	0.40	0.14
	4	0.40	0.21	0.40	0.21	0.40	0.21
	5	0.40	0.21	0.40	0.21	0.40	0.21
	6	0.40	0.21	0.40	0.21	0.40	0.21
	7	0.40	0.14	0.40	0.14	0.40	0.14
	8	0.40	0.10	0.40	0.12	0.40	0.10
	9	0.24	0.07	0.24	0.07	0.24	0.07
Tractor with a Grain Wagon	Girder No. \ Girder Spacing	AASHTO	m/s (2 mph)	AASHTO	5 m/s (11 mph)	AASHTO	10 m/s (22mph)
	1	0.24	0.05	0.24	0.11	0.24	0.08
	2	0.40	0.10	0.40	0.13	0.40	0.12
	3	0.40	0.17	0.40	0.20	0.40	0.17
	4	0.40	0.23	0.40	0.33	0.40	0.24
	5	0.40	0.21	0.40	0.26	0.40	0.21
	6	0.40	0.23	0.40	0.33	0.40	0.24
	7	0.40	0.17	0.40	0.20	0.40	0.17
	8	0.40	0.10	0.40	0.13	0.40	0.12
	9	0.24	0.05	0.24	0.11	0.24	0.08
Tractor with a One Tank	Girder No. \ Girder Spacing	AASHTO	m/s (2 mph)	AASHTO	5 m/s (11 mph)	AASHTO	10 m/s (22mph)
	1	0.24	0.05	0.24	0.07	0.24	0.05
	2	0.40	0.11	0.40	0.09	0.40	0.10
	3	0.40	0.15	0.40	0.15	0.40	0.15
	4	0.40	0.27	0.40	0.21	0.40	0.21
	5	0.40	0.21	0.40	0.21	0.40	0.21
	6	0.40	0.27	0.40	0.21	0.40	0.21
	7	0.40	0.15	0.40	0.15	0.40	0.15
	8	0.40	0.11	0.40	0.09	0.40	0.10
	9	0.24	0.05	0.24	0.04	0.24	0.04
Tractor with a Two Tanks	Girder No. \ Girder Spacing	AASHTO	m/s (2 mph)	AASHTO	5 m/s (11 mph)	AASHTO	10 m/s (22mph)
	1	0.24	0.04	0.24	0.06	0.24	0.06
	2	0.40	0.09	0.40	0.10	0.40	0.10
	3	0.40	0.16	0.40	0.17	0.40	0.17
	4	0.40	0.25	0.40	0.25	0.40	0.25
	5	0.40	0.20	0.40	0.20	0.40	0.20
	6	0.40	0.25	0.40	0.25	0.40	0.25
	7	0.40	0.16	0.40	0.17	0.40	0.17
	8	0.40	0.09	0.40	0.10	0.40	0.10
	9	0.24	0.04	0.24	0.06	0.24	0.06
Highway Truck (Semi)	Girder No. \ Girder Spacing	AASHTO	m/s (2 mph)	AASHTO	5 m/s (11 mph)	AASHTO	10 m/s (22mph)
	1	0.24	0.03	0.24	0.09	0.24	0.09
	2	0.40	0.10	0.40	0.11	0.40	0.11
	3	0.40	0.14	0.40	0.15	0.40	0.14
	4	0.40	0.32	0.40	0.34	0.40	0.34
	5	0.40	0.24	0.40	0.24	0.40	0.24
	6	0.40	0.32	0.40	0.34	0.40	0.34
	7	0.40	0.14	0.40	0.15	0.40	0.14
	8	0.40	0.10	0.40	0.11	0.40	0.11
	9	0.24	0.03	0.24	0.09	0.24	0.09

4.5 Regulating Implements of Husbandry on the Idaho Bridge Inventory

Idaho has a big road network (60,000 miles) that serves farms throughout the state and various commodities with enormous production values. Thousands of miles of local roads connect various farming points. The bridge inventory data showed that of Idaho's 4,492 highway bridges, 19.2 percent are structurally deficient. The harsh climate in Idaho, combined with the aging of the infrastructure, are reflected in the loads posted to the bridges in the inventory, as well as the number of structurally deficient bridges. The evolution of farming vehicles and farming activities nationwide has led to an increase in truck size and weight limits in many different places. Some farming vehicles now have a gross weight of 100,000 lbs., which induces forces and weights on bridges that exceed the standard truck weight design limit. Police have found various cases in which tractors with two tanks (100,000 lbs.) were supported by only a few axles moving on state highways.

4.6 Assessing the Resources Available for Analysis

There is no centralized database with size and weight information for farming vehicles in Idaho, and a process to query implement users was needed. The authors recommend extending the current study to investigate the effects of agricultural equipment and vehicles on the highway and non-highway bridge systems. A field investigation is needed to evaluate the most popular vehicles being used in the state of Idaho on local bridges, and that will produce truly comprehensive recommendations on how to regulate the implementation of agricultural vehicles.

The other way to regulate structural support for oversized and overweight vehicles is to develop software for live loads to check the moment and shear for various vehicles with multiple axles and weights at a time. The software should be prepared to use the vehicle type, picture, gross weight, axle loads, and spacing, whether or not that meets the bridge formula. The results of the developed code will tell users the expected impacts of such vehicles on a bridge under investigation.

Conclusions and Recommendations

Live-load distribution factors (LLDFs) for steel-concrete girder bridges loaded with different agricultural farming vehicles and a standard highway vehicle were investigated and determined on the basis of the LLDFs provided by the AASHTO LRFD, and, Finite Element Analysis (FEA) model simulations. The vehicles used for the simulation were four farm 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 the 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 from to nine, and the speed of the vehicles from 2 mph to 22 mph. All the analytical LLDFs were compared with those resulting from the AASHTO LRFD. The following conclusions were drawn:

- For most of the girder spacings and vehicle types, the analytical LLDFs values were lower than the AASHTO design values.
- The Terragator created a higher (4 percent) LLDF for the middle girder when the girder spacing was 1.64 ft, than the values obtained from the AASHTO code.
- When the spacing between girders increased, the Terragator showed very comparable LLDFs for the middle girder.
- At girder spacings of 4.10 ft. and 4.92 ft., the LLDFs were less than the AASHTO values by 57 percent and 56 percent, respectively, and for all other vehicles, the LLDFs were less than the AASHTO values.
- The LLDFs of the exterior and interior girders (girder spacing= 1.64 ft.) due to the Terragator were higher than the highway standard truck by 88 percent, and 62 percent,

  respectively. Similar observations were obtained when the 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 those of the standard highway truck by 70 percent on average.

  - The Terragator produced LLDFs for the exterior girders that were higher by 17 percent, 24.7 percent, and 93.6 percent for bridges with four, six, and nine girders, respectively. For the interior girders (a bridge with four girders), no significant difference in the LLDFs were observed. On the other hand, for bridges with six and nine girders, the Terragator resulted in higher LLDFs than the standard truck by 5 percent and 43 percent, respectively.
  - The shear LLDFs for the exterior and interior girders (girder spacing= 1.64 ft.) due to the Terragator were higher than the highway standard truck by 27 percent, and 9 percent, respectively.
  - The Terragator produced shear LLDFs for the exterior girders that were higher by 27 percent, 237 percent, and 267percent for bridges with four, six, and nine girders, respectively
  - The speeds of the vehicles had no significant impact on the shear of the moment LLFDs of the bridges.
- The authors recommend performing field tests to investigate the effects of agricultural vehicles on various bridges in Idaho under multiple key parameters, such as girder material types (timber, concrete, etc.), and girder spacing and configurations.

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