IMPACT OF AUTONOMOUS AND CONNECTED TRUCK PLATOONS IN THE PACIFIC NORTHWEST ON TRANSPORTATION INFRASTRUCTURE

FINAL PROJECT REPORT

by

Mohamed Elshazli, Ahmed Ibrahim and Ahmed Abdel-Rahim
National Institute for Advanced Transportation Technology (NIATT)
University of Idaho

for

Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700

In cooperation with U.S. Department of Transportation,
Office of the Assistant Secretary for Research and Technology (OST-R)

DISCLAIMER

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	**2. Government Accession No.** 01784882	**3. Recipient's Catalog No.**

4. Title and Subtitle Impact of Autonomous and Connected Truck Platoons in the Pacific Northwest on Transportation Infrastructure	**5. Report Date** 6-15-2022 **6. Performing Organization Code**
7. Author(s) and Affiliations Mohamed Elshazli, Ph.D. student, Department of Civil and Environmental Engineering, National Institute for Advanced Transportation Technology (NIATT University of Idaho. Ahmed Ibrahim, Ph.D, 0000-0002-3039-4560, Associate Professor, National Institute for Advanced Transportation Technology (NIATT), University of Idaho. and Ahmed Abdel-Rahim, Ph.D., P.E., 0000-0001-9756-554X, Professor, Director of National Institute for Advanced Transportation Technology (NIATT), University of Idaho.	**8. Performing Organization Report No.** 2021-S-UI-2
9. Performing Organization Name and Address PacTrans Pacific Northwest Transportation Consortium University Transportation Center for Federal Region 10 University of Washington More Hall 112 Seattle, WA 98195-2700	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** 69A355174110
12. Sponsoring Organization Name and Address United States Department of Transportation Research and Innovative Technology Administration 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** **14. Sponsoring Agency Code**

15. Supplementary Notes

Report uploaded to: www.pactrans.org

16. Abstract

The operational characteristics of freight shipments will significantly change after implementation of autonomous and connected trucks (ACTs). This change will have major impacts on mobility, safety, and infrastructure service life. Truck platooning is one of the truck arrangements that will soon become feasible with connected vehicle technology. It will enable trucks to be connected with themselves and the surrounding infrastructure. Although truck platooning will increase fuel efficiency and improve transportation services, the platooning configuration is expected to accelerate damage to the existing infrastructure. This damage, if accumulated, will cost the country billions of dollars to fix and will affect the mobility of people and goods. This research aimed to develop a well-defined framework for assessing and data-driven solution for addressing the influence of truck platoons on existing bridges in the Pacific Northwest to be ready for the near future implementation of ACTs and to preserve the current bridge inventory. An extensive parametric study of 59,200 models considering a wide range of parameters was conducted. Four bridge cases were included: simple span, two-span, three-span, and four-span bridges. The effects of bridge continuity was demonstrated by the two-, three-, and four-span bridges. Spans varied from 20 ft. to 200 ft. (6 m to 60 m), increments of 5 ft. (1.5 m). The HS-20 design truck was arranged, according to the parametric study, to form different platooning configurations by using up to 20 trucks at headway spacings varying from 10 to 30 ft. The results were then used to provide guidelines for the optimum parameters and load rating charts for future truck platooning applications.

17. Key Words Bridge; Truck; Platoon; Autonomous; Load Rating		**18. Distribution Statement**	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 109	**22. Price** N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AASHTO:	American Association of State Highway and Transportation Officials
ACT:	Autonomous and connected trucks
ADTT:	Average daily traffic
ASD:	Allowable stress design
ASR:	Allowable stress rating
AV:	Autonomous vehicles
DOT:	Department of transportation
FBF:	Federal Bridge Formula
FDOT:	Florida Department of Transportation
FHWA:	Federal Highway Administration
GVW:	Gross vehicle weight
LFR:	Load Factor Rating
LRFD:	Load and Resistance Factor Design
LRFR:	Load and Resistance Factor Rating
LFD:	Load Factor Design
MBE:	Manual for Bridge Evaluation
M-E PDG:	Mechanistic-Empirical Pavement Design Guide
MPF:	Multiple presence factor
NBI:	National Bridge Inventory
NCHRP:	National Cooperative Highway Research Program
NDOT:	Nebraska Department of Transportation
NJTA:	New Jersey Turnpike Authority
PacTrans:	Pacific Northwest Transportation Consortium
PDF:	Probability density function
RF:	Rating factor
SU:	Single unit
TRB:	Transportation Research Board
WIM:	Weigh in motion

ACKNOWLEDGMENTS

The authors acknowledge the resources provided to the researchers by the National Institute for Advanced Transportation Technology (NIATT) at the University of Idaho and the funding provided by the Pacific Northwest Transportation Consortium (PacTrans)

EXECUTIVE SUMMARY

The operational characteristics of freight shipments will significantly change after implementation of autonomous and connected trucks (ACTs). This change will have major impacts on mobility, safety, and infrastructure service life. Truck platooning is one of the truck arrangements that will soon become feasible with connected vehicle technology. It will enable trucks to be connected with themselves and the surrounding infrastructure. Although truck platooning will increase fuel efficiency and improve transportation services, platooning configurations are expected to accelerate damage to the existing infrastructure. This damage, if accumulated, will cost the country billions of dollars to fix and will affect the mobility of people and goods. This research aimed to develop a well-defined framework for assessing and a data-driven solution for addressing the influence of truck platoons on existing bridges in the Pacific Northwest to be prepared for future implementation of ACTs and to preserve the current bridge inventory.

SAP 2000 is commercial software that was used for the analysis, and the developed models were verified by using results obtained from the literature. A coded script was written using MATLAB to generate the input data files for SAP 2000 and to analyze the numerous output results. An extensive parametric study of 59,200 computer models that considered a wide range of variables was conducted. Four bridge spans were included: simple span, two-span, three-span, and four-span bridges. The effects on bridge continuity was demonstrated by the two-, three-, and four-span bridges. Spans varied from 20 ft. to 200 ft. (6 m to 60 m) with increments of 5 ft. (1.5 m). The HS-20 design truck was arranged to form different platooning configurations with up to 20 trucks, with headway spacing varying from 10 to 30 ft. The results were then used to provide guidelines for the optimum parameters and load rating charts for future truck platoons.

The specific conclusions drawn from this study are as follows:

- An increase in span length allowed more trucks to be fully accommodated on the bridge simultaneously, which increased the bending moment.
- As headway spacing decreased, the bending moment increased.
- Allowing two trucks to be fully accommodated on a simple span bridge simultaneously increased the maximum moment up to 77 percent for 200-ft. spans at a 10-ft. headway spacing, and this percentage decreased to 56 percent when the headway spacing increased to 30 ft.

- Allowing more than two trucks to be fully accommodated on a simple span bridge increased the bending moment by as much as three times the single truck moment.
- The shear force results for simple span bridges had the same as that for bending moments.
- For continuous spans, critical positive moments for long-span bridges (longer than 100 ft.) occurred when the maximum number of trucks was located on a single span. Therefore, continuous bridges with short and medium spans (shorter than 100 ft.) were not expected to experience a considerable increase in positive moment because their spans could not accommodate many trucks at the same time.
- The critical negative moment for short and medium span bridges (up to 100 ft.) occurred when two adjacent spans were loaded simultaneously. Bridges with spans shorter than 75 ft. showed a significant increase in negative bending moment in comparison to the AASHTO 90 percent design live load condition.
- In comparison to simple span bridges, continuous bridges would be expected to experience a reduction in positive moments because of the development of negative moments. Also, internal shear forces would be expected to be higher than the maximum shear force in simple span bridges.
- The average reductions in positive moments were around 21 to 24 percent for two-span bridges, 18 to 22 percent for three-span bridges, and approximately 19 to 23 percent for four-span bridges.
- The linear regression models showed acceptable results, with an R^2 of more than 95 percent, while polynomial and exponential models showed a great ability to predict the results, with an R^2 of more than 99 percent.
- Charts were developed to determine the percentage of bridge load rating reduction based on the number of trucks and the headway distance.

CHAPTER 1. INTRODUCTION

1.1. Background

Transportation is the second-largest consumer of oil in the U.S. (around 52 million barrels per day). Within the transportation segment, freight movement has the most significant oil demand, and freight vehicles consume about 17 million barrels per day. This demand is predicted to increase by 240 percent by 2050 (Teter et al., 2017). Significant attempts are being made to improve freight vehicle oil efficiency. Gungor et al. (2016) proposed the implementation of wide-base tires, while Smith et al (2012) proposed an alternative truck design to enhance their aerodynamic characteristics. If freight trucks are positioned very closely in such a way to follow one another (using autonomous and connected truck (ACT) technology), this platooning configuration might enhance transport efficiency. The spacing between platoons might be as close as 30 feet, enabling good connectivity between trucks and infrastructure (Browand et al., 2004). The platooning configuration uses sensors to gather data that control the trucks' braking systems and speeds. The technology uses a forward collision avoidance system and vehicle-to-vehicle communication to allow two trucks to travel closely (Bergenhem et al., 2012, TxDOT/FHWA, 2017). The close distance between platooning trucks improves the aerodynamic characteristics (drag coefficient) of the whole fleet, decreasing the overall drag coefficient (Gaudet and Eng, 2014). In the platooning configuration, the leading truck blocks the air flowing to the trailing trucks, enhancing the pressure drag and increasing mobility and efficiency.

The 615,000 bridges in the U.S. are currently designed for a hypothetical live-load model that comprises the effects of extreme forces from current conventional truck configurations. Soon with the implementation of platoon ACT technology, those bridges may no longer be safe to operate, requiring all transportation departments to load rate those bridges. Platoons usually include three to four trucks; however, the future of ACTs will definitely include more trucks (perhaps up to 10). The effects of the number of trucks and spacing between them in a platoon need to be determined to enable stakeholders to evaluate the transportation infrastructure.

The number and spacing of trucks in a platoon need to be optimized. A platoon is modeled as a series of axle loads to let the whole platoon be treated as one long truck. Several steps must be taken by infrastructure owners to introduce platooning safely into practice. More research is needed to develop practice design procedures and standards for new and existing infrastructure, given new truck platooning loads. In addition, engineering assessment and evaluation of existing transportation infrastructure must be undertaken with the swift implementation of ACT technology.

The bridge weight formula was ratified by Congress in 1975 to limit the maximum allowable weight on bridges. In 2000, a U.S. Department of Transportation study found that each state has its own vehicle weight limits, and some states allow higher truck loading above 80,000 lbs. (the federal gross weight limit). For example, Idaho allows 129,000-lb. trucks on specific routes. Studies have been carried out to estimate what replacement costs would be if legal loads were increased (Wassef, 2017); however, none has addressed the impacts of truck platooning on existing bridges.

1.2. Research Objectives

The main objectives of this project were as follows:

- Evaluate the impacts of different truck platooning configurations on existing bridge load ratings.
- Develop a framework to determine how much a platoon permit load might be increased based on different configuration characteristics.
- Provide general guidelines for managing and implementing truck platooning at operating and inventory level ratings.
- Provide charts and tables that can be used for future work to find the optimum platooning configuration for a specific bridge.
- Provide regression equations that can be used to calculate the effects of different truck platooning configurations.

1.3. Research Scope

An extensive parametric study of 59,200 computer models was conducted to address the impacts of a wide range of platoon configurations on the load ratings of existing bridges as a new load case. The parameters under the scope of this study were as follows:

- Bridge number of spans: simple-, two-, three-, and four-spans.
- Length of spans: 20 to 200 ft.
- Number of trucks: 1 to 20.
- Spacing between trucks: 10 to 30 ft.
- ASR, LFR, and LRFR load ratings for moment and shear.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

The operational characteristics of freight shipments will significantly change after implementation of autonomous and connected trucks (ACTs). This change will have major impacts on mobility, safety, and infrastructure service life. Truck platooning is one of the truck arrangements that soon will become feasible with connected vehicle technology. It will enables truck to be connected with themselves and the surrounding infrastructure. Although truck platooning will increase fuel efficiency and improve transportation services, platooning configurations are expected to accelerate damage to existing infrastructure such as pavements and bridges. This chapter describes an in-depth literature review, including a detailed discussion of the implementation of truck platooning and its effects on the load carrying capacity of infrastructure.

2.2. Connected and Automated Driving Trucks

The transportation sector has become the second-largest consumer of energy in the United States, with an oil demand of 52 million barrels per day (Gungor et al., 2020). Freight shipping is considered one of the critical components in the transportation sector, with significant oil consumption. Statistics show that freight vehicles consumed 17 million barrels per day in 2016, and this demand is expected to increase 2.5 times by 2050 (Teter et al., 2017).

Much research has been done to reduce the oil demand of freight vehicles. Innovative solutions have been introduced to improve vehicle fuel efficiency, such as utilizing wide-base tires (Gungor et al., 2016), improving the aerodynamic design of trucks (Gungor et al., 2018), and optimizing truck routes (Suzuki, 2011). If freight trucks are placed very closely one after another (by using autonomous and connected truck technology) then this platooning configuration is expected to enhance transportation efficiency **(**figure 2.1**).** The distance between trucks in a platoon may be as close as 10 ft. This will enable good connectivity between trucks and infrastructure (Browand et al., 2004). This platooning configuration will use sensors to gather data to control a truck's braking system and speed. A forward collision avoidance system and vehicle-to-vehicle communication will also be used to allow two trucks to travel close to each other (Bergenhem et al., 2012; Bishop, 2017; TxDOT/FHWA, 2017).

Figure 2.1 A three-truck platoon (U.S. Department of Transportation)

Recently, autonomous and connected truck technology has been tested for application in several U.S. states and other countries. The stakeholders (governments, transportation companies, and technology developers) have spent significant effort studying the consequences of applying this innovative technology. In addition to saving fuel consumption, truck platoons are expected to reduce traffic congestion, reduce carbon dioxide emission, improve travel safety, and speed the delivery of goods (Bishop, 2017).

The total drag force incurred by every truck in the platoon could be reduced by placing trucks at small inter-vehicle spacing. Zabat et al. (1995) performed a wind tunnel test to study the effects of headway spacing on the truck aerodynamics. The results showed that the drag force was affected by the relative position of the adjacent vehicle. It was also observed that there was no reduction in the drag force when the vehicles were placed farther apart or were entirely misaligned. The aerodynamic drag was mainly caused by the difference in pressure between the front and rear parts of a truck (Gaudet and Eng, 2014). In a platoon, the front truck blocks the air, which lowers the pressure in the frontal zone and reduces the pressure drag on trailing trucks. In addition, the trailing trucks compress the turbulent flow, which increases the pressure in the rear area and decreases the pressure drag on the leading truck. This reduction in aerodynamic drag increases fuel efficiency and reduces fuel consumption.

A wide range of studies has been carried out to evaluate the effectiveness of platooning configuration on fuel consumption. Two tandem trucks traveling at a speed of 50 miles per hour (80 *km/hr.*) were arranged to create a platoon with inter-vehicle spacing of 30 ft. (10 *m*) (Tsugawa et al., 2016, Bonnet and Fritz, 2000). The results showed a reduction in fuel consumption by 20 percent for the trailing truck and 6 percent for the leading truck. Browand et al. (2004) performed a study using two identical trucks spaced at 10, 13, 20, 26, and 30 ft. (3, 4, 6, 8, and 10 *m*) and traveling at speeds of 30 and 50 miles per hour. The results showed an average savings in fuel consumption of 11 percent for a 10- to13-ft. headway and 8 percent for a 26- to 30-ft. headway.

Overall, saving fuel strongly depends on the truck's position within the platoon. Interior vehicles experience the most savings in fuel consumption, 10 percent more than the "traveling-in-isolation" value. Increasing the number of trucks in a platoon increases the average fuel savings for the whole configuration. Average fuel savings of 5.5, 7.5, and 8.5 percent have been reported for two-, three-, and four-truck platoons, spaced at 10 ft. (3 *m*), respectively (Michaelian and Browand, 2001). Additional research has shown the effectiveness of using truck platoons (Lu and Shladover, 2011, Tsugawa et al., 2011, Tsugawa, 2014, Robinson et al., 2010, Eilers et al., 2015, Jacob and de Chalendar, 2018, Lammert et al., 2014, Alam et al., 2015, Humphreys et al., 2016). In addition to saving on fuel consumption, truck platoons are expected to reduce traffic congestion and improve travel safety.

2.3. Impacts of ACTs on Existing Infrastructure

Although truck platooning will increase fuel efficiency and improve transportation services, the platooning configuration is expected to accelerate damage to the existing infrastructure. Previous research has illustrated the negative impact of truck platooning on existing pavement. Chen et al. (2016) numerically studied the long-term consequences of road infrastructure after the implementation of ACTs. A potential for accelerated pavement rutting has been observed with a decrease in a vehicle's wheel wander and increase in lane capacity. However, an increase in traffic speed can diminish this effect. Salama et al. (2007) calibrated the FHWA Mechanistic-Empirical Pavement Design Guide (M-E PDG) method to improve its prediction of pavement rutting due to multiple axles. The rutting damage has been shown to be proportional to the number of axles. Tirado et al. (2010) has also demonstrated that pavement damage depends on the truck's gross vehicle weight and the number of axles.

The 615,000 U.S. bridges are currently designed for a hypothetical live-load model that includes the effects of extreme forces resulting from the current conventional truck configuration. Soon with the implementation of ACT technology, those bridges might not be safe to operate (Sayed et al., 2020), requiring all transportation departments to load rate those bridges.

Platoons usually include three to four trucks; however, the future of ACTs will definitely include more trucks (maybe up to ten). The appropriate number of trucks and the spacing between them need to be determined to enable stakeholders to evaluate the transportation infrastructure.

A study was done by the Florida Department of Transportation (FDOT) (DeVault and Beitelman, 2017) on the impact of two platooned trucks on bridges. The existing National Bridge Inventory (NBI) rating factors were scaled to estimate the load rating for truck platoons. The results showed a need to improve the load rating methodology to consider new truck platoons with different configurations and bridge conditions.

Kamranian (2018) evaluated the effects of Alberta Permit and Non-Permit truck platoons by using two, three, and four trucks on the Hay River Bridge. The bridge had shown an adequate capacity for two trucks, but the load ratings were insufficient when three and four trucks were used. Couto Braguim et al. (2021) found that while truck platooning induces high load effects, the fatigue damage decreases because of a reduction in the number of stress cycles.

Another study was done by Yarnold and Weidner (2019) to identify possible situations in which the design of existing bridges may not be adequate for the implementation of truck platooning. Simple, two-, and three-span steel bridges, with span lengths of between 20 and 200 ft. (6 and 91 *m*) at 20-ft. (6 *m*) increments, were included in this study. The Florida C5 five-axle semi-tractor trailer was used in this study. Five headway spacings (20, 25, 30, 35, and 40 ft.) were considered in the study. The results for existing bridges, designed according to AASHTO Standard Specifications for Highway Bridges, revealed many concerns related to positive bending and shear forces, which could restrict the future implementation of truck platoons on these old bridges. On the other hand, bridges designed according to the AASHTO LRFD were adequate for a wide range of platoon configurations. The critical case happened when longer span bridges were subjected to closely spaced platoons. However, the negative impact of truck platooning could be controlled by setting limitations and regulations on truck spacing within the platoon.

Tohme and Yarnold (2020) studied the effects of using truck platooning on the load rating of steel bridges. This study used the AASHTO Manual for Bridge Evaluation (MBE) A1 example bridge cross-section, shown in figure 2.2. This cross-section was used as a benchmark; then the girders were redesigned for different spans. Simple, two- and three-span bridges with span lengths of 20, 66, 112, and 245 ft. (6, 20, 37, and 74 *m*) were included in the study. Two-, three-, and four-truck platoons with a Florida C5 five-axle semi-tractor trailer were used again in this study. This study considered two headway spacings (20 and 40 ft.). Each bridge was load rated by using the three load rating methods: Allowable Stress Rating (ASR), Load Factor Rating (LFR), and Load and Resistance Factor Rating (LRFR). If the ratio of the truck platoon to the design operating rating factor was greater than 1.0, then the bridge was adequate. Otherwise, the ratio of the truck platoon to legal load rating was calculated. If this ratio was greater than 1.0, then the bridge was sufficient for truck platooning. On the basis of the Tohme and Yarnold (2020) study, bridges rated with ASR experienced a reduction in bending moment rating factors for almost all spans. Although bridges rated with LFR were adequate for positive moments, they experienced a reduction in the rating factor for negative moments. Finally, LRFR bridges did not show any issues with negative moment ratings. However, there was a reduction in the rating factor for the positive moment for longer spans with closely spaced trucks.

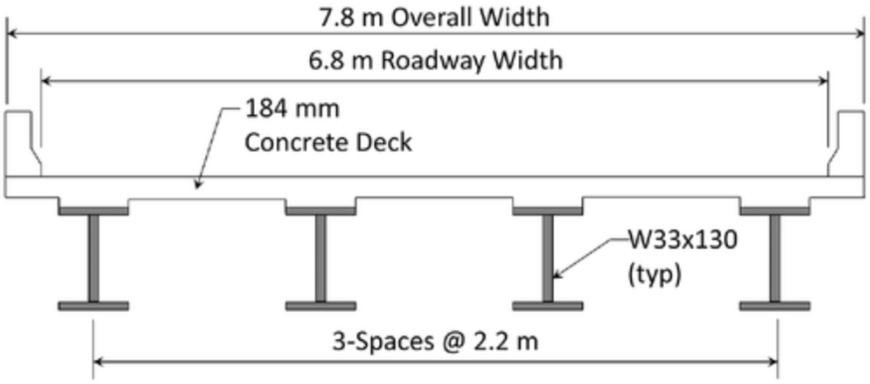

Figure 2.2 AASHTO MBE example bridge A1 cross-section (Tohme and Yarnold, 2020)

A new bridge prioritization methodology was developed by Thulaseedharan and Yarnold (2020) for the future application of truck platooning. The NBI database was used to select the bridges and gather the required information for the study. On the basis of data obtained from the NBI database, the bridge design methodology was identified depending on the year built. After that, bridge load ratings were evaluated for the original case and the case in which platooned trucks were used. This study considered six different five-axle truck types: the Alabama 3S2 AL (18-wheeler), Delaware T540 (DE 5 axle Semi), Florida C5, Kentucky Type 4, Mississippi HS-Short, and AASHTO Type 3S2. Two- and three-truck platoon configurations were considered with headway spacings of 30 and 40 ft. (9 and 12 *m*). The load rating results showed a reduction in the rating factors with an increase in the bridge's span resulting from the increased number of trucks that could fit on a single span. That's why the spacing between trucks within a platoon significantly affects bridge load rating. Truck type and axle weights also have a moderate influence on bridge loads. The heavier and shorter the trucks, the more damage they can do to the bridge.

2.4. Reliability Analysis

Structural reliability is a method for evaluating the structural probability of failure through the reliability index (β). A general limit state function containing the resistance (R) and load effect (Q) was provided by Nowak and Collins (2012), see **(**Equation 2.1**)**

$$g(R, Q) = R - Q \qquad \text{(Equation 2.1)}$$

where R and Q are random variables having their own probability density function (PDF). Figure 2.3 shows the PDF of the Load, Resistance, and Safety Index. The structure is considered safe when the R – Q is greater than zero. On the other hand, when the R – Q is less than zero, the structure is considered unsafe, and this area represents the probability of failure, as shown in figure 2.3.

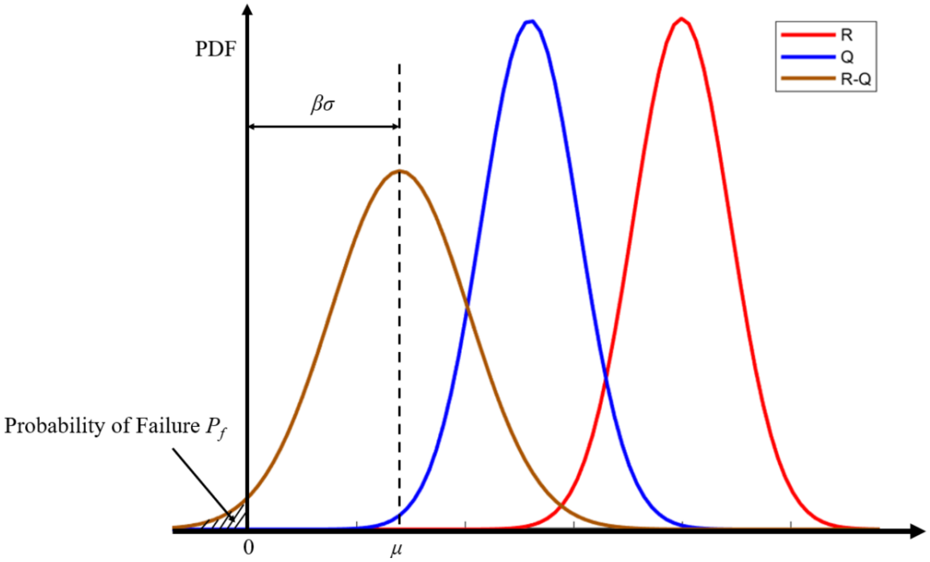

Figure 2.3 PDF of Load, Resistance, and Safety Index (Steelman et al., 2021)

As described in NCHRP report 368, Nowak (1999) used two weeks of weigh in motion (WIM) data obtained in Canada to estimate the load effects of different truck designs to calibrate the LRFD method. Load and resistance factors were proposed to satisfy a minimum reliability index (β) of 3.5 for the LRFD method. Live load factors were calibrated by Moses (2001) using the same data used by Nowak (1999). The resistance was assumed to be affected just by the live load effect, which was not a reasonable assumption, especially for long-span bridges. Kulicki et al. (2007) updated the calibrated load and resistance factors in NCHRP report 368 to take into account an updated database of bridges designed with ASD, LFD, and LRFD specifications, with different structural configurations and materials, including prestressed concrete I-beams, reinforced concrete T-beams, non-composite and composite steel girders, and simple-span and continuous bridges. Much other research work has been done to calibrate load factors using different WIM data and truck designs (Bala Sivakumar, 2011, Barker and Puckett, 2016, Sivakumar, 2007, Sivakumar et al., 2011). Not much work has been done to consider the effects of truck platooning configurations.

Steelman et al. (2021) used the WIM data from Barker and Puckett (2016) and the live load characterization methodology used by Nowak (1999) to evaluate the potential effects of platooning adjacent to heavy traffic routes. Numerous parameters were considered, such as girder spacing, spans, number of spans, number of trucks, headway spacing, and the presence of multiple factors. The results showed that platooning loads were significantly higher than legal loads. However, this could be acceptable with lower uncertainties while maintaining a reliability operating index of 2.5.

CHAPTER 3. RESEARCH METHODOLOGY

3.1. Overview

This research aimed to develop a well-defined framework for assessing and data-driven solution for addressing the influence of truck platoons on existing bridges in the Pacific Northwest to be ready for the near future implementation of ACTs and to preserve the current bridge inventory. An extensive parametric study of 59,200 computer simulations was conducted to address the impacts of a wide range of platooning configurations on the load ratings of existing bridges as a new load case. The results were then used to provide guidelines for the optimum parameters for future applications. SAP 2000, a structural analysis software, was used for the analysis, and the model was verified by using the results obtained from Sayed et al. (2020). A coded script was written with MATLAB to generate the input data files for SAP 2000 and analyze the numerous output results.

3.2. Methodology

This section describes the methodology used in this research to achieve the project objectives. As mentioned earlier, the main aim of this study was to develop a well-defined framework for assessing and data-driven solution for addressing the future application of truck platooning. The following methodology was prepared to provide general guidelines that can be used for any bridge that lies within the limits of the parametric study. First, an extensive parametric study was conducted to find the straining actions of different truck platooning configurations on different bridge cases. The results were then used to evaluate the changes in bridge load ratings and to find optimum truck platoon configurations. Finally, regression models were developed to help with future study and implementation. More details are discussed in the following sections.

3.2.1. Parametric Study Matrix

An extensive parametric study of 59,200 computer models was designed to investigate the effects of different truck platooning configurations on the load ratings of existing bridges. A wide range of parameters was included, such as the number of bridge spans, span lengths, number of truck platoons, and spacing between trucks (headway). Table 3.1 shows the parametric study matrix. The results of moment and shear were computed for the exterior and interior spans for each bridge case.

Table 3.1 Parametric study matrix

Parameter	**Variables**
No. of Spans (4 variables)	Simple Span, Two Spans, more than Two (Three and Four)
Spans (ft.) (37 variables)	20, 25, 30, 35, 40, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195, and 200
No. of Trucks (20 variables)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20
Spacing between Trucks (ft.) (20 variables)	10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, and 30

3.2.1.a Bridge Type

Four bridge cases were included in this study: simple spans, two spans, three spans, and four spans. The effect of bridge continuity was demonstrated by the two-, three-, and four-span bridges. The spans varied from 20 ft. to 200 ft. (6 m to 60 m) with increments of 5 ft. (1.5 m).

3.2.1.b Truck Type

Much research work has been carried out by many state departments of transportation (DOTs) to find a reliable truck that can effectively represent different types of trucks, which reduces the uncertainty involved in live load calculations. Knowing actual load spectra can reduce costs of replacement and repair and increase the life cycle of bridges. For this purpose, an extensive WIM project, sponsored by the Federal Highway Administration (FHWA), was carried out to develop a crucial truck-weight database. Truck weights were measured by stationary scales located on various highways in the United States for many years (Nowak et al., 1993).

The federal legislation regulating truck weights, also known as the Federal-Aid Highway Act, set the maximum gross vehicle weight as 80,000 lb. (356,000 N). The federal limits for individual axle and tandem weights are 20,000 lb. (89,000 N) and 34,000 lb. (151,000 N), respectively (Ghosn, 2000). The Federal Bridge Formula (FBF), also known as the Bridge Weight Formula, was enacted in 1975 to regulate axle group weight (see Equation 3.1). The equation was designed to avoid overstressing bridges by more than 5 percent, and was designed based on the HS-20 design truck (James et al., 1985).

$$W = 2{,}224\left(\frac{0.305BN}{N-1} + 12N + 36\right) \qquad \text{(Equation 3.1)}$$

where W is the overall gross vehicle weight of any group consisting of two or more axles in newtons (N); B is the length of the axle group in meters (m); N is the number of axles in the group.

Many states' DOTs have criticized the Federal Bridge Formula (FBF) for being overly conservative. Different jurisdictions, such as the province of Ontario, Canada, the state of Michigan, and other states, allow higher truck weights than the weights enacted by the FBF for the same bridges designed according to AASHTO code criteria (Agarwal, 1978, Harman, 1985). However, observation of those bridges has shown no deterioration nor a reduction in life cycle in comparison to other bridges (Ghosn, 2000). Therefore, the FHWA developed another truck weight formula referred to as the TTI Formula. The new formula has been designed according to the same overstressing criteria in the FBF, but it has more capabilities for heavier trucks. More weights for short vehicles are allowed **(**Equation 3.2), while the weights for longer trucks are reduced **(**Equation 3.3**)** (James et al. 1985). The TTI Formula can be written as follow:

$$W = 4{,}448(34 + 3.28 \cdot B) \qquad for\ B < 17\ m \qquad \text{(Equation 3.2)}$$

$$W = 4{,}448(62 + 1.64 \cdot B) \qquad for\ B > 17\ m \qquad \text{(Equation 3.3)}$$

where W is the overall gross vehicle weight of any group consisting of two or more axles in newtons (N); B is the length of the axle group in meters (m).

In 1990, the TTI Formula was improved by the Transportation Research Board (TRB) to allow more truck gross weights while reducing the limits of the axle weight for HS-20 bridges only. The TRB recommended that all states establish truck permits to allow trucks with up to nine axles to carry over 80,000 lb. (356,000 N) if they satisfy the FBF given in Equation 3.1 (Study and Council, 1990).

According to the FHWA report in 2015, the FBF is being followed in all states. However, truck weights may exceed the FBF in some states on non-Interstate highways. A study by Wassef (2017) provided a roadmap of actions to show the replacement costs that each state could spend in the case of increased loads. Implementation of autonomous connected trucks (ACTs) or truck platooning is expected to increase the loads on existing bridges designed with the current AASHTO code criteria. However, there is a lack of data in the literature to address the impacts of platooned trucks on existing bridges.

A limited number of studies have been conducted on this subject. The FHWA sponsored a study to identify the optimum platoon configuration based on the WIM data available from ten states. The FHWA Class 9 configuration, shown in figure 3.1, was used in this study. A recent study by Steelman et al. (2021), sponsored by the Nebraska Department of Transportation, was carried out to evaluate the impacts of truck platooning on existing bridge load ratings and live load factor calibration. The New Jersey Turnpike Authority (NJTA) Type 3S2 configuration, shown in figure 3.2, which the NJTA uses, was selected for that study. The NJTA Type 3S2 has a gross vehicle weight (GVW) of 80,000 lb., which follows the upper limit of the FBF. A study carried out by the Florida Department of Transportation (FDOT) (DeVault and Beitelman, 2017) indicated that the FDOT C5 truck, shown in figure 3.3, is expected to be more commonly used when ACT technology is implemented. As a result, Tohme and Yarnold (2020) considered the FDOT C5 truck in their study to find the impacts of truck platooning on the load ratings of steel bridges. Thulaseedharan and Yarnold (2020) provided a new bridge prioritization methodology for future applications of ACTs. Six different five axle truck types were considered: the AASHTO Type 3S2 (figure 3.4), the Alabama 3S2 AL (18-wheeler) (figure 3.5), Delaware T540 (DE 5 axle Semi) (figure 3.6), Florida C5 (figure 3.3), Kentucky Type 4 (figure 3.7), and the Mississippi HS-Short (figure 3.8).

The majority of U.S. bridges are designed on the basis of two live load models (HS-20 and HL-93), according to AASHTO. The HS-20 is a notional live load configuration that comprises the response from a truck and lane load. The HL-93 is another notional live load configuration that comprises a combination of truck and lane loads or tandem and lane loads. Figure 3.9 shows the characteristics of the HS-20 and HL-93 design trucks. No previous studies have considered the effects of the standard AASHTO design truck as a platoon. Therefore, the HS-20 and HL-93 design live loads were used in this study. Because the main objective of this study was to illustrate increases in live loads, the lane load was considered to be a common value and eliminated from the equation. According to the parametric study matrix, the HS-20 truck was arranged to form a platoon.

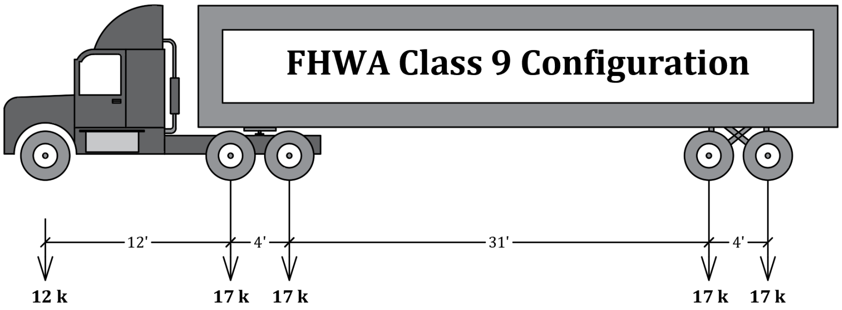

Figure 3.1 FHWA Class 9 configuration (GVW = 80,000 lb.)

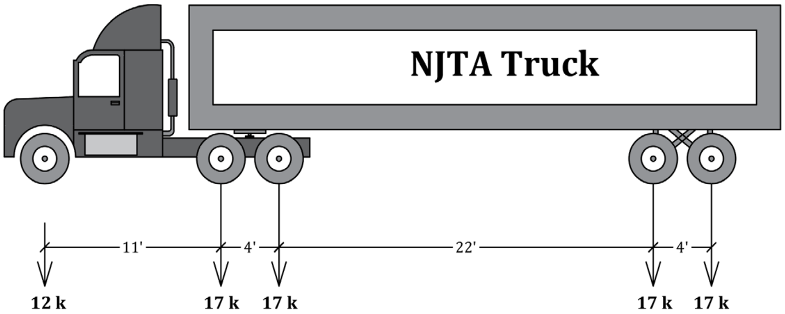

Figure 3.2 Type 3S2 configuration modified for NJTA (GVW = 80,000 lb.)

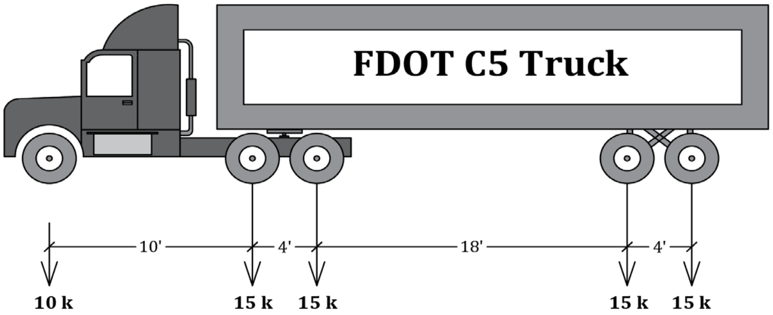

Figure 3.3 FDOT C5 Truck (GVW = 70,000 lb.)

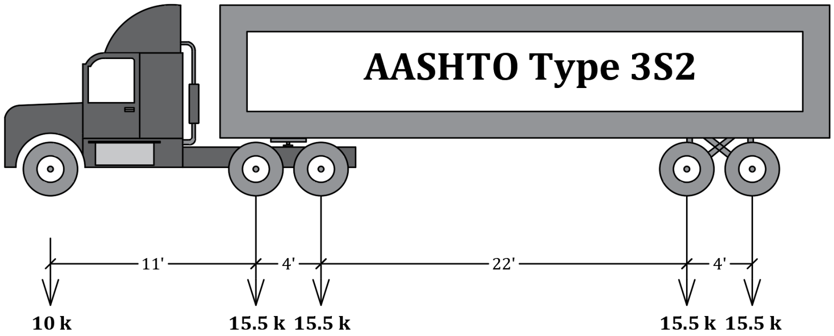

Figure 3.4 AASHTO Type 3S2 (GVW = 72,000 lb.)

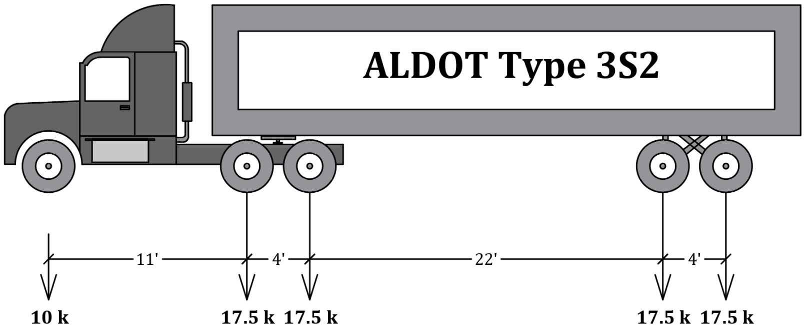

Figure 3.5 Alabama Type 3S2_AL (18-Wheeler) (GVW = 80,000 lb.)

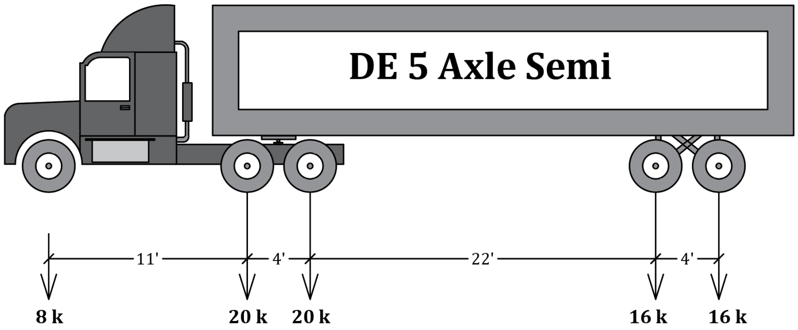

Figure 3.6 Delaware T540 (DE 5 Axles Semi) (GVW = 80,000 lb.)

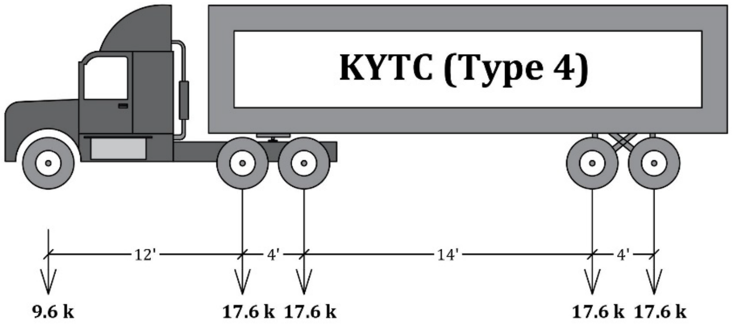

Figure 3.7 Kentucky (Type 4) (GVW = 80,000 lb.)

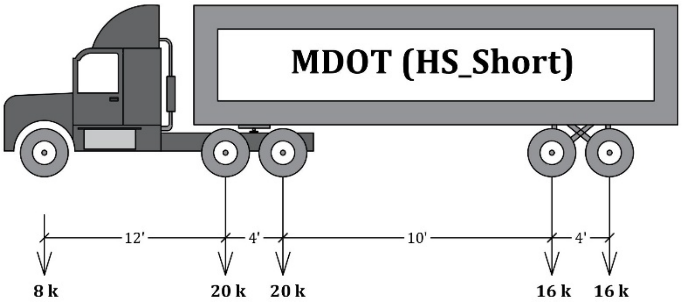

Figure 3.8 Mississippi HS-Short (GVW = 80,000 lb.)

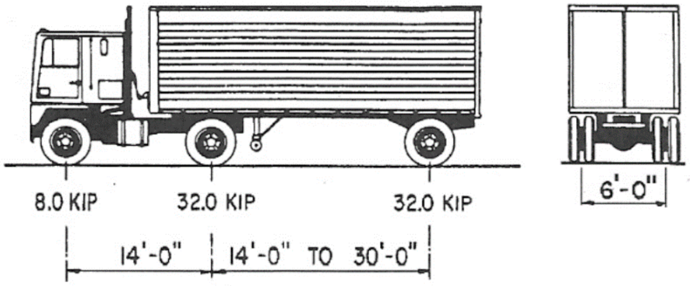

Figure 3.9 Characteristics of the HS-20 and HL-93 design truck (AASHTO LRFD 2020)

3.2.1.c Number of Truck Platoons

The ACT technology is expected to be applied soon with up to five platoon trucks, and this number may increase to ten trucks in each platoon. However, none of the previous studies considered these numbers. Therefore, this study covered a wide range of truck platoons, up to 20 trucks.

3.2.1.d Spacing between Trucks (Headways)

The spacing between trucks (headway) is measured as the distance between the leading truck's last axle and the following truck's first axle. Previous studies indicated that the minimum safe spacing between trucks can be 10 ft. (around 3 m). In this study, 20 different headways were used, varying from 10 ft. to 30 ft. (3 m to 9 m), with increments of 1 ft. (0.30 m).

3.2.2. Analysis and Verification

SAP 2000 v23.3.1 was used in the analysis of this study. The bridges were modeled as beam sections, and appropriate boundary conditions were assigned. Four hundred load cases, with varying numbers of trucks and headways, were defined as moving loads. The influence lines and maximum straining actions were generated by using moving-load analysis. In addition, a station step size of 1 ft. was used in all models to get accurate results.

The HS20 design truck, as mentioned in section 3.2.1.b, was used for all models. The platooned trucks were modeled by defining the axle load and the distance between axles. The load cases were designated as HS20_X_Y, where X indicated the number of trucks and Y showed the headways between the trucks in ft. For example, HS20_4_15 means four HS20 trucks with a headway spacing of 15 ft. A total number of 59,200 models were generated and analyzed in this study. A coded script was written with MATLAB to generate the input data files and manage the numerous output results. A sample of the input data can be seen in Appendix A.

The study performed by Sayed et al. (2020) was used to verify the analysis method followed in this research work. In Sayed et al. (2020), the effects of different two- and three-truck platoon configurations were compared to a single truck unit. The design live load HL-93 was used. Lane loading was not considered in the analysis to give a clearer picture of the trucks themselves.

3.2.3. Bridge Load Rating

The majority of U.S. bridges were designed on the basis of two live load models (HS-20 and HL-93), according to AASHTO. Three bridge design methodologies have been developed on the basis of these two live load models: Allowable Stress Design (ASD), Load Factor Design (LFD), and Load and Resistance Factor Design (LRFD). In the ASD method, the actual loads (unfactorized) are combined to produce the maximum stress in the bridge element. This stress should not exceed the allowable stress. In the LFD method, loads are factored and compared with the bridge element capacity. Most recently bridges have been designed according to the LRFD method, providing uniform reliability by factoring loads and capacities.

The bridge load rating is a methodology used by bridge owners to evaluate the current condition of a bridge and indicate the ability of a bridge to carry a given live load. The rating factor (RF) is determined by subtracting the dead load demand from the capacity and dividing the result by the live load demands. According to AASHTO, there are three load rating methods: Allowable Stress Rating (ASR), Load Factor Rating (LFR), and Load and Resistance Factor Rating (LRFR). Each method is performed at two classifications (inventory and operating).

The LRFR method is consistent with the AASHTO LRFD Bridge Design Specifications in reliability-based limit states. The equation used to determine the RF_{LRFR} is given in Equation 3.4.

$$RF_{LRFR} = \frac{C - \gamma_{DC}.DC - \gamma_{DW}.DW}{\gamma_{LL}\,(LL * IM)} \qquad \text{(Equation 3.4)}$$

where *C* is the element capacity; *DC* is the dead load of the element; *DW* is the wearing surface; *LL* is the live load; $\gamma_{DC},\ \gamma_{DW},\ \gamma_{LL}$ are the load factors; and *IM* is the dynamic amplification effect.

The LFR and ASR methods are consistent with the AASHTO LFD and ASD methods. LFR assumes a high uncertainty of some design loads, such as the live load (L), in comparison to other loads, such as the dead load (D). The ASR method ensures that the stresses produced by service loads do not exceed the allowable stresses of the material. The equation used to determine the $RF_{LFR\text{-}ASR}$ is given in Equation 3.5.

$$RF_{LFR-ASR} = \frac{C - A_1.D}{A_2.L(1+I)} \qquad \text{(Equation 3.5)}$$

where C is the element capacity, D is the dead load of the element, L is the live load, A_1 and A_2 are the load factors, and I is the dynamic amplification effect. Although LFR and ASR have the same equation, the calculations of the capacity (C) and the load factors (A_1 and A_2) are different.

Two different rating levels are used in bridges: inventory rating and operating rating. Inventory rating is the vehicle load that a given bridge can safely utilize for an infinite time, corresponding to a 3.5 LRFR reliability index. Operating rating is the absolute maximum load that a given bridge can safely accommodate, corresponding to a 2.5 LRFR reliability index.

This study addressed the effects of a change in the live load of a general bridge due to platooning configurations. Increases in live loads due to truck platooning are expected to decrease bridge load ratings. The reduced percentages for different bridge spans and the wide range of truck platooning configurations were used to create charts that engineers can use to find the optimum parameters for any bridge case. Therefore, bridge capacity, dead loads, and impacts were kept constant, and the only variable considered was the live load.

3.2.4. Regression Analysis

Regression analysis is used to estimate the relationship between two or more variables. The dependent variable is the primary variable you are looking to predict (moment and shear in this study). Independent variables are the factors that might influence the dependent variables (bridge type, span length, number of trucks, and headway spacing in this study). Regression analysis helps to understand how the dependent variable correlates to the independent variables and allows the analyst to mathematically determine the primary factor of any independent variables, which helps for future applications.

The regression analysis model is based on the sum of squares, which is a mathematical way to find the dispersion of data points. The goal of a model is to get the smallest possible sum of squares and draw a curve that comes closest to the data points. In this study, the built-in regression function in EXCEL was used to provide regression models for different bridge cases.

CHAPTER 4. PLATOONING LIVE LOAD RESULTS

4.1. Overview

This chapter presents the bending moments and shear forces results from different truck platoon configurations for simple, two-span, and more than two-span bridges. As described in Chapter 3, an extensive parametric study of 59,200 models was conducted using SAP2000 to investigate the effects of a wide range of platooning configurations on different bridge cases. The results were then used to provide a guideline on the optimum parameters for future application. The design truck (HS20) was used and arranged in platoons by varying the number of trucks and headway spacings according to the study matrix. A coded script was written with MATLAB to generate the input data files for SAP 2000 and to analyze the numerous output results.

4.2. Model Verification

The results obtained by Sayed et al. (2020) were used to validate the analysis method used in this study. Figures 4.1 and 4.2 show the results of the bending moments and shear forces obtained from the SAP2000 model and Sayed et al. (2020). The verification was carried out for a simple span bridge at different span lengths and different load cases: a single unit (SU), two-truck platoons (2TP), three-truck platoons (3TP), and five-truck platoons (5TP). Three headway spacings were used: 4.6, 9.1, and 18.3 m. The results showed good agreement between the results of the SAP2000 model and those of Sayed et al. (2020). It can also be observed that there was a slight increase in the shear results for some SAP2000 load cases in comparison to those of Sayed et al. (2020) because with SAP2000, any truck axle located on the bridge is considered in the calculations, even if the whole truck might not be entirely on the bridge.

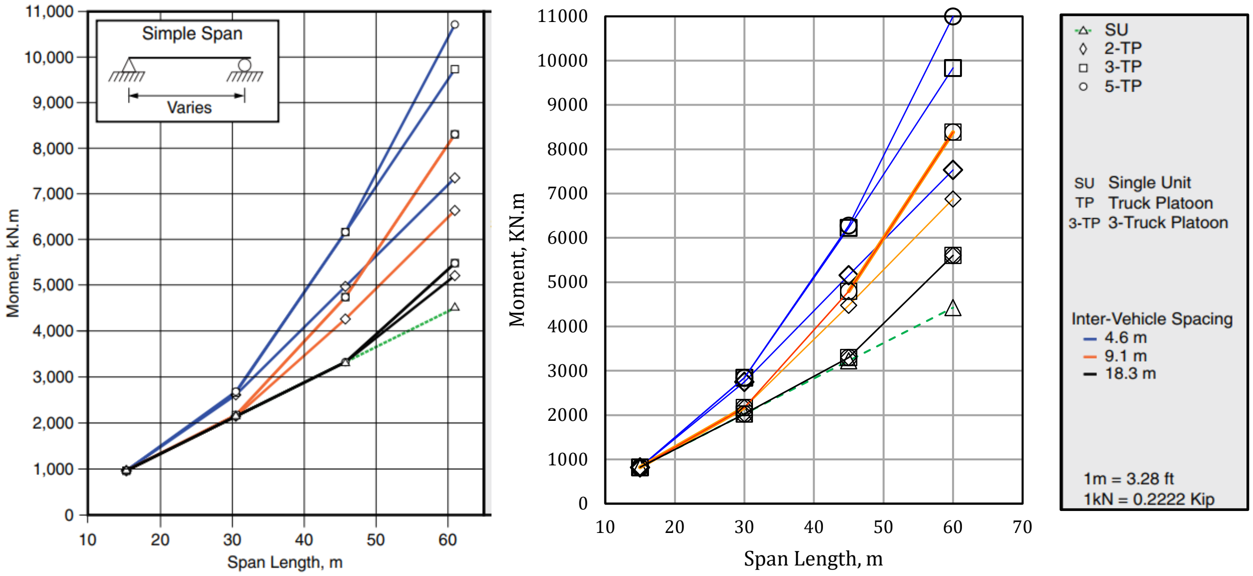

Figure 4.1 Moment results for SU, 2TP, 3TP, and 5TP for simple span bridges at a headway spacing of 15 ft. (4.6 *m*); a) Sayed et al. (2020) results, b) SAP2000 results.

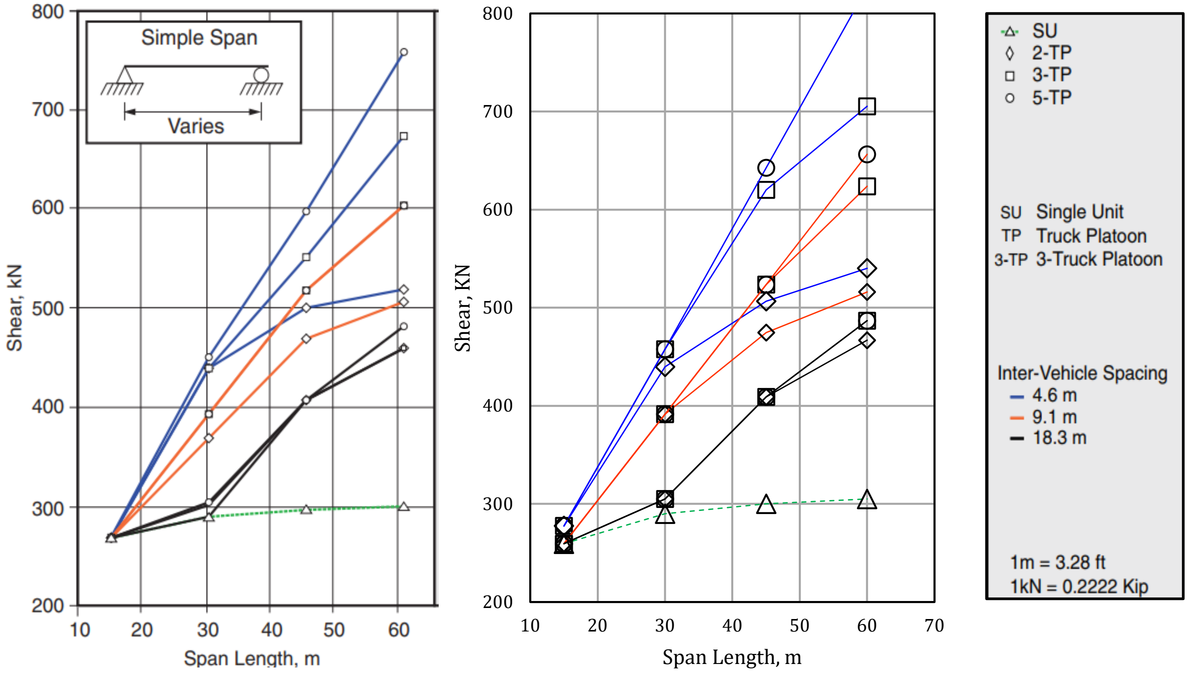

Figure 4.2 Shear results for SU, 2TP, 3TP, and 5TP for simple span bridges at a headway spacing of 15 ft. (4.6 *m*); a) Sayed et al. (2020) results, b) SAP2000 results.

4.3. Simple Span Bridges

The positive moment and shear force for simple span bridges were calculated under the effects of different truck platoon configurations. The influence line method, provided in SAP2000, was used as described in Chapter 3. The maximum bending moments and shear forces results are provided in Appendix B. Detailed discussion is provided in the following sections.

4.3.1. Bending Moment

Figures 4.5 to 4.8 show the normalized maximum moment results for simple span bridges under two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.). All results were normalized to the results of a single HS20 truck at each span.

The 50-ft. simple span bridge results showed no increase in the maximum moment under the effects of platooned trucks because the 50-ft. span could not accommodate more than two trucks simultaneously. (This is illustrated in the first group of bars in figure 4.5.) However, at a 10-ft. headway spacing, one axle from the second truck was considered and slightly increased the bending moment by 6 percent (see figure 4.3).

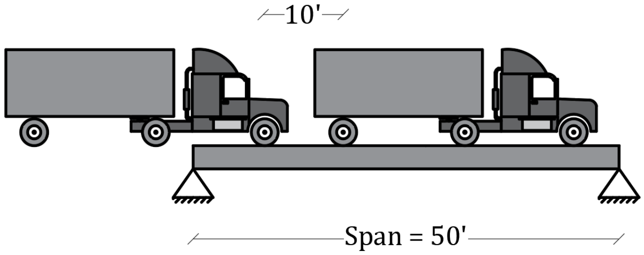

Figure 4.3 A two-truck platoon configuration for a 50-ft. simple span bridge at a 10-ft. headway

The 75-ft. simple span bridge showed slight increases in the maximum moment of 7 percent, 16 percent, and 29 percent under the effects of platooned trucks spaced by 20, 15, and 10 ft, respectively. (This is illustrated in the second group of bars in figures 4.5 to 4.8). The 75-ft. simple span bridge could not accommodate more than two trucks simultaneously. Moreover, when the two trucks were spaced by more than 20 ft., the bridge was not able to accommodate all the axles, which reduced the bending moment (see figure 4.4).

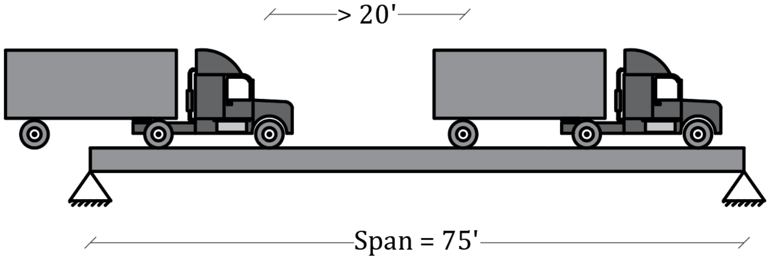

Figure 4.4 A two-truck platoon configuration for a 75-ft. simple span bridge at a headway spacing longer than 20 ft.

The 100-ft. simple span bridge showed an increase in the maximum moment of 49 percent for two platooned trucks (as seen in the third group of bars in figure 4.5) and 60 percent for more than two platooned trucks (as seen in the third group of bars in figures 4.6 to 4.8) at a 10-ft. headway spacing. In addition, as the headway spacing increased, the percentage of the increase in bending moment diminished to 10 percent at a 30-ft. headway spacing.

The 125-ft. simple span bridge showed an increase in the maximum moment of 61 percent for two platooned trucks (as seen in the fourth group of bars in figure 4.5) and 90 percent for more than two platooned trucks (as seen in the fourth group of bars in figures 4.6 to 4.8) at a 10-ft. headway spacing. In addition, as the headway spacing increased, the percentage of the increase in bending moment diminished to 28 percent at a 30-ft. headway spacing.

Allowing two trucks to be fully accommodated on bridges longer than 125 ft. increased the maximum moment by up to 77 percent for a 10-ft. headway. This percentage decreased to 56 percent when the headway spacing increased to 30 ft. On the other hand, allowing more than two trucks to be entirely accommodated on simple span bridges significantly increased the bending moment by as much as three times the single truck shear force, as shown in figures 4.6 to 4.8.

Overall, it can be concluded that an increase in span length allowed more trucks to be entirely accommodated on the bridge simultaneously, which increased the bending moment. Allowing two trucks to be fully accommodated on a simple span bridge simultaneously produced an increase in the maximum moment of up to 77 percent for 200-ft. spans, at a 10-ft. headway spacing, and this percentage decreased to 56 percent when the headway spacing increased to 30 ft. On the other hand, allowing more than two trucks to be fully accommodated on a simple span bridge significantly increased the bending moment to three times the single truck moment. In addition, as the headway spacing decreased, the bending moment increased.

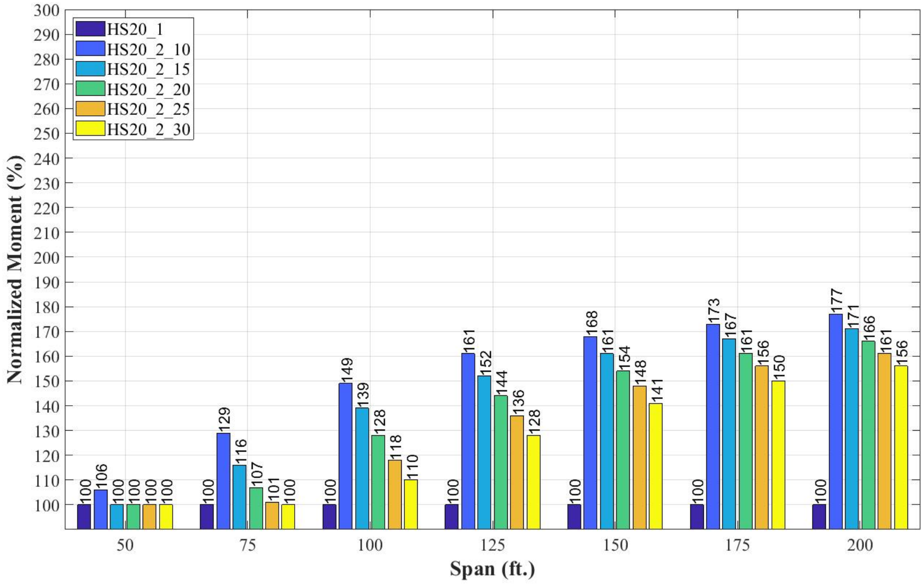

Figure 4.5 Normalized maximum bending moment results for simple span bridges under two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

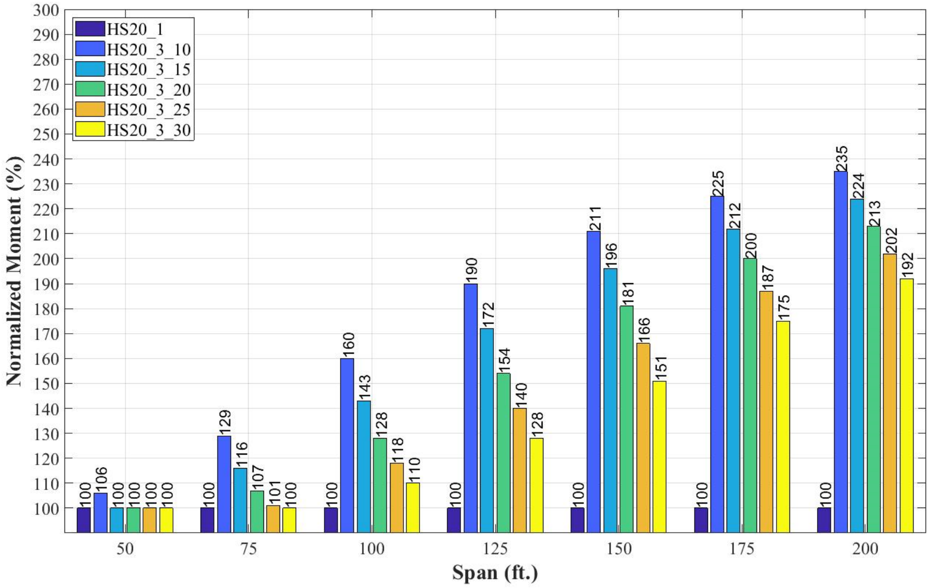

Figure 4.6 Normalized maximum bending moment results for simple span bridges under three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

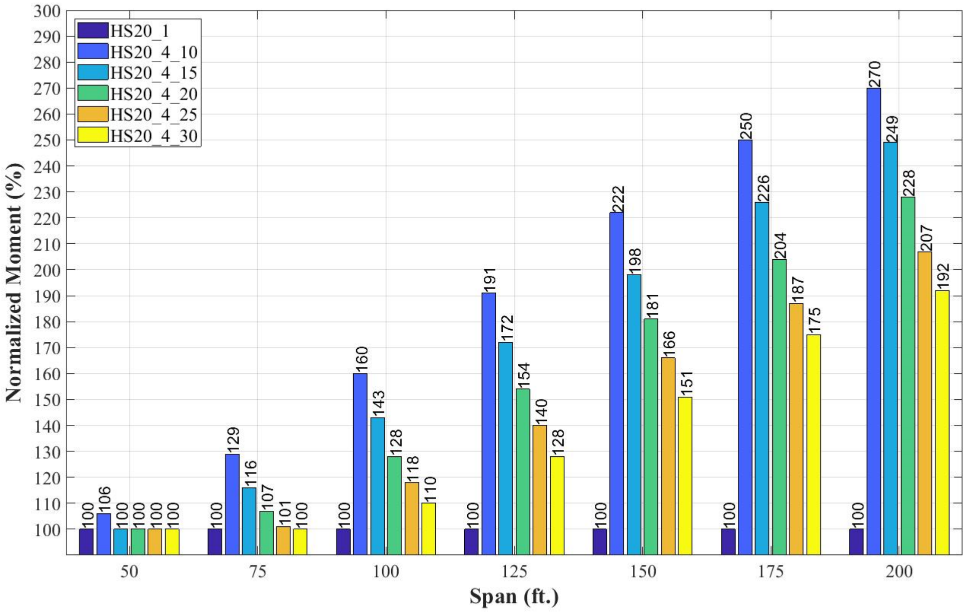

Figure 4.7 Normalized maximum bending moment results for simple span bridges under four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

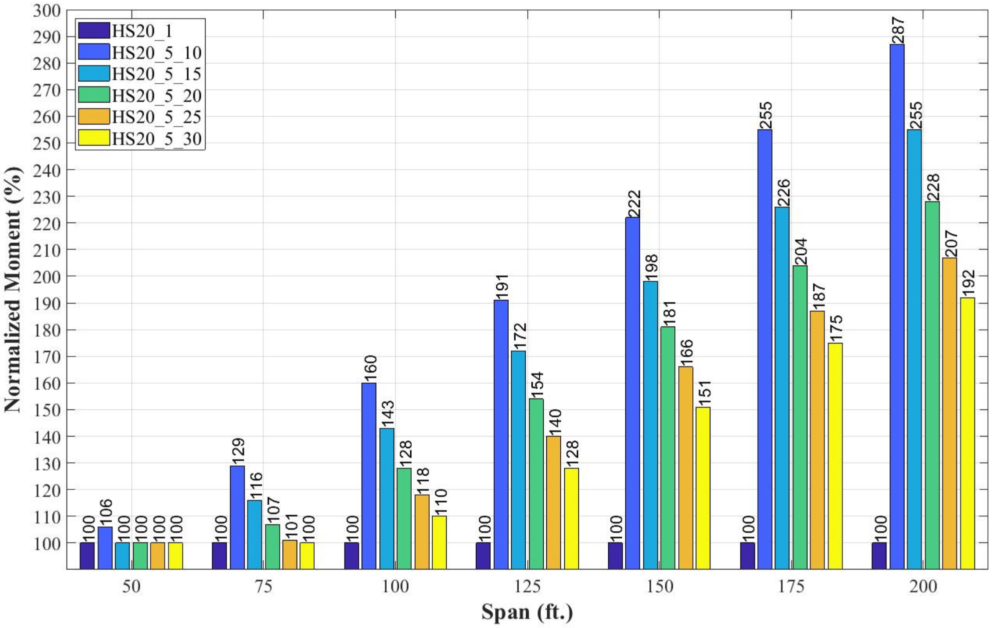

Figure 4.8 Normalized maximum bending moment results for simple span bridges under more than four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

4.3.2. Shear Force

Shear forces indicated increases in reaction forces due to platooned trucks. Those reactions are transferred to the foundation and the soil substructure systems. Therefore, more analysis of sub-structure systems is required for all bridges expected to be used by platooned trucks. The maximum shear usually occurs when the most significant load is located over or close to the supports and as many as possible of the remaining loads are still on the span. This critical configuration is shown in figure 4.9. Figures 4.10 to 4.13 show the normalized shear force results for simple span bridges under two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.). All results were normalized to the results of a single HS20 truck at each span.

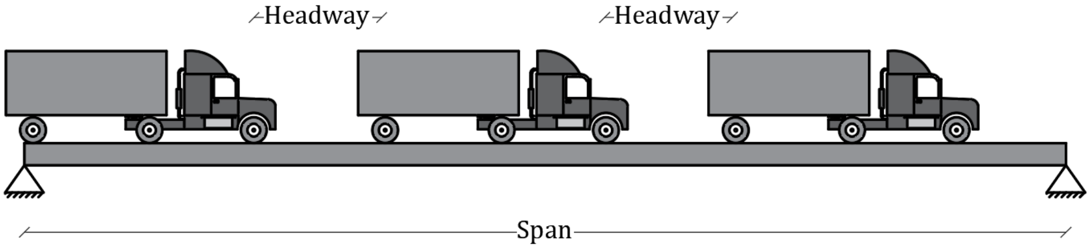

Figure 4.9 Critical maximum shear configuration for simple span bridges

The 50-ft. simple span bridge showed no increase in the maximum shear force since the bridge would not be able to accommodate more than two trucks at the same time for headway spacings of 20, 25, and 30 ft. Decreasing the headway spacing to 15 and 10 ft. increased the shear force by 8 percent and 15 percent, respectively. This is illustrated in the first group of bars in figures 4.10 to 4.13.

The 75-ft. simple span bridge showed an increase in the maximum shear force of 43 percent at a 10-ft. headway spacing (as can be seen in the second group of bars in figures 4.10 to 4.13). No matter the number of platooned trucks, the shear results stay the same because the 75-ft. simple span bridge could not accommodate more than two trucks simultaneously. In addition, as the headway spacing increased, the percentage of increase in the shear force decreased to 14 percent at a 30-ft. headway spacing.

The 100-ft. simple span bridge showed an increase in the maximum shear force of 59 percent for two platooned trucks (as seen in the third group of bars in figure 4.10) and 76 perce3nt for more than two platooned trucks (as seen in the third group of bars in figures 4.11 to

4.13) at a 10-ft. headway spacing. In addition, as the headway spacing increased, the percentage of increase in the shear force diminished to 37 percent at a 3- ft. headway spacing.

The 125-ft. simple span bridge showed an increase in the maximum shear force due to platooned trucks of 68 percent for two platooned trucks (as seen in the fourth group of bars in figure 4.10) and 107 percent for more than two platooned trucks (as seen in the fourth group of bars in figures 4.11 to 4.13) at a 10-ft. headway spacing. In addition, as the headway spacing increased, the percentage of the increase in the shear force diminished to 50 percent at a 30-ft. headway spacing.

Allowing two trucks to be fully accommodated on a bridge longer than 125 ft. increased the maximum shear force by up to 81 percent for a 10-ft. headway. This percentage decreased to 70 percent when the headway spacing increased to 30 ft. On the other hand, allowing more than two trucks to be entirely accommodated on a simple span bridge significantly increased the shear force by as much as three times the single truck shear force, as shown in figures 4.10 to 4.13.

Overall, it can be concluded that an increase in span length allowed more trucks to be fully accommodated on the bridge simultaneously, increasing the shear force. Allowing two trucks to be fully accommodated on a simple span bridge simultaneously produced an increase in the maximum shear of up to 81 percent for a 10-ft. headway. This percentage decreased to 70 percent when the headway spacing increased to 30 ft. On the other hand, allowing more than two trucks to be entirely accommodated on simple span bridges significantly increased the shear force by as much as three times the single truck shear force. In addition, as the headway spacing decreased, the shear force increased.

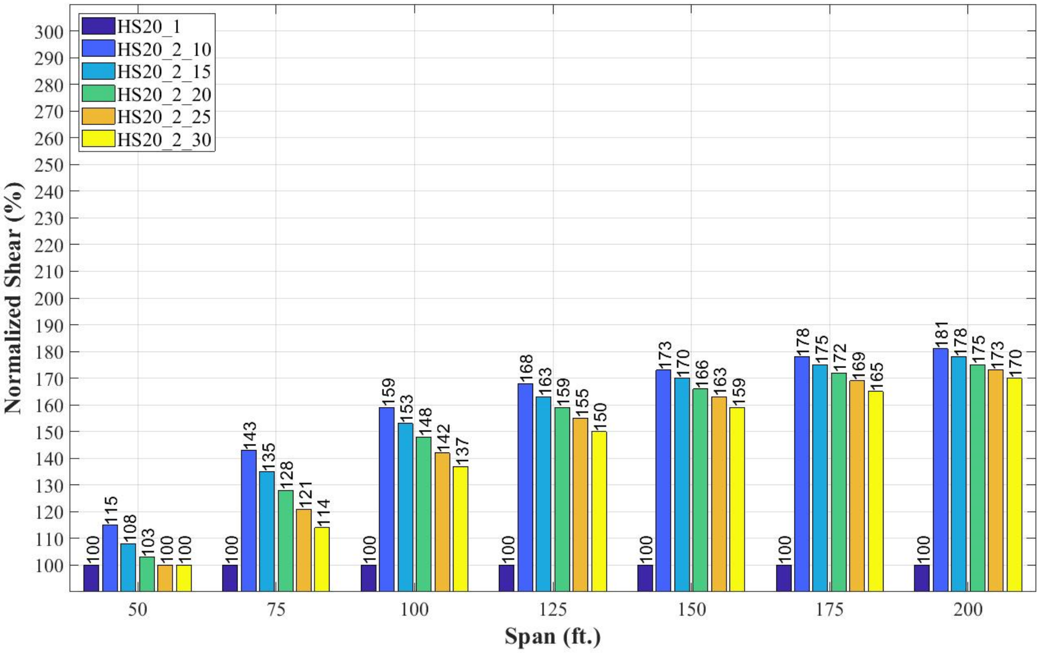

Figure 4.10 Normalized maximum shear force results for simple span bridges under two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

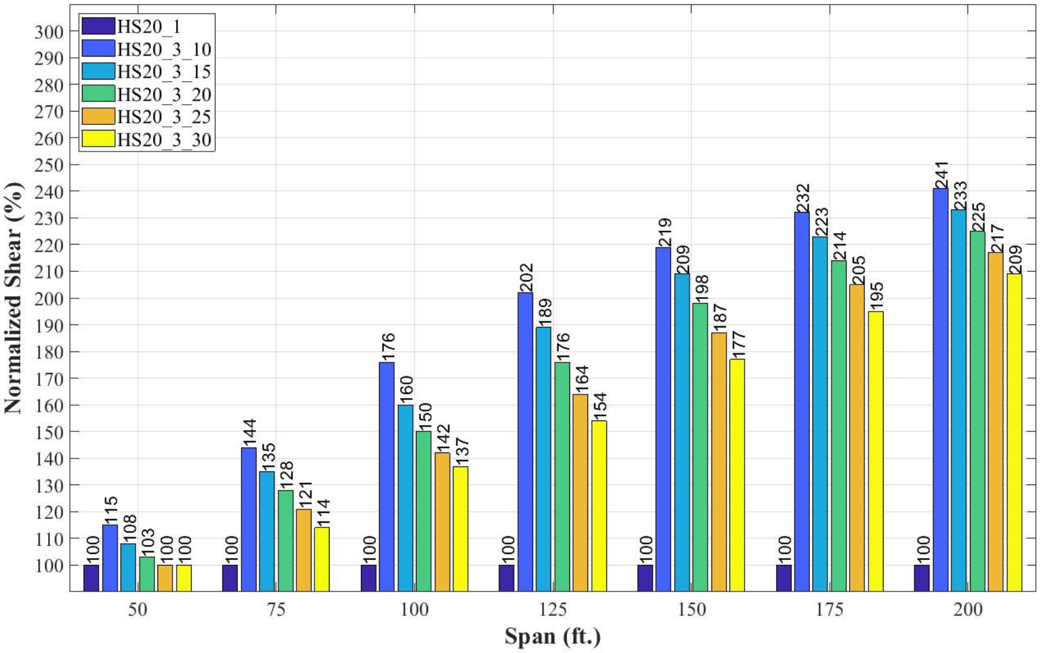

Figure 4.11 Normalized maximum shear force results for simple span bridges under three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

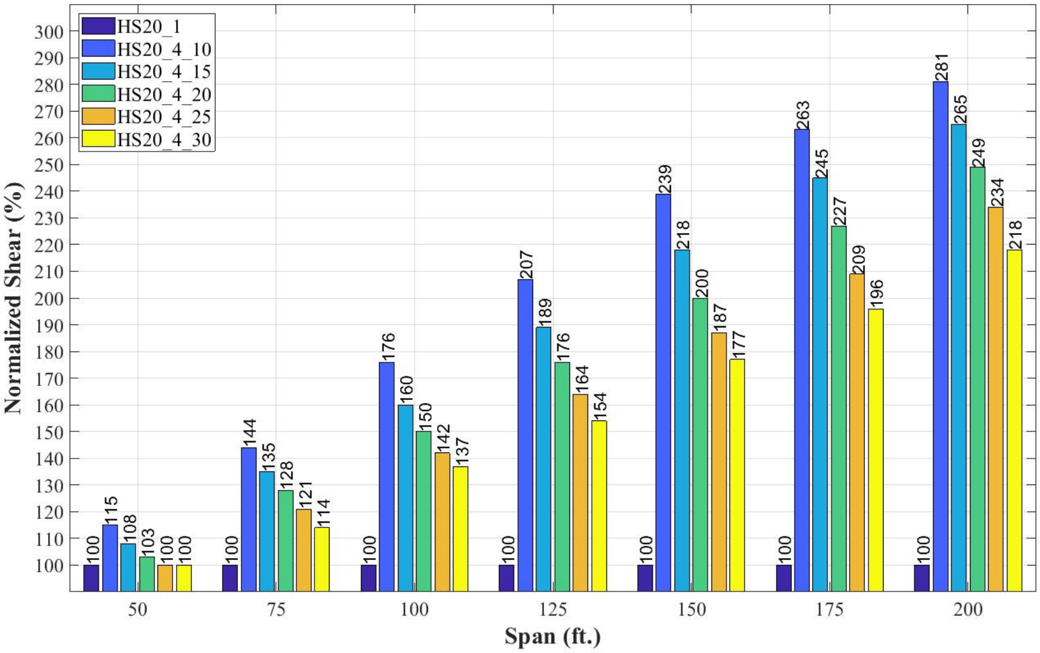

Figure 4.12 Normalized maximum shear force results for simple span bridges under four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

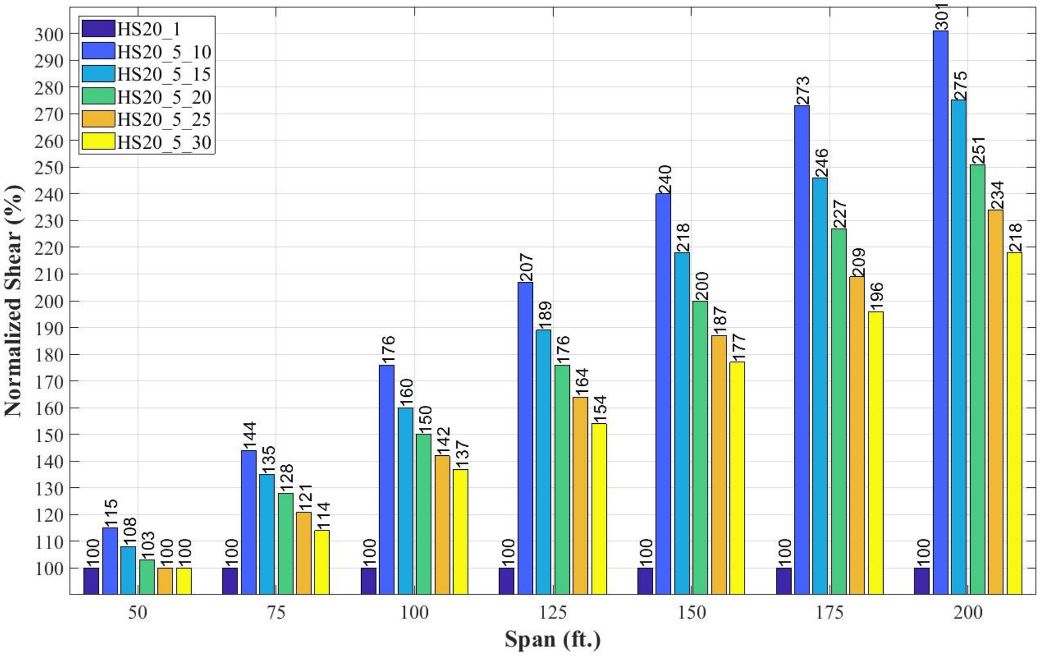

Figure 4.13 Normalized maximum shear force results for simple span bridges under more than four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

4.4. Continuous Two-Span Bridges

While simple span bridges are governed by positive moments and end shear, continuous spans may be controlled by negative moments. Therefore, two-, three-, and four-span continuous bridges were analyzed and studied for moments and shear under different truck platoon configurations. For continuous short and medium span bridges (up to 100 ft.), critical negative moments may occur when two adjacent spans are loaded at the same time. On the other hand, for long-span bridges (longer than 100 ft.), critical positive moments can occur when many trucks are located on a single span. Figures 4.14 and 4.15 show the critical configurations for positive and negative moments on continuous bridges. The maximum bending moment and shear force results are provided in Appendix C. Detailed discussion is provided in the following sections.

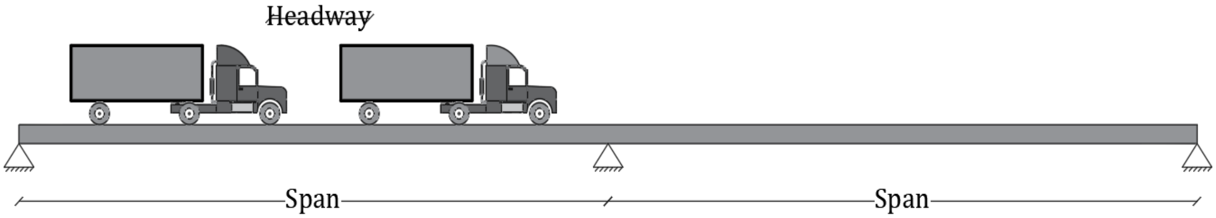

Figure 4.14 Critical maximum positive moment configuration for two-span bridges

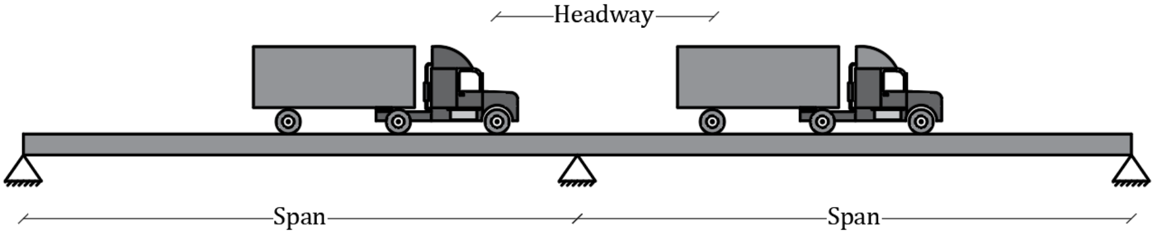

Figure 4.15 Critical maximum negative moment configuration for two-spans bridges

4.4.1. Positive Moment

Figures 4.19 to 4.22 show the normalized maximum positive moment results for two-span bridges under two-, three-, four, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.). All results were normalized to the results of a single HS20 truck at each span. The positive moment results of continuous bridges showed the same trend as that of simple span bridges, with lower values because of the continuity.

The critical positive moments for long-span bridges (longer than 100 ft.) occurred when the maximum number of platooned trucks was located on a single span. The 50-ft. two-span bridge could not accommodate more than two trucks simultaneously, which kept the results the same without any increase. (This is illustrated in the first group of bars in figure 4.19.) However, at a 10-ft. headway spacing, one axle from the second truck was considered and slightly increased the bending moment by 6 percent (see figure 4.16).

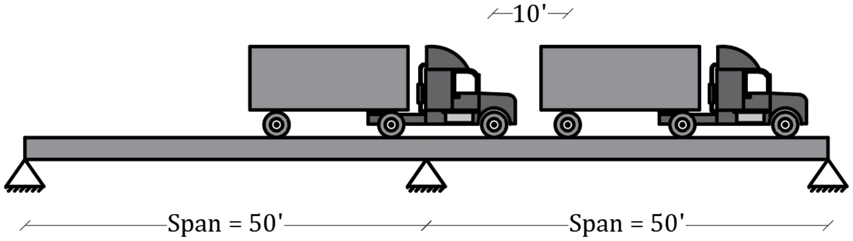

Figure 4.16 A two-truck platoon configuration for a two 50-ft. span bridge with a 10-ft. headway

The 75-ft. two-span bridge showed slight increases in the maximum positive moment of 7 percent, 14 percent, and 26 percent under the effects of platooned trucks spaced at 20, 15, and 10 ft, respectively. (This is illustrated in the second group of bars in figures 4.19 to 4.22.) The 75-ft. span could not accommodate more than two trucks simultaneously. Moreover, when the two trucks were spaced by more than 20 ft., the bridge was not able to accommodate all the axles on a single span, which reduced the positive bending moment (see figure 4.17).

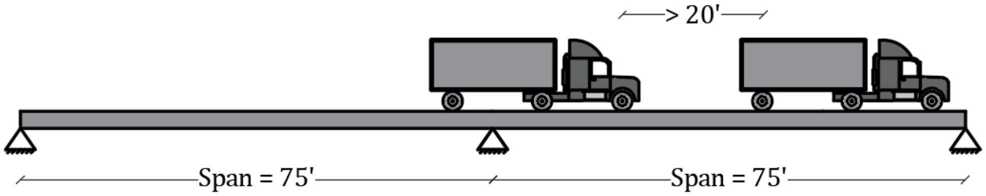

Figure 4.17 A two-truck platoon configuration for a two 75-ft. span bridge with a headway spacing of longer than 20 ft.

The 100-ft. two-span bridge showed an increase in the maximum positive moment of 45 percent for two platooned trucks (as seen in the third group of bars in figure 4.18) and 53 percent for more than two platooned trucks (as seen in the third group of bars in figures 4.19 to 4.21) at a 10-ft. headway spacing. In addition, as the headway spacing increased, the percentage of the increase in positive bending moment diminished to 9 percent at a 30-ft. headway spacing.

The 125-ft. two-span bridge showed an increase in the maximum positive moment of 56 percent for two platooned trucks (as seen in the fourth group of bars in figure 4.18) and 81 percent for more than two platooned trucks (as seen in the fourth group of bars in figures 4.19 to 4.21) at a 10-ft. headway spacing. In addition, as the headway spacing increased, the percentage of the increase in positive bending moment diminished to 25 percent at a 30-ft. headway spacing.

Allowing two trucks to be fully accommodated on a two-span bridge, with spans longer than 125 ft., increased the maximum positive moment by up to 73 percent for a 10-ft. headway. This percentage decreases to 52 percent when the headway spacing increased to 30 ft. On the other hand, allowing more than two trucks to be entirely accommodated on a single span significantly increased the positive bending moment by as much as three times the single truck moment, as shown in figures 4.18 to 4.21.

Critical positive moments for long-span bridges (longer than 100 ft.) occurred when the maximum number of trucks was located on a single span. Therefore, continuous bridges with short and medium spans (shorter than 100 ft.) were not expected to experience a considerable increase in the positive moment because their spans could not accommodate many trucks simultaneously. Allowing two trucks to be fully accommodated on a two-span bridge, with spans longer than 125 ft., increased the maximum positive moment by up to 73 percent for a 10-ft. headway. This percentage could be limited by controlling the headway spacing; as the headway spacing increased, the percentage of the increase in positive bending moment diminished. On the other hand, allowing more than two trucks to be entirely accommodated in a single span significantly increased the positive bending moment by as much as three times the single truck moment.

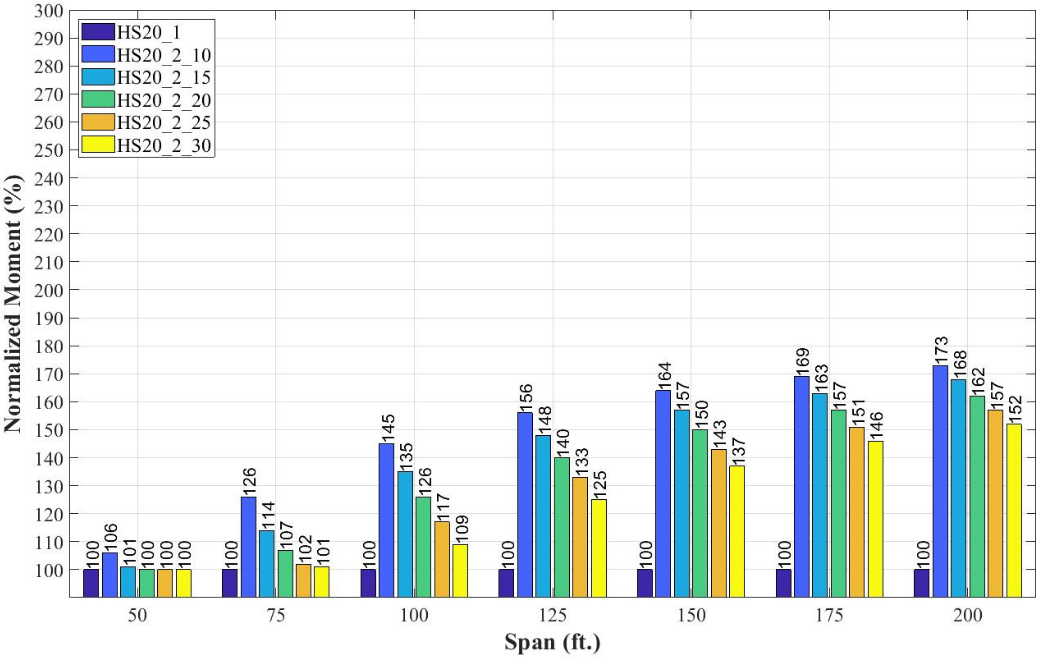

Figure 4.18 Normalized maximum positive moment results for two-span bridges under two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

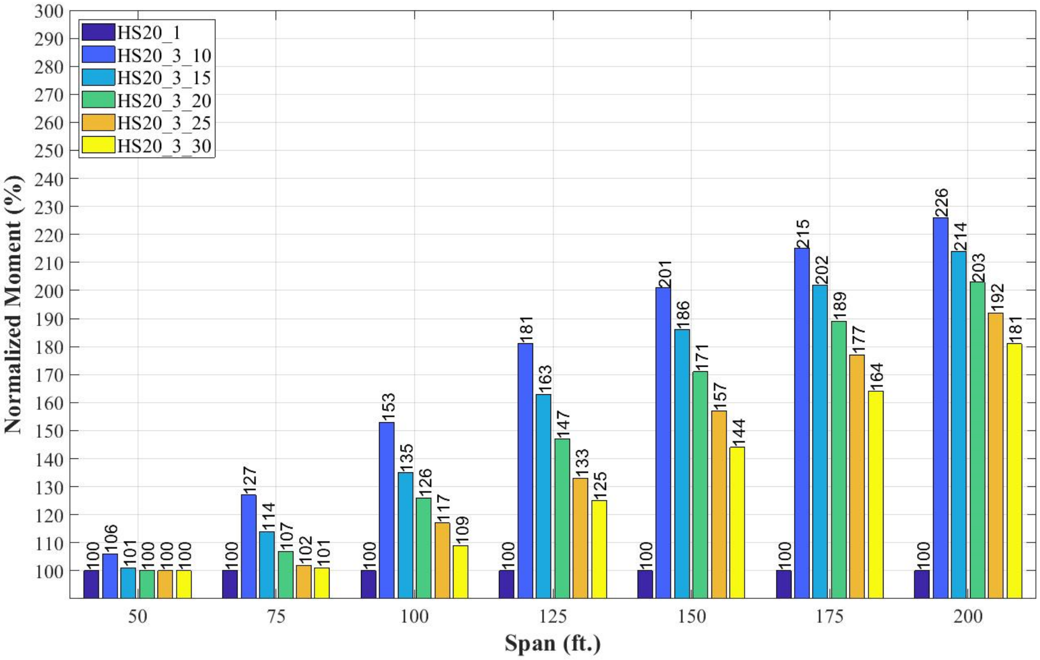

Figure 4.19 Normalized maximum positive moment results for two-span bridges under three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

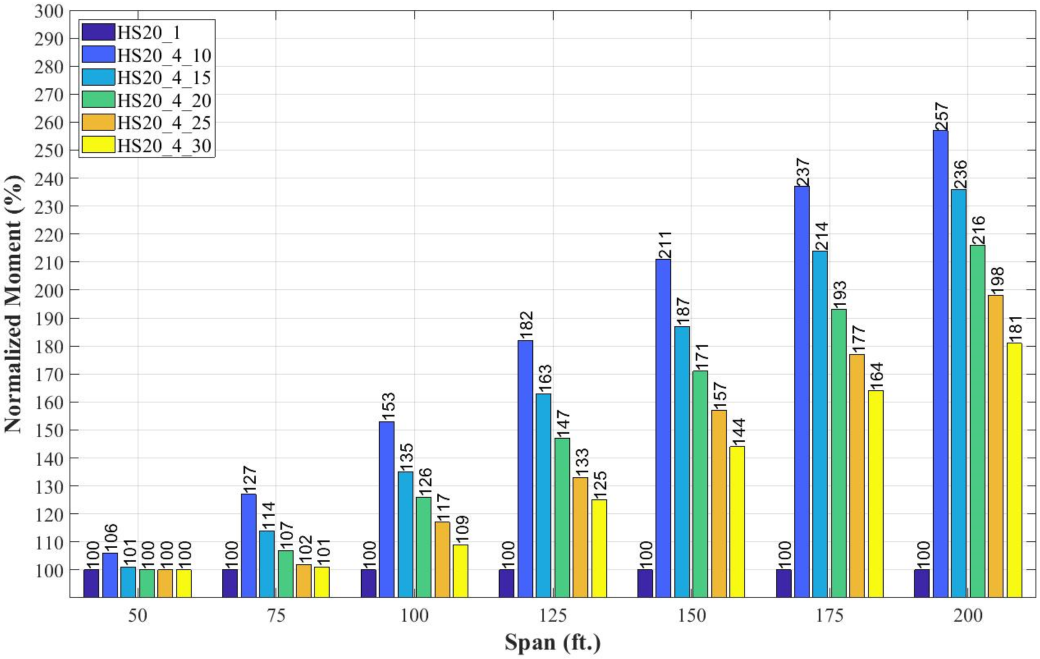

Figure 4.20 Normalized maximum positive moment results for two-span bridges under four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

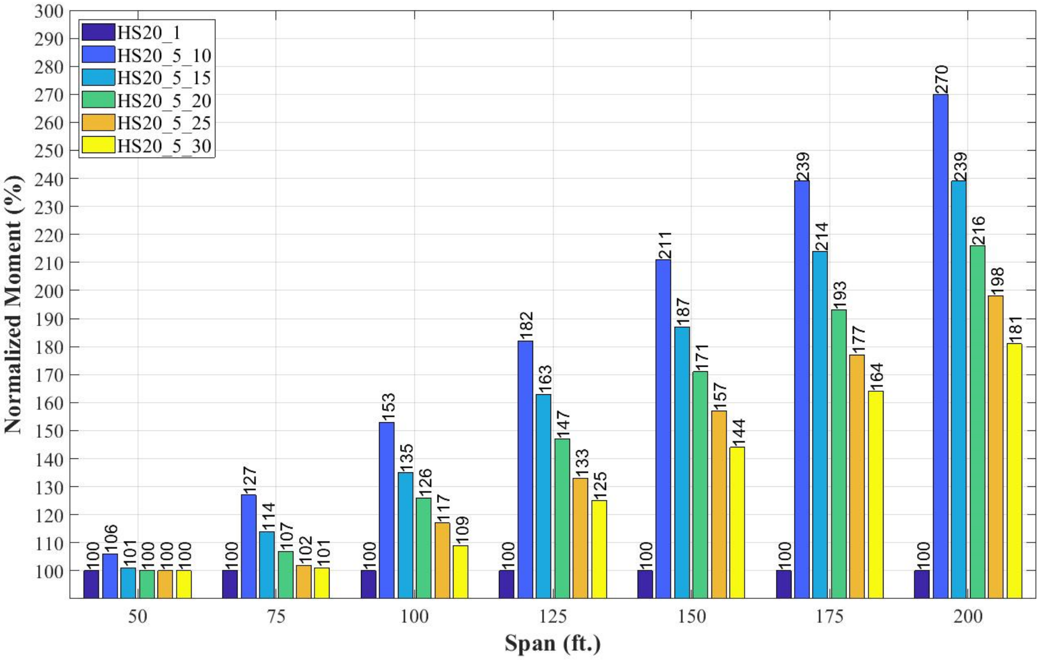

Figure 4.21 Normalized maximum positive moment results for two-span bridges under more than four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

4.4.2. Negative Moment

Figures 4.23 to 4.31 show the normalized maximum negative moment results for two-spans bridges under two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.). According to AASHTO 3.6.1.3.1, for bridges designed on the basis of the HL-93 design load, 90 percent of two HS-20 trucks, spaced at 50 ft. should be used to determine negative moments between points of contraflexure and pier reactions. Therefore, all results were normalized to the AASHTO 90 percent design live load.

As mentioned earlier, the critical negative moment for short and medium span bridges (up to 100 ft.) occurred when two adjacent spans were loaded simultaneously (see figure 4.15). The two-span bridges, with spans shorter than 70 ft., showed a significant increase in the negative moment by as much as two times as a result of platooned trucks in comparison to the AASHTO 90 percent design live load. (This can be seen in the first group of bars in figures 4.23 to 4.31.) The reason for that was the low values of the AASHTO 90 percent effect of two HS20 trucks spaced by 50 ft., since the two adjacent spans could not accommodate all axles of both trucks. (This can be seen in figure 4.22.)

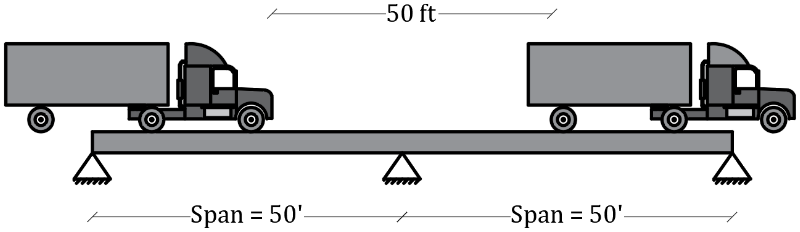

Figure 4.22 AASHTO critical negative moment configuration for a 50-ft., two-span bridge

Allowing two trucks to be fully presented on a two-span bridges, with spans longer than 75 ft., showed no considerable increase in the maximum negative moment in comparison to the AASHTO 90 percent design live load, as shown in figure 4.23. In addition, allowing three trucks to be fully presented on two-span bridges increased the maximum negative moment by 20 to 40 percent. Moreover, allowing four trucks to be fully present on two-spans bridges increased the maximum negative moment by 40 to 80 percent.

The increases in the maximum negative moments of two-span bridges due to different numbers of platooned trucks can be seen in figures 4.23 to 4.31. It can also be observed that allowing more than four trucks to be fully present on two-span bridges significantly increased the negative moment by as much as two to four times the single truck moment.

Overall, a critical negative moment for short and medium span bridges (up to 100 ft.) occurred when two adjacent spans were loaded simultaneously. Bridges with spans shorter than 75 ft. showed a significant increase in the negative bending moment in comparison to AASHTO's 90 percent design live load. On the other hand, allowing two trucks to be fully present on two-span bridges, with spans longer than 75 ft., showed no considerable increase in the maximum negative moment. In addition, an increase in the negative moment by 20 to 40 percent and 40 to 80 percent were observed when three and four trucks were used, respectively. Moreover, a significant increase in the negative moment by two to four times resulted when more than four trucks were used.

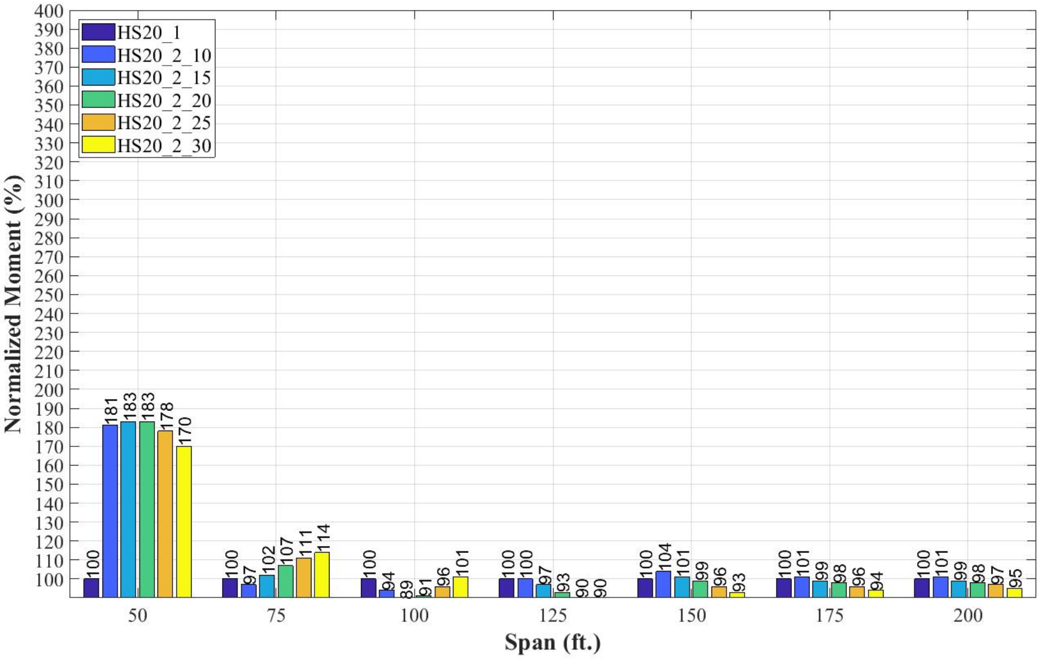

Figure 4.23 Normalized maximum negative moment results for two-span bridges under two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

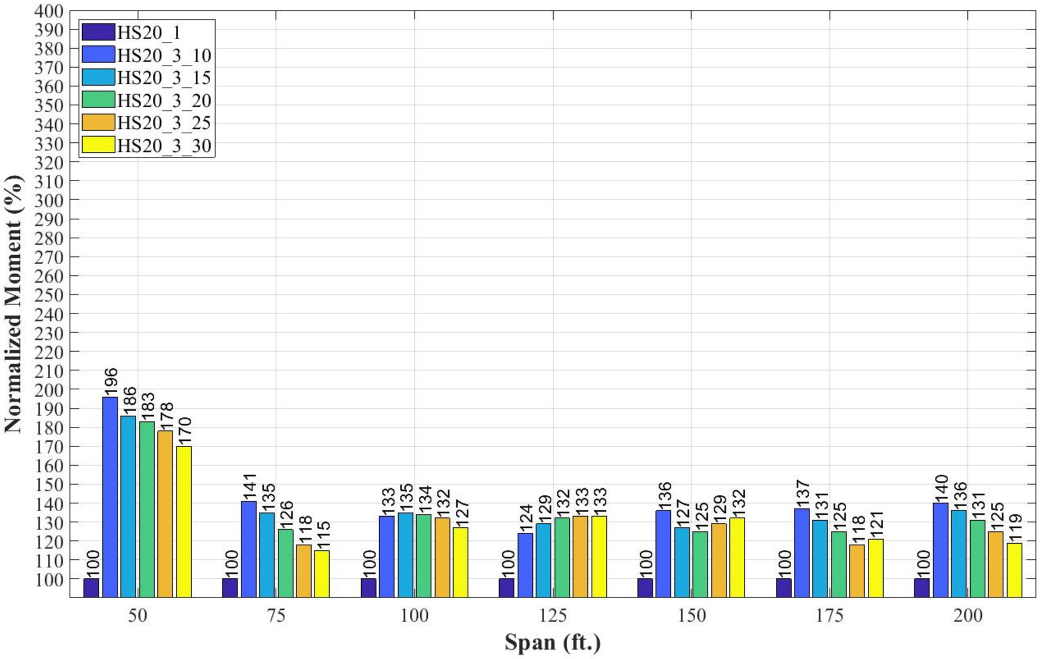

Figure 4.24 Normalized maximum negative moment results for two-span bridges under three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

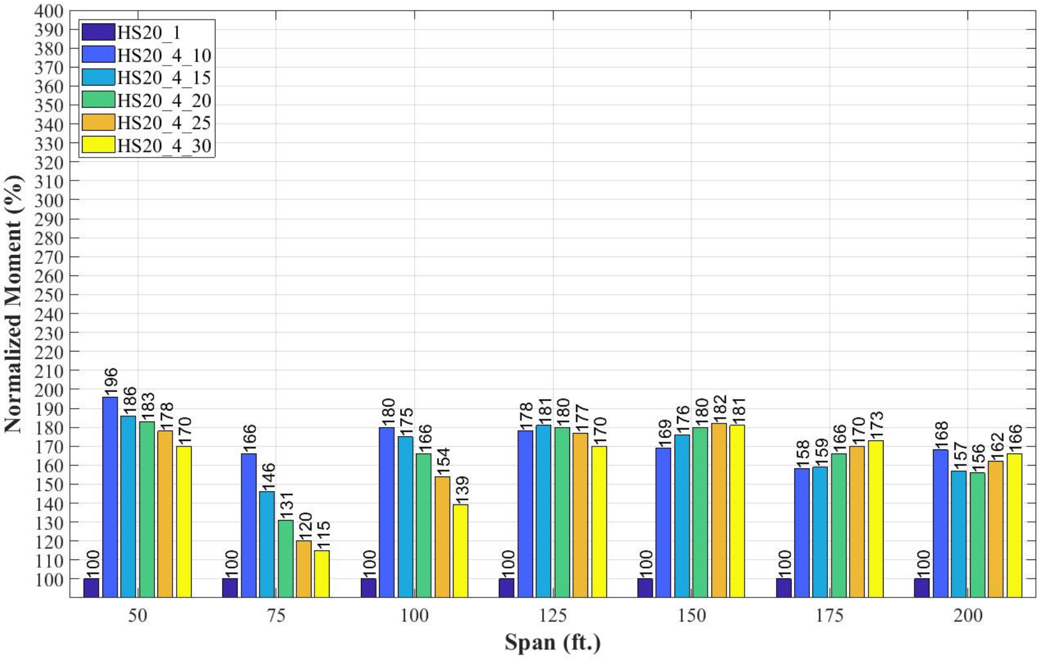

Figure 4.25 Normalized maximum negative moment results for two-span bridges under four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

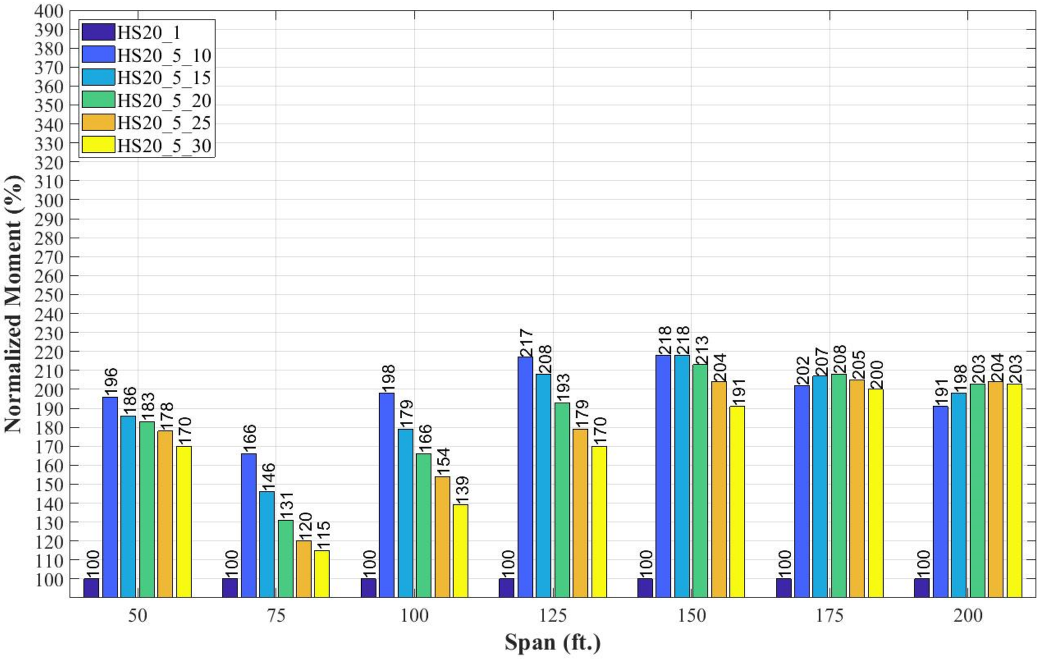

Figure 4.26 Normalized maximum negative moment results for two-span bridges under five platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

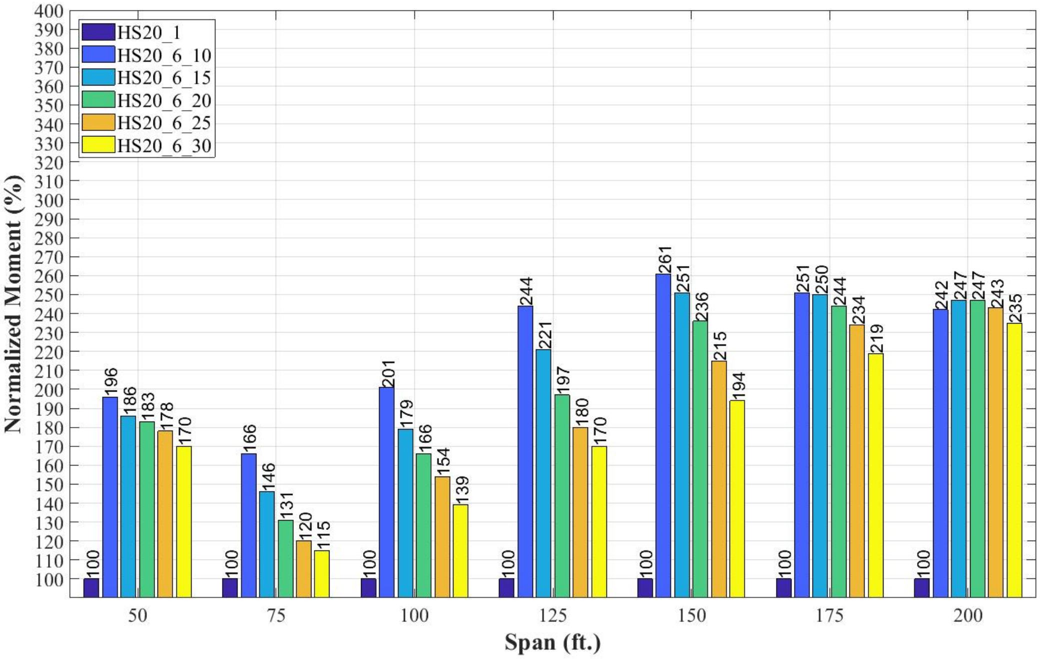

Figure 4.27 Normalized maximum negative moment results for two-span bridges under six platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

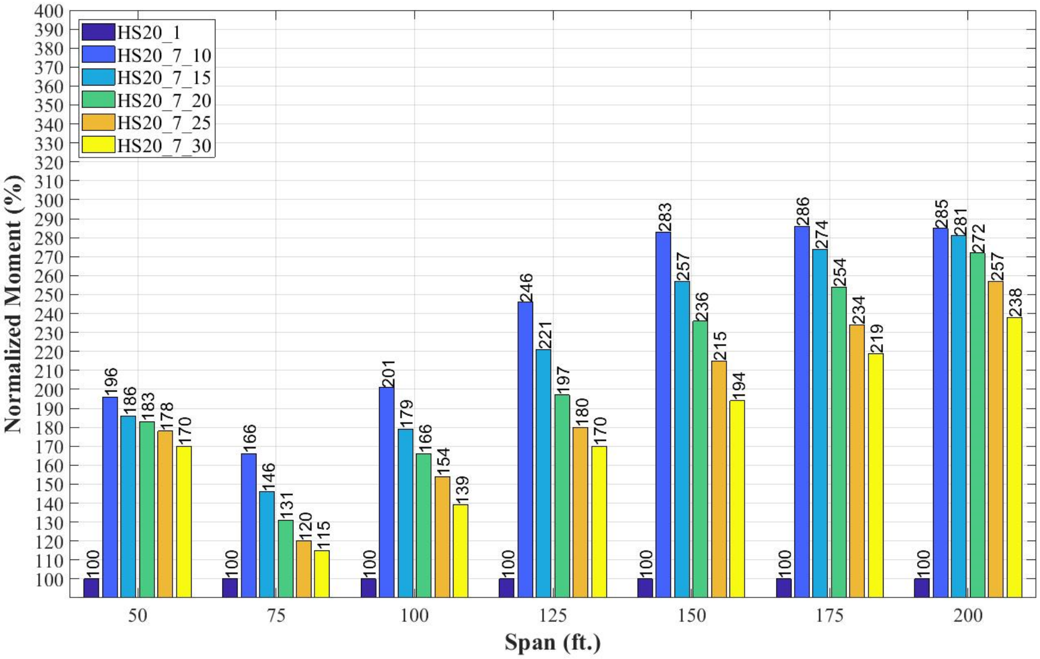

Figure 4.28 Normalized maximum negative moment results for two-span bridges under seven platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

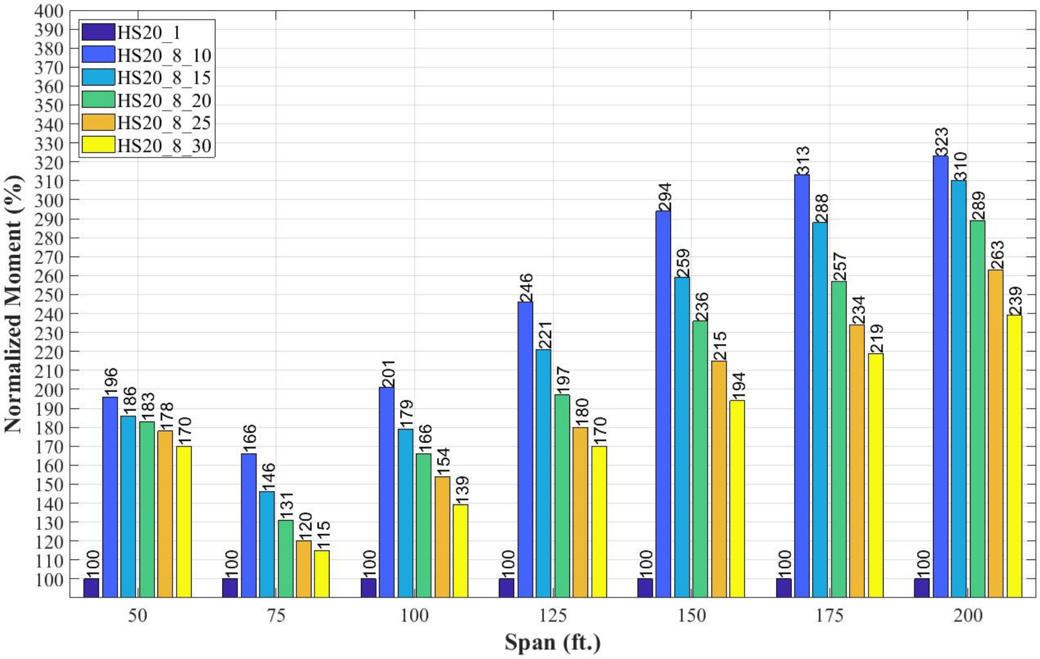

Figure 4.29 Normalized maximum negative moment results for two-span bridges under eight platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

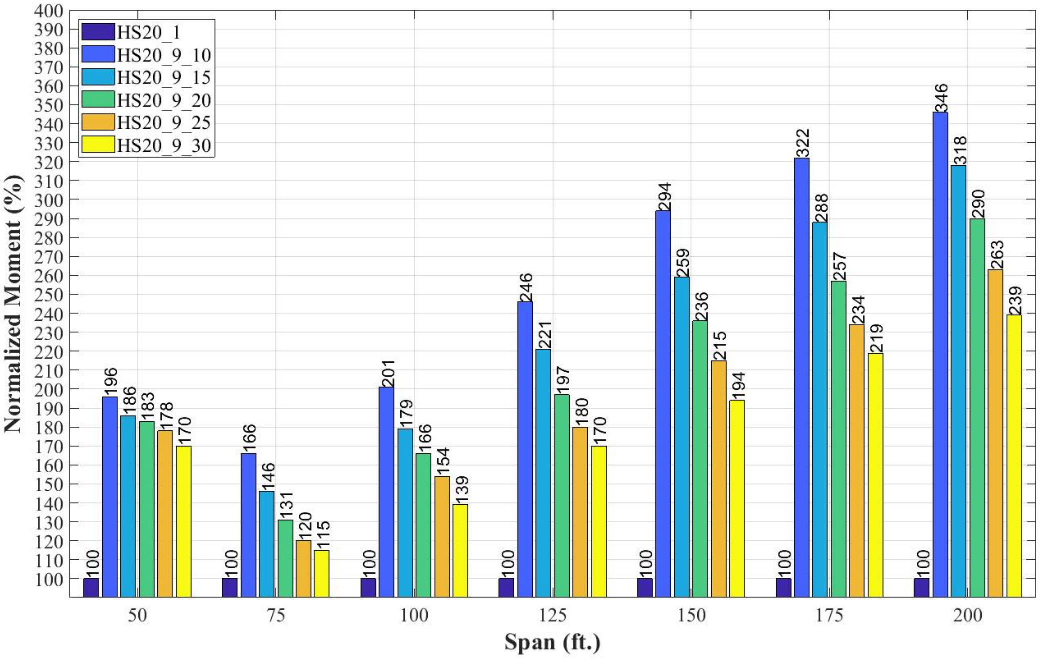

Figure 4.30 Normalized maximum negative moment results for two-span bridges under nine platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

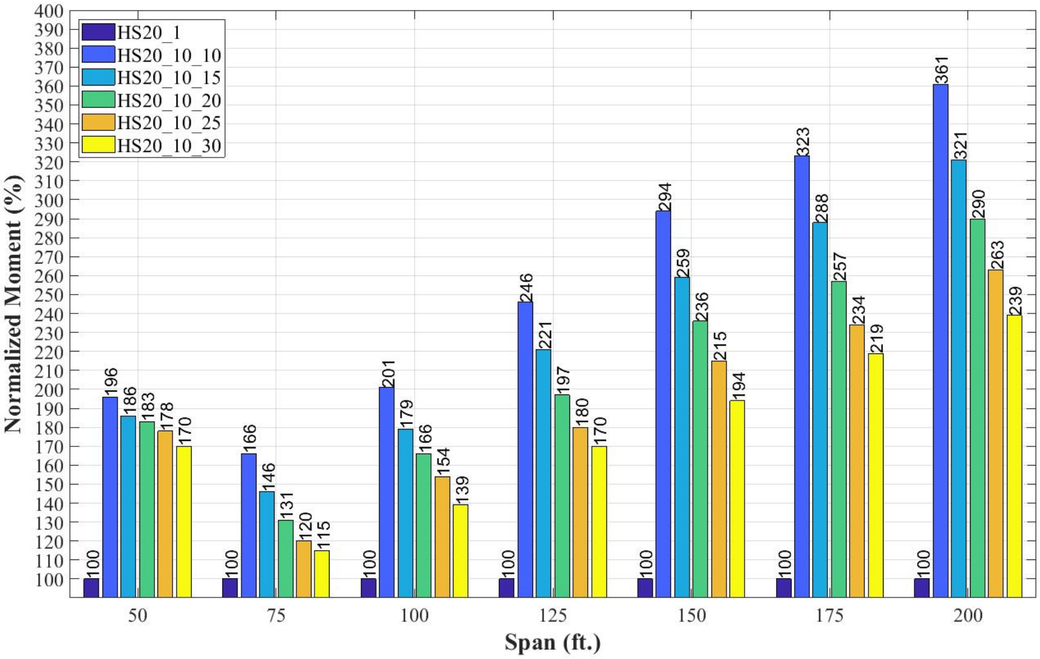

Figure 4.31 Normalized maximum negative moment results for two-span bridges under more than nine platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

4.4.3. Shear Force

The maximum shear usually occurred at the interior supports when the most significant load was located over the supports and as many as possible of the remaining loads were present over the two adjacent spans. This critical configuration produced the maximum shear shown in figure 4.32. Figures 4.33 to 4.41 show the normalized shear force results for two-span bridges under two-, three-, four-, and more than four-truck platoons, at different headway spacings (10, 15, 20, 25, and 30 ft.). All results were normalized to the results of a single HS20 truck shear force at each span.

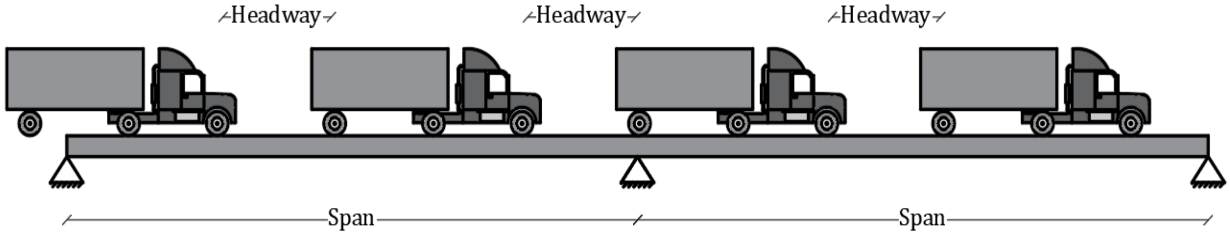

Figure 4.32 Critical maximum shear configuration for continuous span bridges

The 50-ft. two-span bridge showed no increase in the maximum shear force because the bridge would not be able to accommodate more than two trucks at the same time for headway spacings of 20, 25, and 30 ft. Decreasing the headway spacing to 15 and 10 ft. increased the shear force by 10 percent and 18 percent, respectively. This is illustrated in the first group of bars in figures 4.33 to 4.41.

The 75-ft. two-span bridge showed an increase in the maximum shear force of 49 percent for two platooned trucks (as can be seen in the second group of bars in figure 4.33), 59 percent for three platooned trucks (as can be seen in the second group of bars in figures 4.34 to 4.41), and 63 percent for more than three platooned trucks (as can be seen in the second group of bars in figures 4.35 to 4.41) at a 10-ft. headway spacing. In addition, as the headway spacing increased, the percentage of the increase in the shear force diminished to be 24 percent at a 30-ft. headway spacing.

The 100-ft. two-span bridge showed an increase in the maximum shear force due to platooned trucks at a 10-ft. headway spacing of 66 percent for two platooned trucks (as can be seen in the third group of bars in figure 4.33), 88 percent for three platooned trucks (as can be seen in the third group of bars in figures 4.35 to 4.41), and 100 percent for more than three platooned trucks (as can be seen in the third group of bars in figures 4.35 to 4.41). In addition, as the headway spacing increased, the percentage of the increase in the shear force diminished to 52 percent at a 30-ft. headway spacing.

The 125-ft. two-span bridge showed an increase in the maximum shear force of up to 87% due to two platooned trucks spaced at 10 ft. This percentage decreased to 78 percent when the headway spacing increased to 30 ft. On the other hand, allowing more than two trucks to be fully present on two-span bridges significantly increased the maximum shear by as much as 3.5 times the single truck shear force, as shown in figures 4.35 to 4.41. The increase in the maximum shear force of two-span bridges due to different numbers of platooned trucks can be seen in figures 4.33 to 4.41.

Overall, it can be concluded that an increase in span length allowed more trucks to be fully accommodated on the bridge at the same time, increasing the shear force. Allowing two trucks to be fully present on two-span bridges simultaneously produced an increase in the maximum shear force of up to 87 percent at a 10-ft. headway spacing, and this percentage decreased to be 78 percent when the headway spacing increased to 30 ft. On the other hand, allowing more than two trucks to be fully present on two-span bridges significantly increased the maximum shear by as much as 3.5 times the single truck shear force.

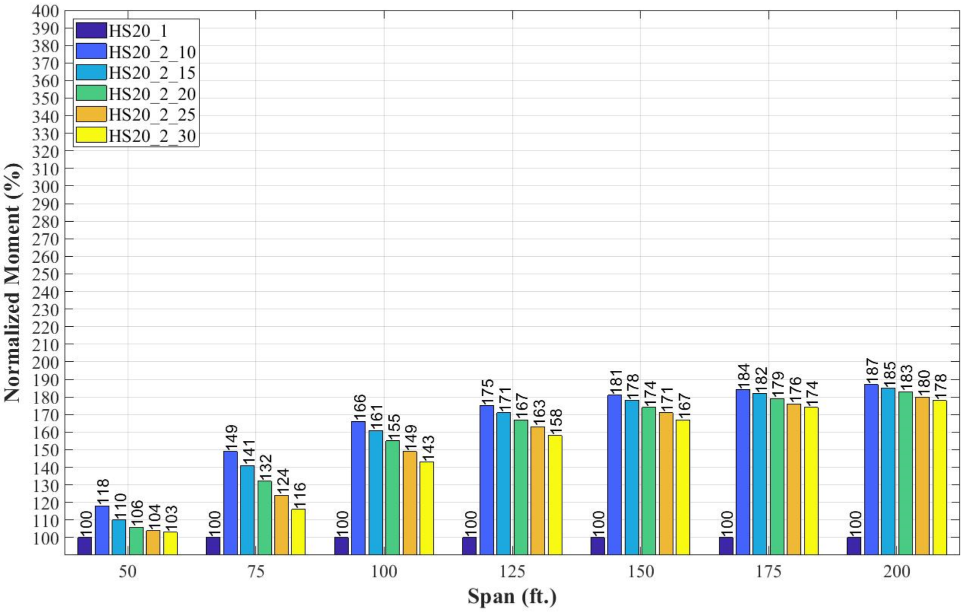

Figure 4.33 Normalized maximum shear force results for two-span bridges under two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

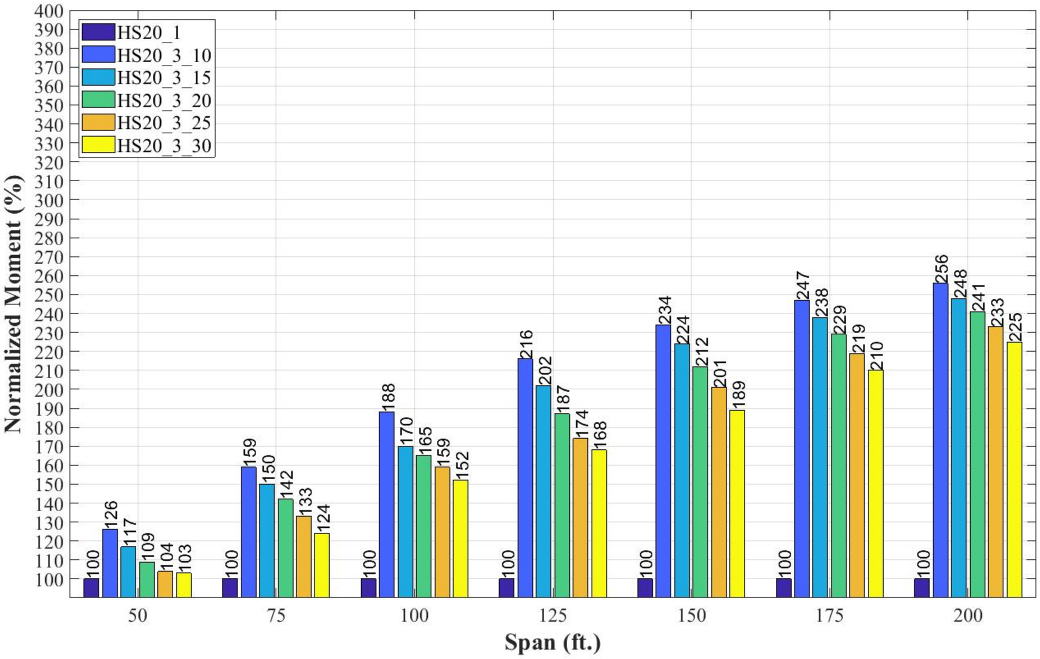

Figure 4.34 Normalized maximum shear force results for two-span bridges under three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

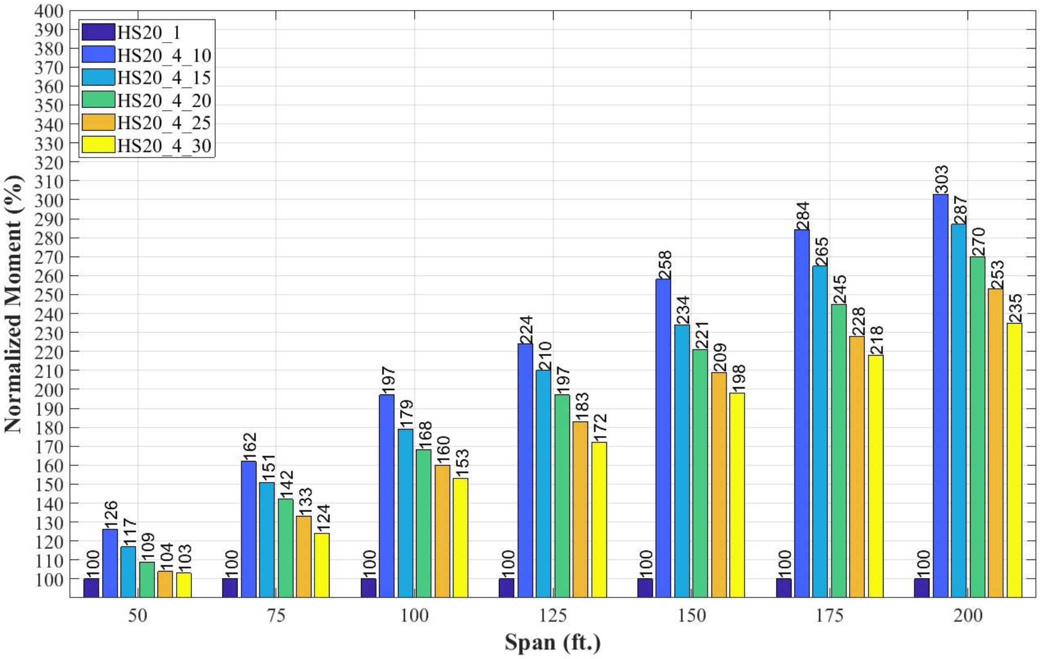

Figure 4.35 Normalized maximum shear force results for two-span bridges under four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

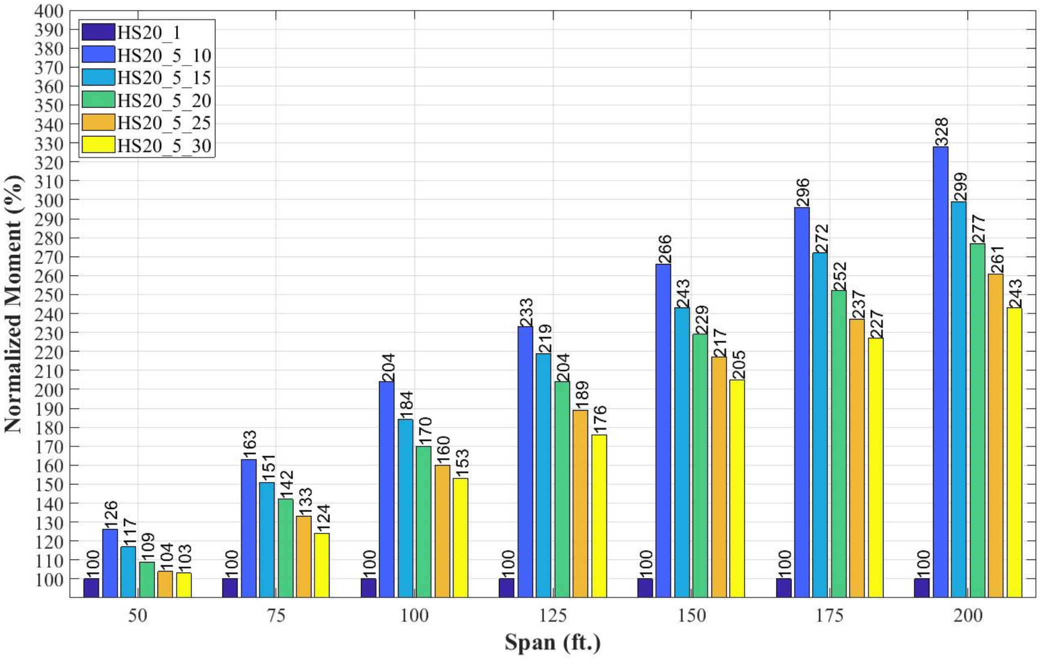

Figure 4.36 Normalized maximum shear force results for two-span bridges under five platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

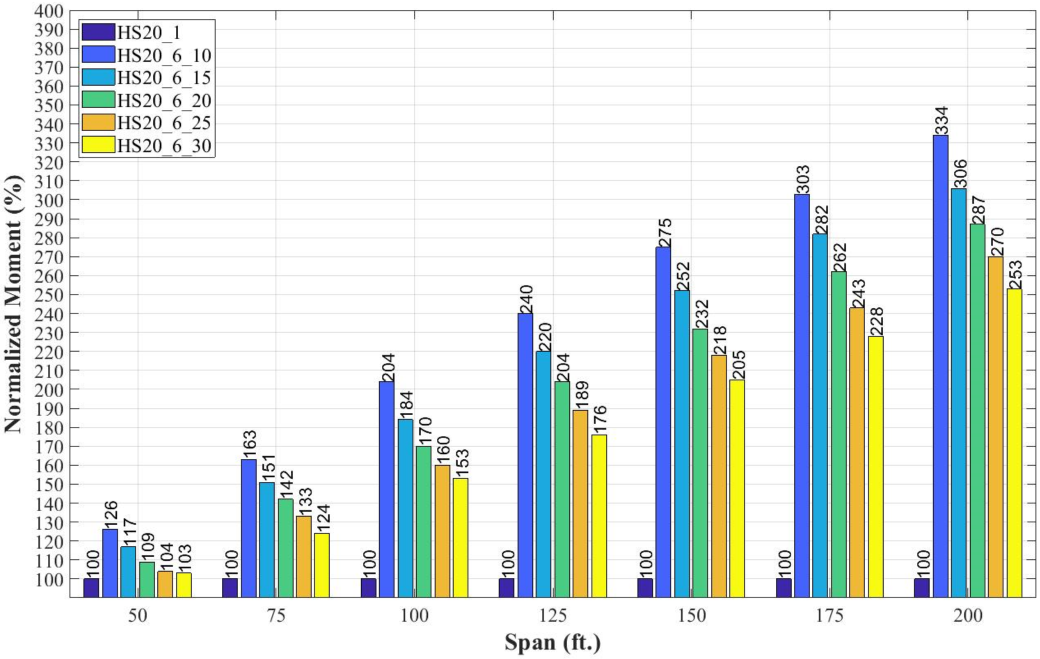

Figure 4.37 Normalized maximum shear force results for two-span bridges under six platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

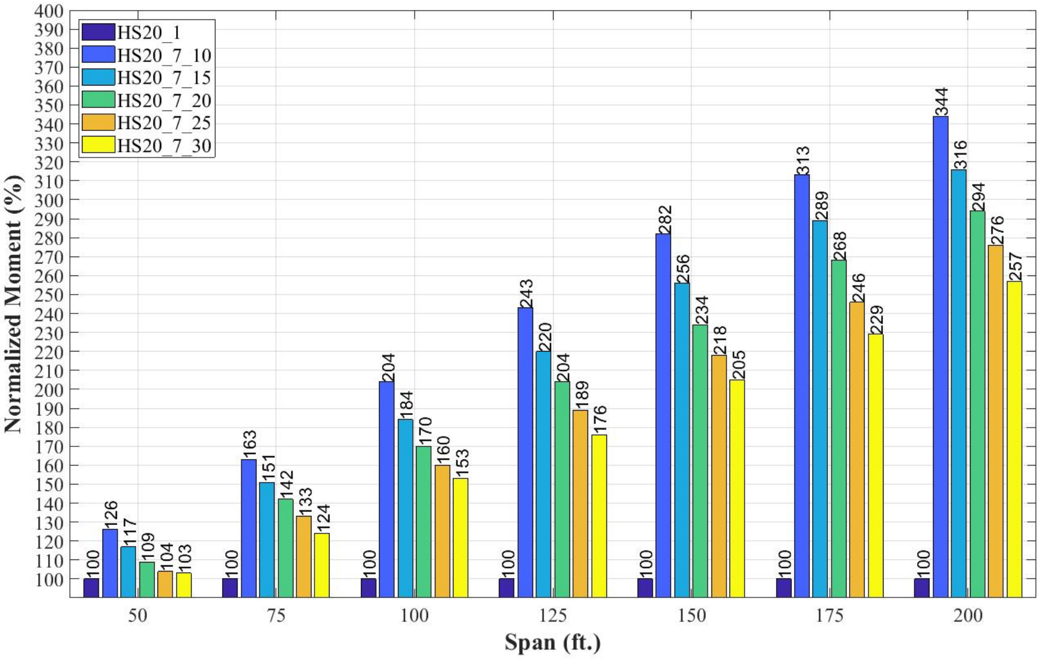

Figure 4.38 Normalized maximum shear force results for two-span bridges under seven platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

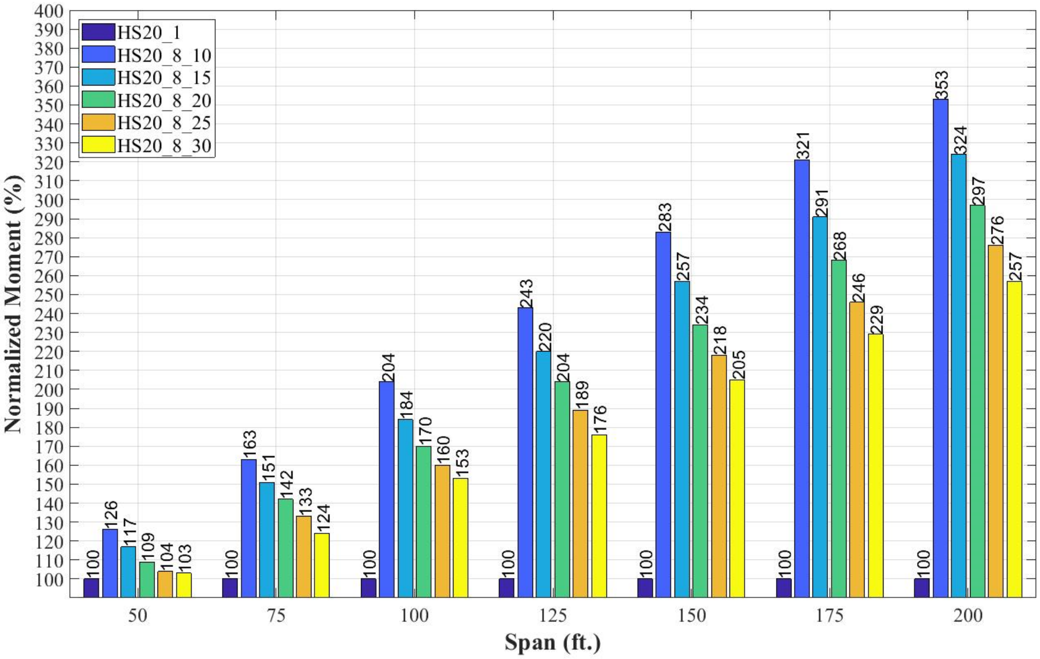

Figure 4.39 Normalized maximum shear force results for two-span bridges under eight platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

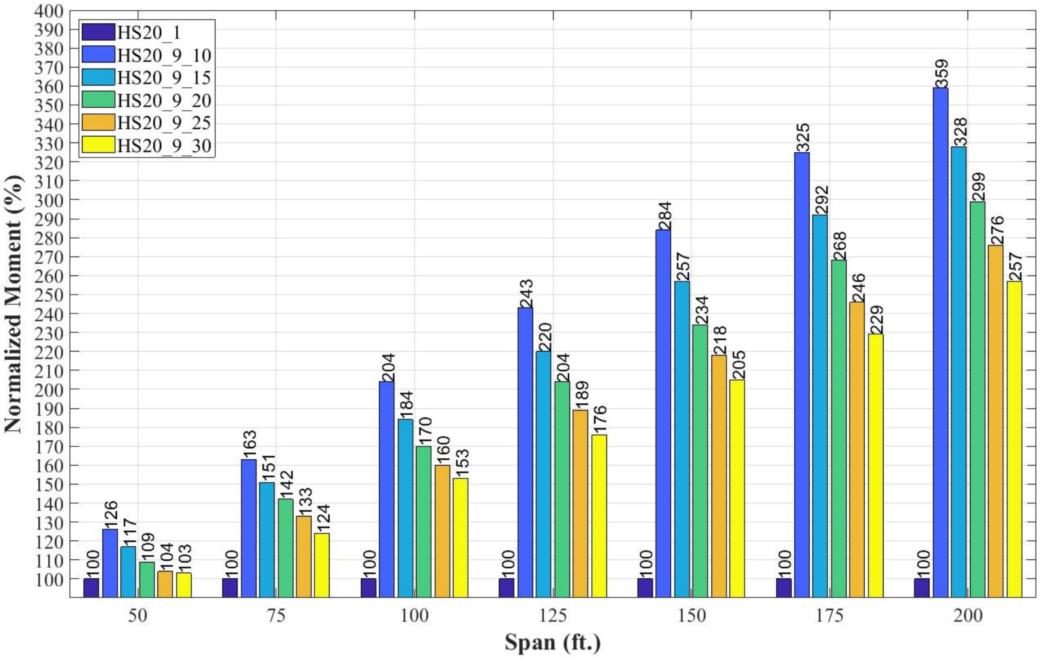

Figure 4.40 Normalized maximum shear force results for two-span bridges under nine platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

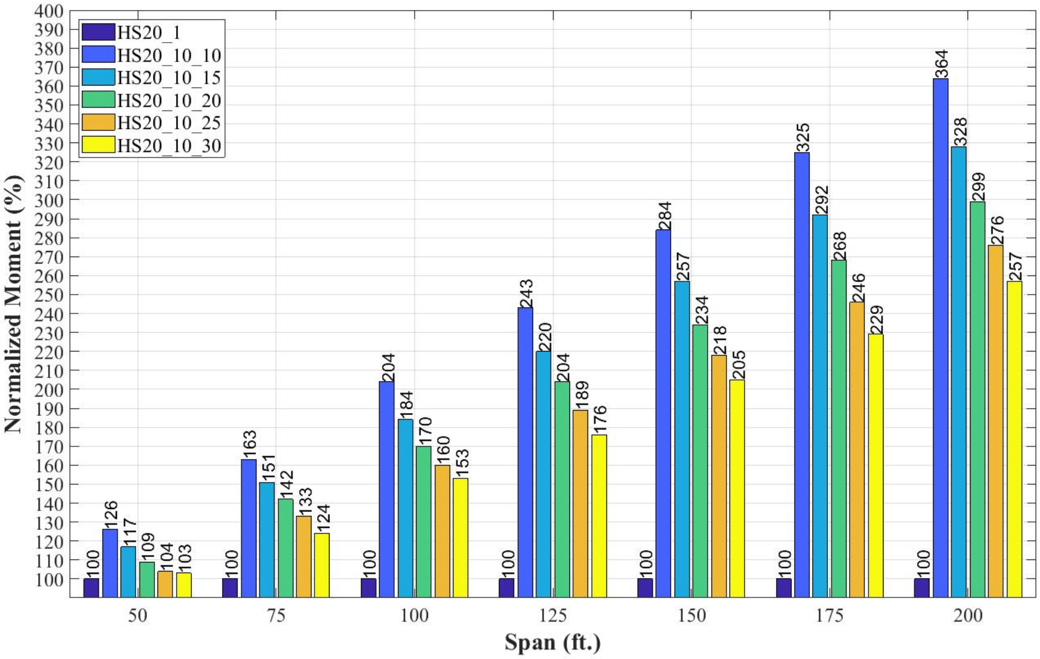

Figure 4.41 Normalized maximum shear force results for two-span bridges under more than nine platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

4.5. Effects of Bridge Continuity

Two-, three-, and four-span bridge results were compared to those of simple span bridges to investigate the effects of continuity on maximum bending moments and shear forces. In comparison to simple span bridges, positive moments in continuous bridges are expected to decrease as a result of the development of negative moments. Also, internal shear forces are expected to be higher than the maximum shear force in simple span bridges.

Figure 4.42 shows the average reduction in the positive moment due to continuity in comparison to that of simple span bridges. It can be observed that the average reductions in positive moments were in the range of 21 to 24 percent for two-span bridges, about 18 to 22 percent for three-span bridges, and approximately 19 to 23 percent for four-span bridges.

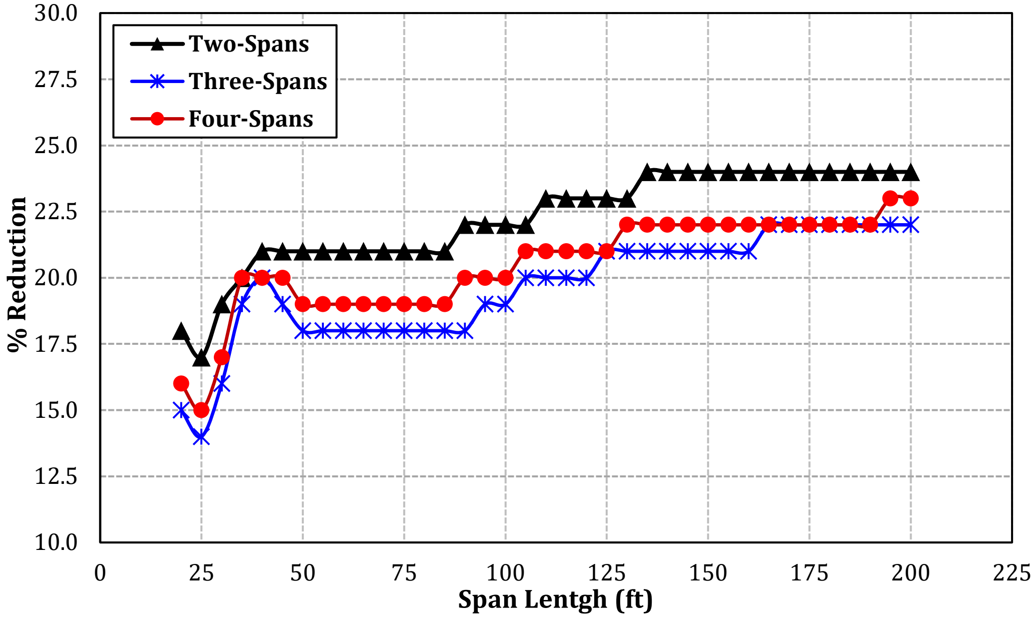

Figure 4.42 Percent of reduction in the positive moment due to continuity in comparison to that of simple span bridges

4.6. Regression Models

Linear, polynomial, and exponential regression models were developed for different truck platooning configurations. Regression models are provided in Appendix D. Note that the variable “y” indicates the bending moment in kip.ft., while the “x” variable represents the span in ft. The linear regression showed acceptable results, with an R^2 of more than 95 percent, while polynomial and exponential models showed great ability to anticipate the results. with an R^2 of more than 99 percent.

4.7. Summary

An extensive parametric study of 59,200 models was conducted using SAP2000 to investigate the effects of a wide range of platooning configurations on different bridge cases. Numerous parameters were included, such as the number of bridge spans, span lengths, number of truck platoons, and spacing between trucks (headway). The following conclusions were obtained:

- An increase in span length allowed more trucks to be fully accommodated on the bridge simultaneously, which increased the bending moment.
- As the headway spacing decreased, the bending moment increased.
- Allowing two trucks to be fully accommodated on a simple span bridge simultaneously produced an increase in the maximum moment of up to 77 percent for 200-ft. spans at a 10-ft. headway spacing, and this percentage decreased to 56 percent when the headway spacing increased to 30 ft.
- Allowing more than two trucks to be fully accommodated on a simple span bridge significantly increased the bending moment by as much as three times the single truck moment.
- Shear force results for simple span bridges showed the same trend as that of bending moments.
- For continuous spans, critical positive moments for long-span bridges (longer than 100 ft.) occurred when the maximum number of trucks was located on a single span. Therefore, continuous bridges with short and medium spans (shorter than 100 ft.) were not expected to experience a considerable increase in the positive moment because their spans could not accommodate many trucks at the same time.
- Critical negative moments for short and medium span bridges (up to 100 ft.) occurred when two adjacent spans were loaded simultaneously. Bridges with spans shorter than 75 ft. showed a significant increase in the negative bending moment in comparison to AASHTO’s 90 percent design live load condition.
- In comparison to simple span bridges, continuous bridges were expected to experience a reduction in positive moments due to the development of negative

moments. Also, the internal shear forces were expected to be higher than the maximum shear force in simple span bridges.

- The average reductions in positive moments were about 21 to 24 percent for two-span bridges, 18 to 22 percent for three-span bridges, and approximately 19 to 23 percent for four-span bridges.
- The linear regression models showed acceptable results, with an R^2 of more than 95 percent, while polynomial and exponential models showed great ability to predict the results, with an R^2 of more than 99 percent.
- Charts were developed to determine the percentage of bridge load rating reduction based on the number of trucks and the headway distance.

CHAPTER 5. BRIDGE LOAD RATING RESULTS

5.1. Overview

This chapter introduces the effects of different truck platooning configurations on simple-span, two-span, and more than two-span bridge load ratings. The parametric study results, described in Chapter 4, were used to find the percentage of reduction in bridge load ratings under the effects of different platoon configurations. The results were then used to provide guidelines and recommendations for future applications. In addition, a case study was carried out to apply the method obtained and provide the optimum configurations.

5.2. Load Rating of Simple-Span Bridges

The effects of different truck platooning configurations on the load ratings of simple span bridges are discussed in this section. Changes in bridge load ratings based on bending moments and shear forces were calculated. Figures 5.1 to 5.8 show reductions in bending moment and shear force rating factors (RF) due to different truck platoon configurations. As shown in figures 5.1 to 5.8, two highlighted zones were created for more clarification. The green zone includes the configurations with a maximum 20 percent reduction in RF, while the red zone presents the configurations with a maximum 40 percent reduction. In addition, table 5.1 provides a guideline that can be used to find the possible truck platoon configurations based on the reduction in bending moment RF.

5.2.1. Rating Factors for Moment

The reductions in the Bending Moment Rating Factors (RF_{moment}) of simple span bridges with two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.) are shown in figures 5.1 to 5.4.

The same trend can be observed in all the figures. As mentioned earlier, an increase in the span length allowed more trucks to be fully accommodated on the bridge at the same time, which increased the bending moment and led to a reduction in rating factors. Allowing two trucks to be fully accommodated on a simple span bridge produced a reduction in the rating factors of up to 40 percent. This could be controlled by increasing the headway spacing because an increase of headway spacing decreased the percentage of the reduction in RF. On the other hand, allowing more than two trucks to be fully accommodated significantly reduced the rating factors by more than 40 percent. (This is illustrated in figures 5.2 to 5.4. The points located out of the green and red zones refer to configurations in which more than two trucks were entirely placed on the bridge.)

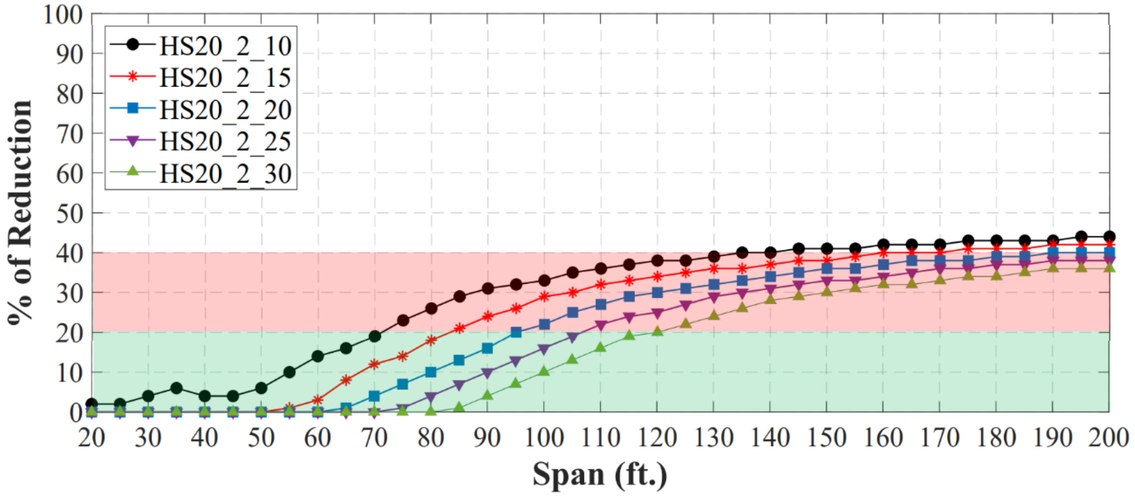

Figure 5.1 Reductions in bending moment RFs for simple span bridges due to two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

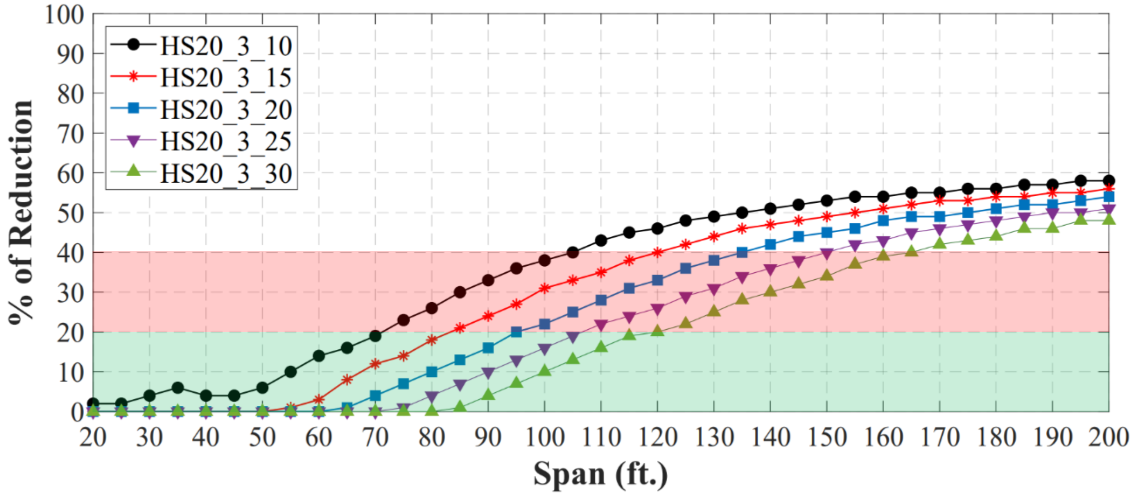

Figure 5.2 Reductions in bending moment RFs for simple span bridges due to three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

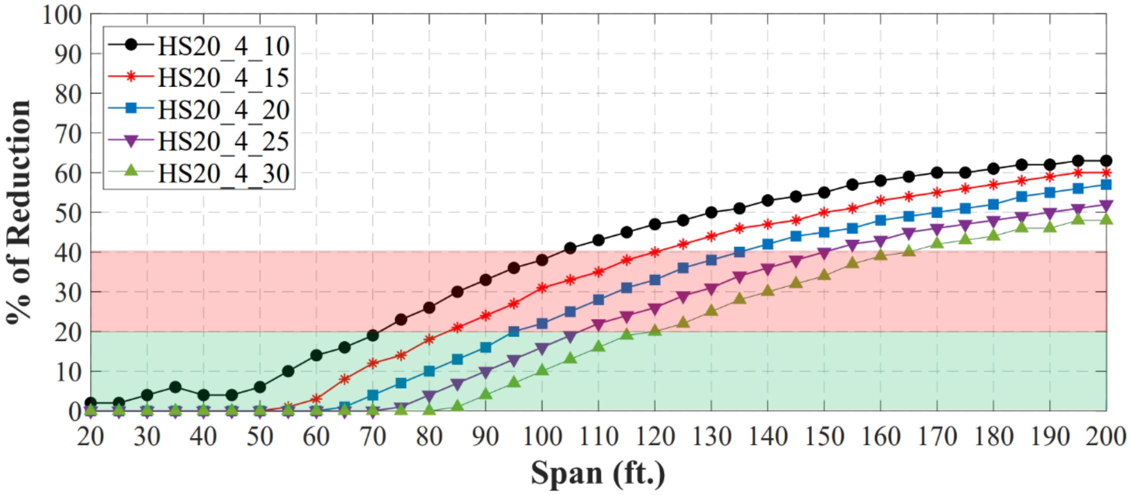

Figure 5.3 Reductions in bending moment RFs for simple span bridges due to four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

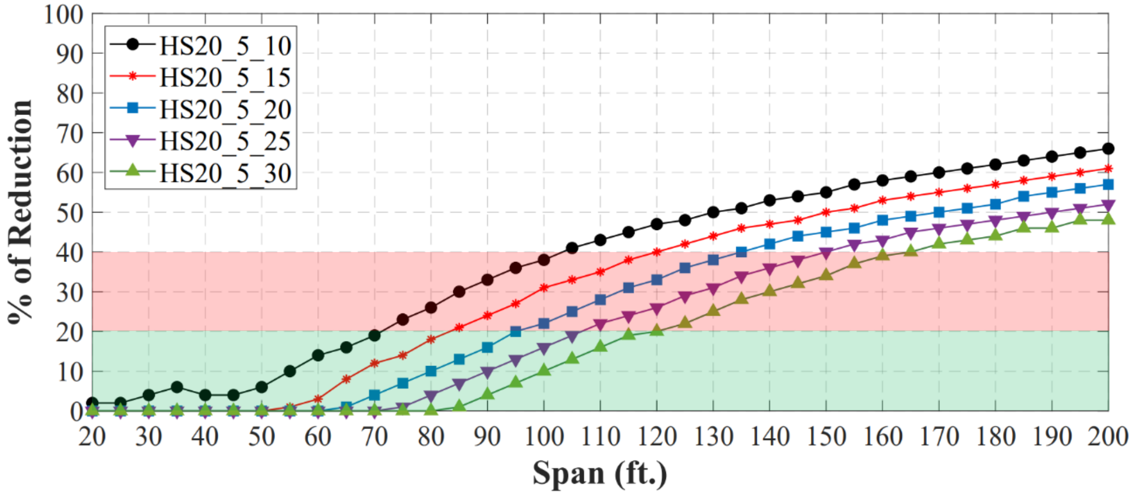

Figure 5.4 Reductions in bending moment RFs for simple span bridges due to more than four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

Table 5.1 Reductions in bending moment RFs for different truck platoon configurations

No. of Spans	No. of Trucks	% Reduction	Headway (ft.)	Maximum Span (ft.)
Simple Span	Two Trucks	Up to 20	10	70
			15	85
			20	95
			25	105
			30	115
		20 – 40	10	70 – 140
			15	85 – 160
			20	95 – 200
			25	105 -200
			30	115 – 200
		More than 40	10	140 – 200
			15	160 - 200
	More than Two Trucks	Up to 20	10	70
			15	85
			20	95
			25	105
			30	115
		20 – 40	10	70 – 105
			15	85 – 120
			20	95 – 130
			25	105 – 150
			30	115 – 160
		More than 40	10	105 – 200
			15	120 – 200
			20	130 – 200
			25	150 – 200
			30	160 - 200

5.2.2. Rating Factors for Shear

The reductions in the Shear Force Rating Factors (RF_{shear}) of simple span bridges with two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.) are shown in figures 5.5 to 5.8.

The same trend can be observed in all the figures. As mentioned earlier, an increase in span length allowed more trucks to be fully accommodated on the bridge at the same time, which increased the shear force and led to a reduction in rating factors. Allowing two trucks to be fully accommodated on a simple span bridge produced a reduction in rating factors of up to 40 percent. This could be controlled by increasing the headway spacing because an increase of headway spacing decreased the percentage of the reduction in rating factors. On the other hand, allowing more than two trucks to be fully accommodated on simple span bridges significantly reduced the rating factors by more than 40 percent (This is illustrated in figures 5.5 to 5.8. The points located out of the green and red zones refer to configurations in which more than two trucks were placed on the bridge.)

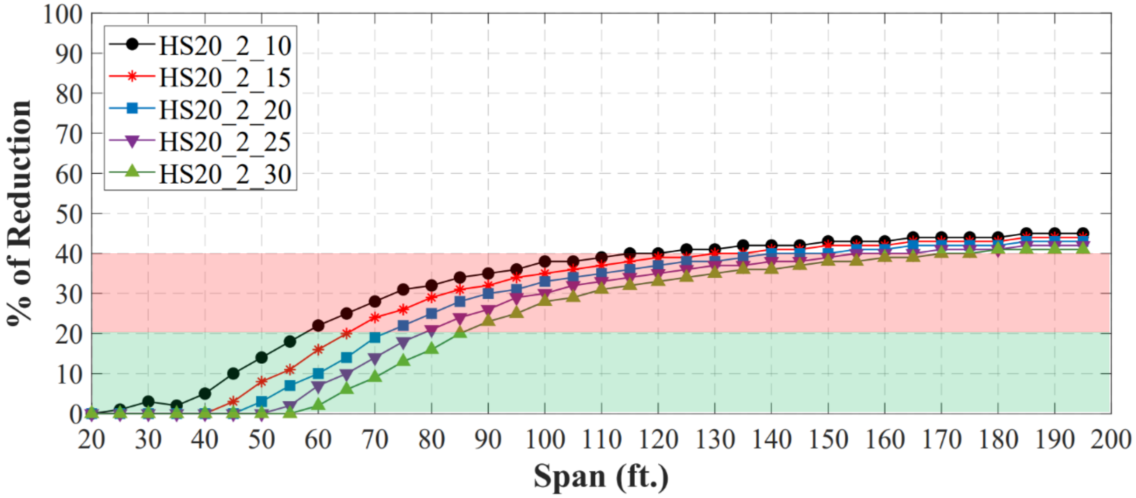

Figure 5.5 Reductions in shear force RFs for simple span bridges due to two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

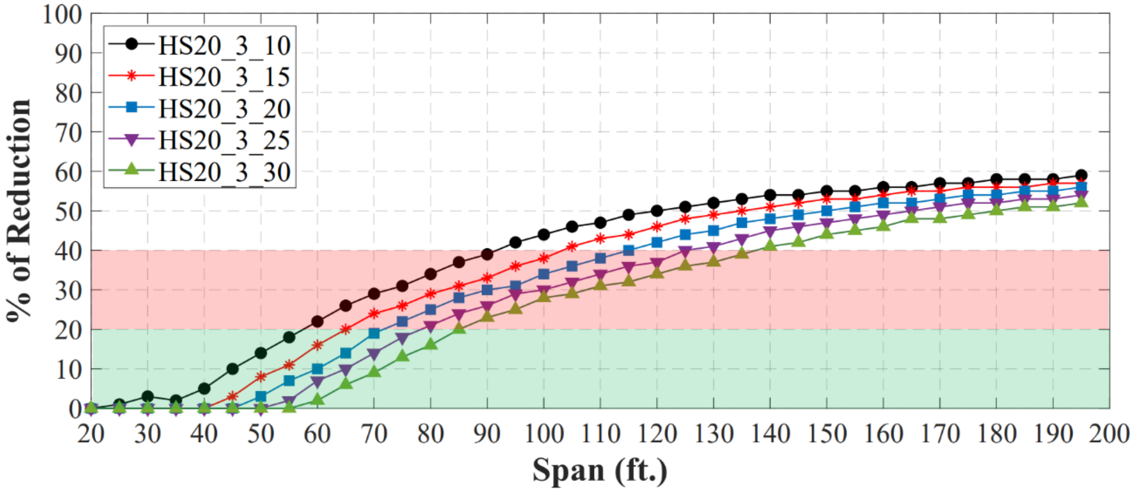

Figure 5.6 Reductions in shear force RFs for simple span bridges due to three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

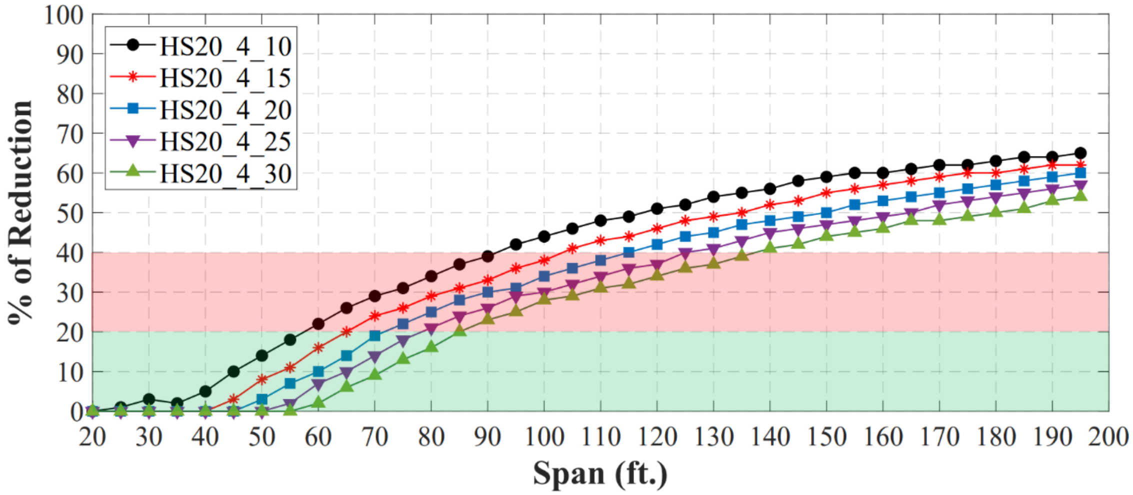

Figure 5.7 Reductions in shear force RFs for simple span bridges due to four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

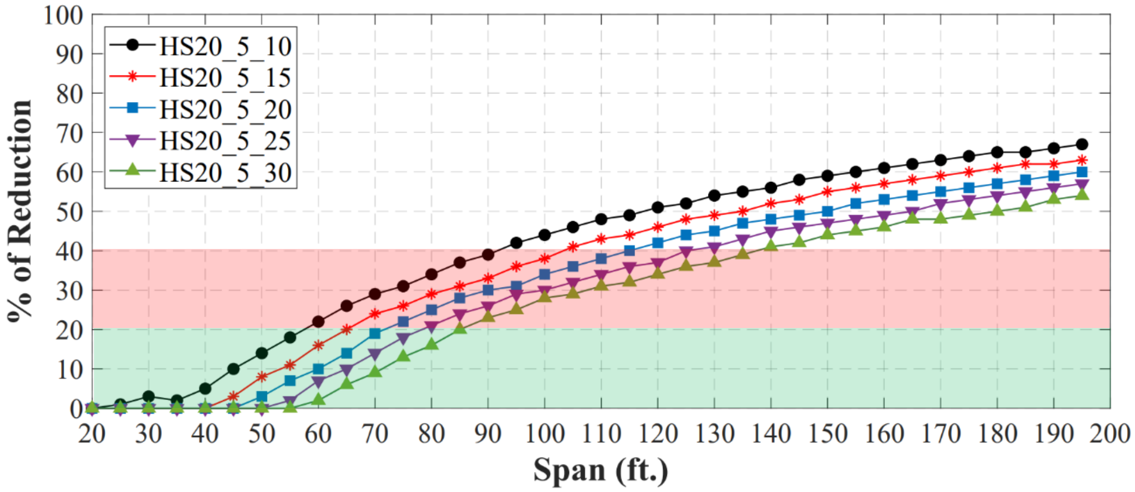

Figure 5.8 Reductions in shear force RFs for simple span bridges due to more than four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

5.3. Load Rating of Two-Span Bridges

The effects of different truck platooning configurations on the load ratings of two-span bridges is discussed in this section. Changes in bridge load ratings based on bending moments and shear forces were calculated. Figures 5.9 to 5.24 show the reductions in bending moment and shear force rating factors due to different truck platoon configurations. Similarly, as mentioned for simple span bridge results, two highlighted zones were created for more clarification.

5.3.1. Positive Moment Rating Factors

The reductions in the Positive Moment Rating Factors (RF_{moment}) of two-span bridges with two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.) are shown in figures 5.9 to 5.12.

Critical positive moments for long-span bridges (longer than 100 ft.) occurred when the maximum number of platooned trucks was located on a single span, which reduced the positive moment rating factor. In addition, reducing the headway spacing from 30 ft. to 10 ft. allowed more trucks to be located on a single span, significantly decreasing the positive moment RF by about 20 to 30 percent.

On the other hand, continuous bridges with short and medium spans (shorter than 100 ft.) were not expected to experience a considerable increase in the positive moment because their spans could not accommodate many trucks at the same time (especially for headway spacings of greater than 20 ft.). As a result, a maximum reduction of 20 percent in positive moment RF could happen. Allowing more than two trucks to be fully accommodated on a single span significantly increased the positive bending moment by as much as three times the single truck moment, which reduced the rating factors by more than 40 percent.

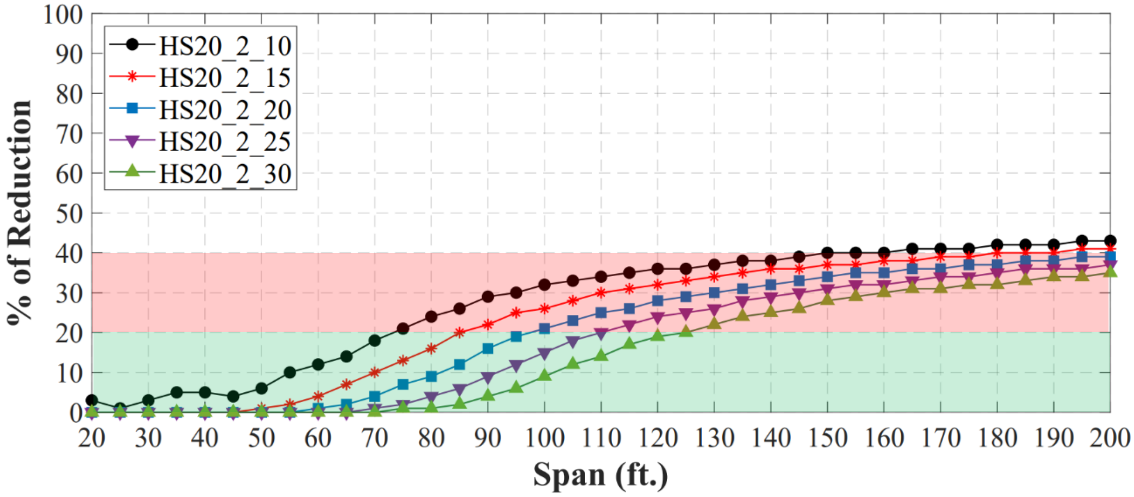

Figure 5.9 Reductions in positive moment RFs for two-span bridges due to two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

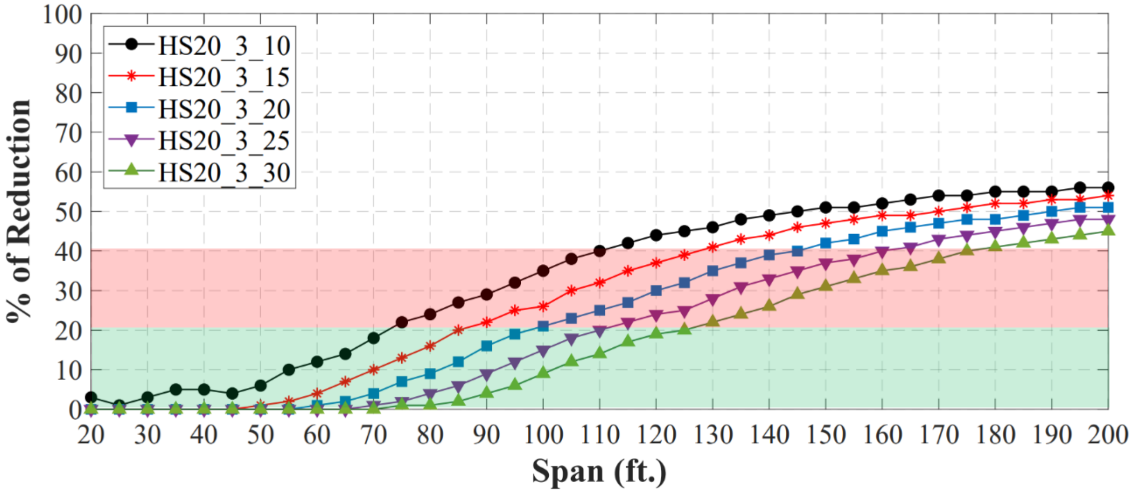

Figure 5.10 Reductions in positive moment RFs for two-span bridges due to three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

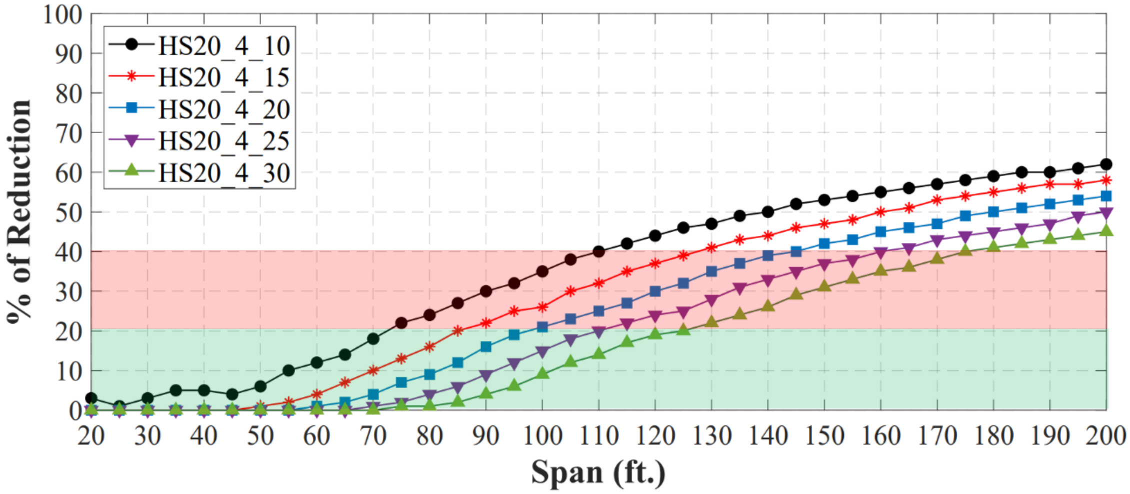

Figure 5.11 Reductions in positive moment RFs for two-span bridges due to four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

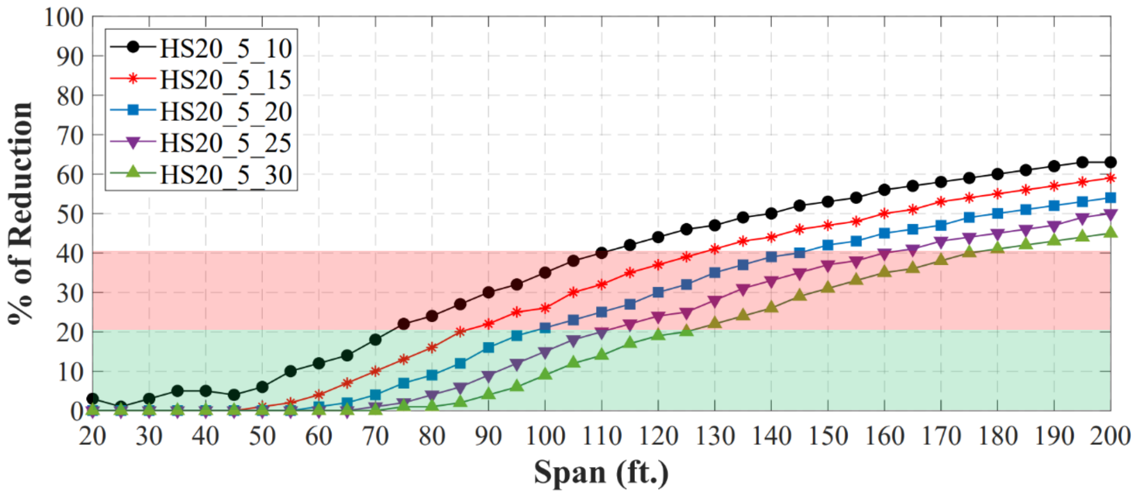

Figure 5.12 Reductions in positive moment RFs for two-span bridges due to more than four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

5.3.2. Negative Moment Rating Factors

The reductions in the Negative Moment Rating Factors (RF_{moment}) of two-spans bridges with two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.) are shown in figures 5.13 to 5.20.

Critical negative moments for short and medium span bridges (shorter than 100 ft.) occurred when two adjacent spans were loaded simultaneously, introducing a crucial reduction in the negative moment rating factor in comparison to the AASHTO 90 percent design live load.

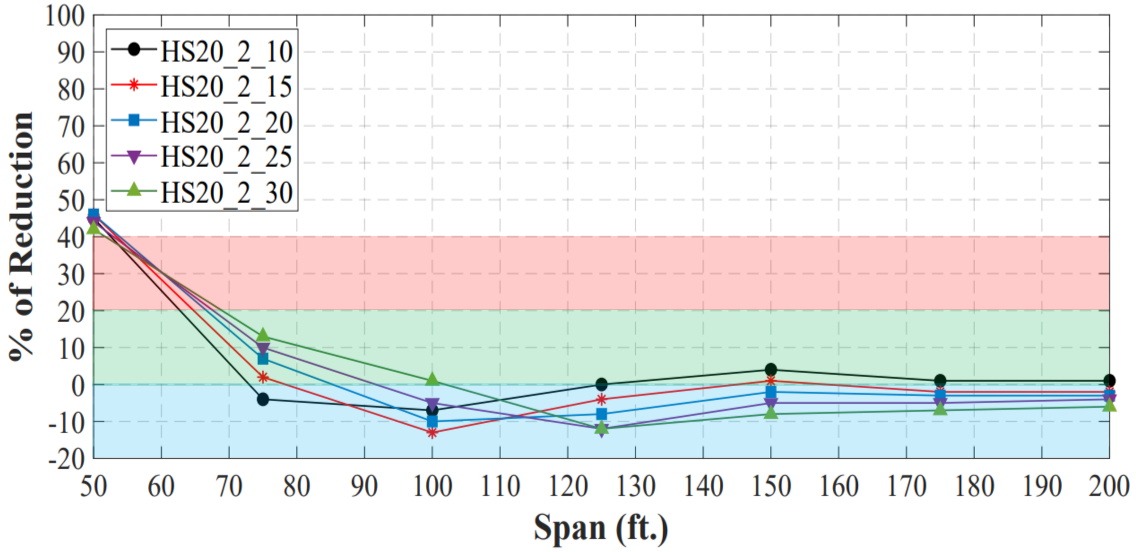

Figure 5.13 Changes in negative moment RFs for two-span bridges due to two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

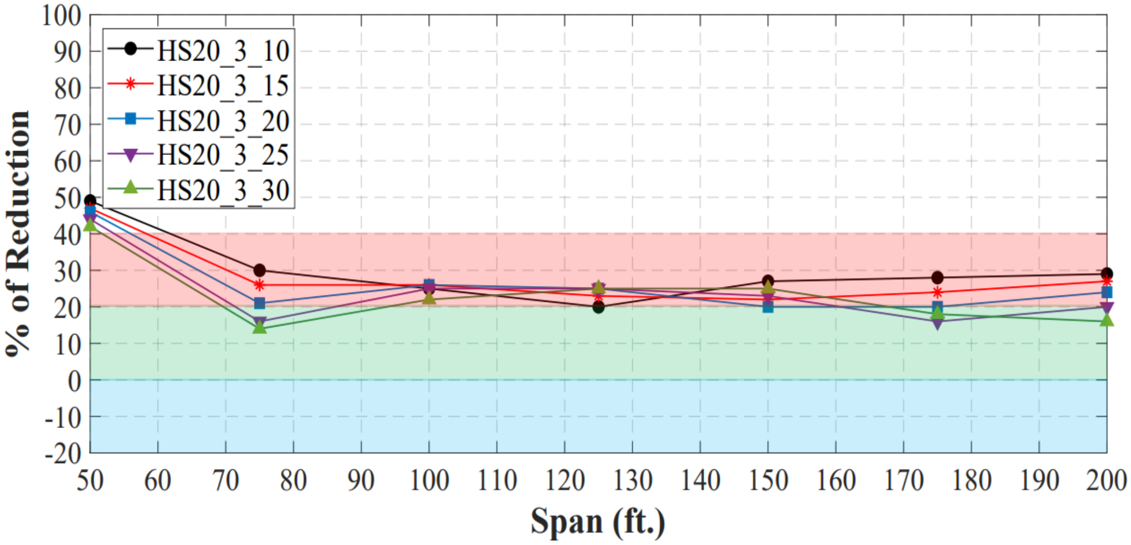

Figure 5.14 Changes in negative moment RFs for two-span bridges due to three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

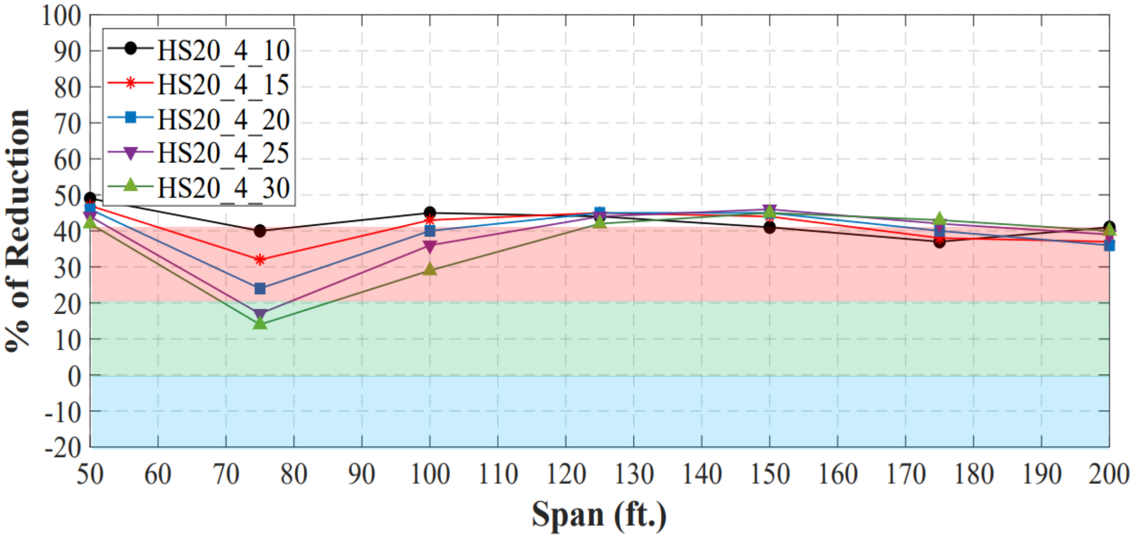

Figure 5.15 Changes in negative moment RFs for two-span bridges due to four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

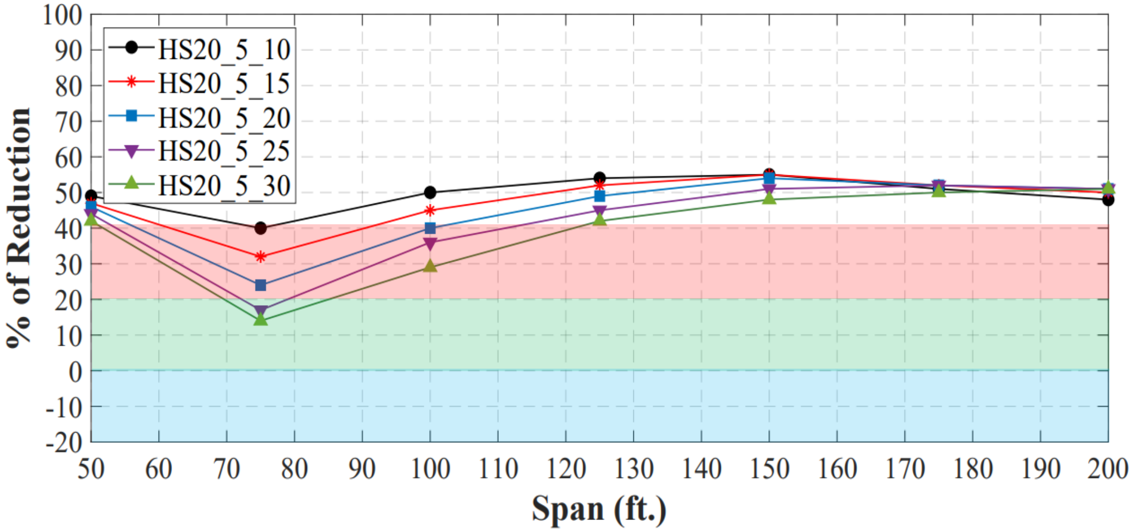

Figure 5.16 Changes in negative moment RFs for two-span bridges due to five platooned trucks, at different headways (10, 15, 20, 25, and 30 ft.)

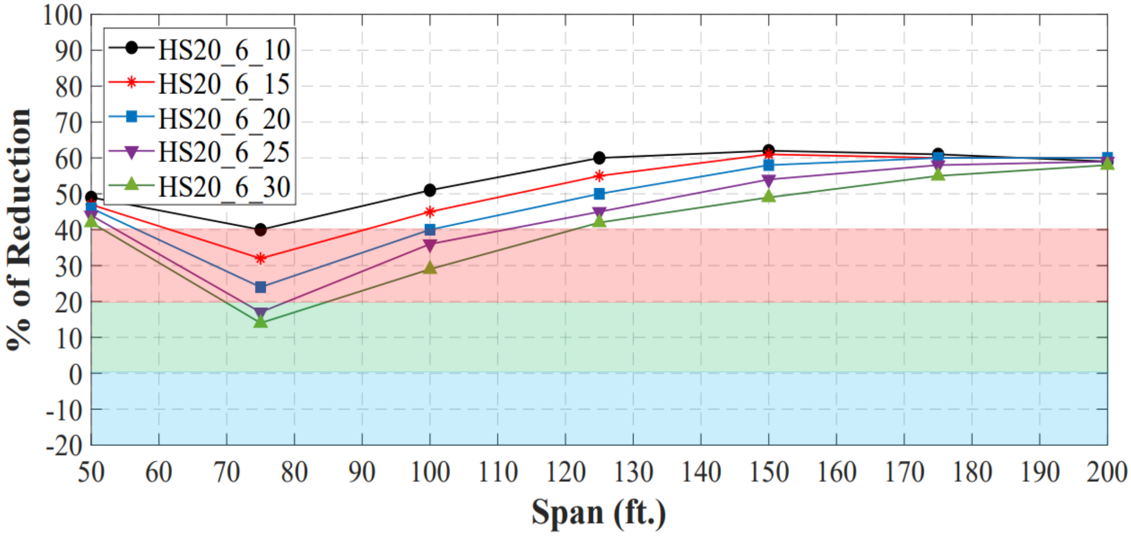

Figure 5.17 Changes in negative moment RFs for two-span bridges due to six platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

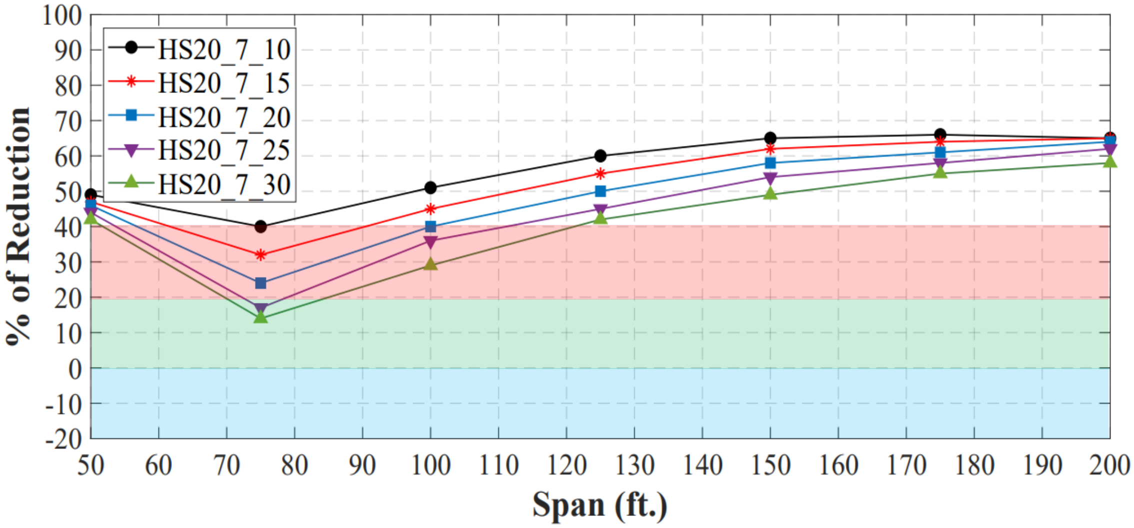

Figure 5.18 Changes in negative moment RFs for two-span bridges due to seven platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

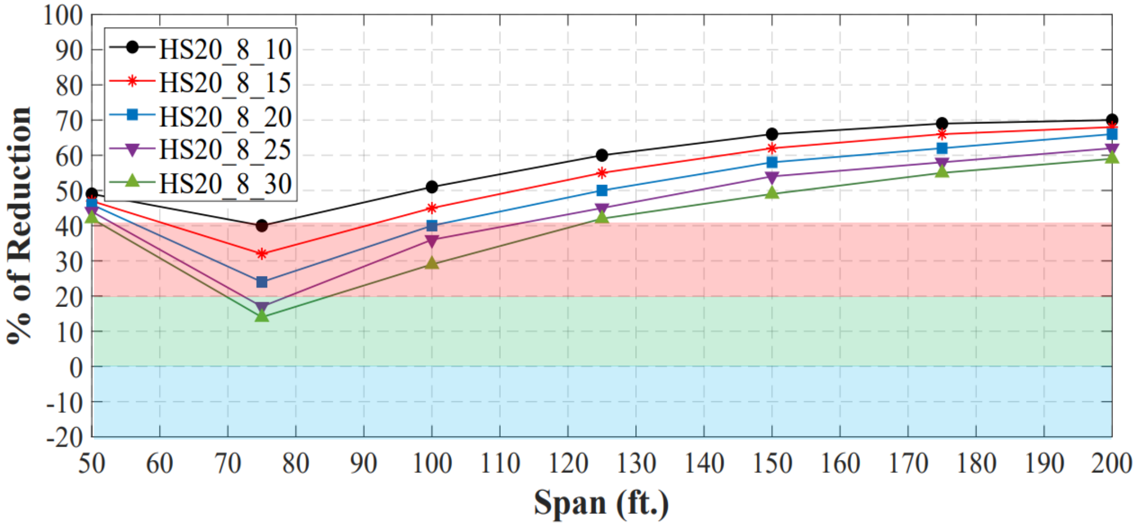

Figure 5.19 Changes in negative moment RFs for two-span bridges due to eight platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

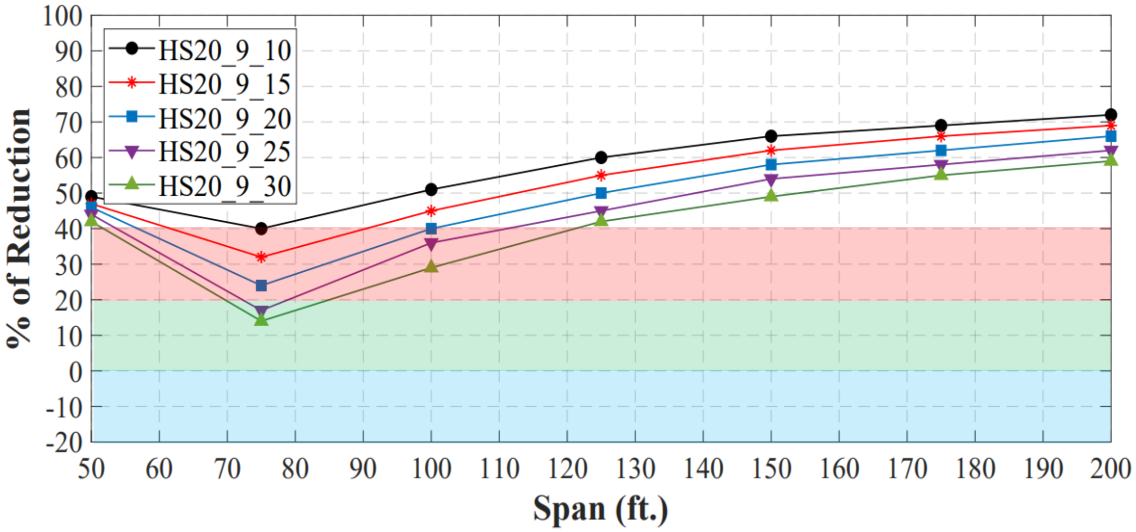

Figure 5.20 Changes in negative moment RFs for two-span bridges due to more than eight platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

5.3.3. Shear Force Rating Factors

The reductions in Shear Force Rating Factors ($\text{RF}_{\text{moment}}$) of two-spans bridges with two-, three-, four-, and more than four-truck platoons at different headway spacings (10, 15, 20, 25, and 30 ft.) are shown in figures 5.21 to 5.24.

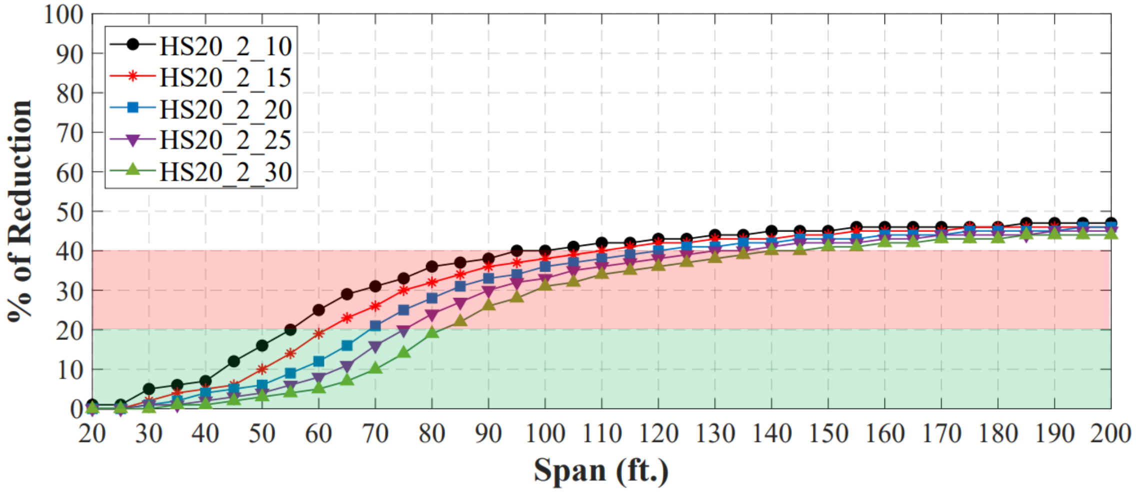

Figure 5.21 Reductions in shear force RFs for two-span bridges due to two platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

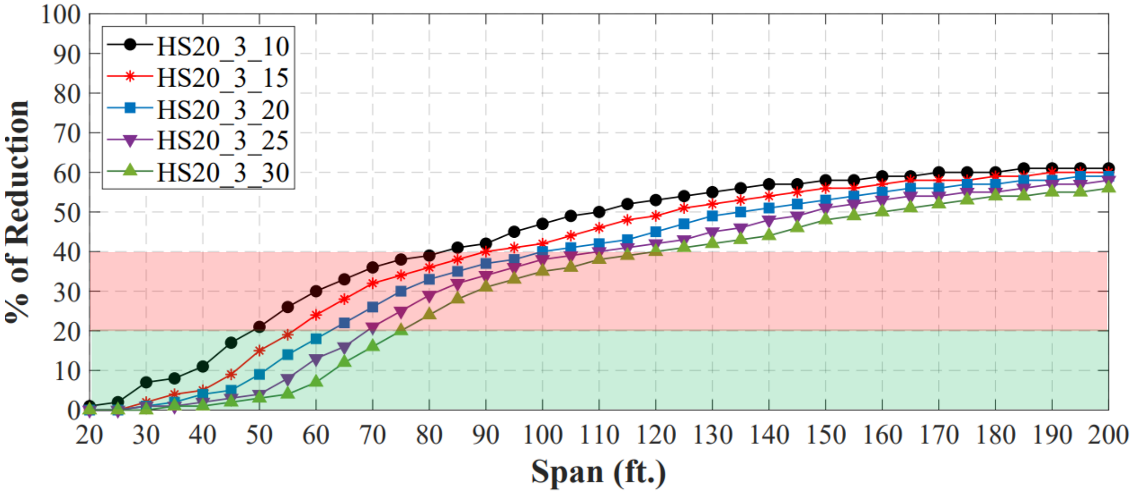

Figure 5.22 Reductions in shear force RF for two-span bridges due to three platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

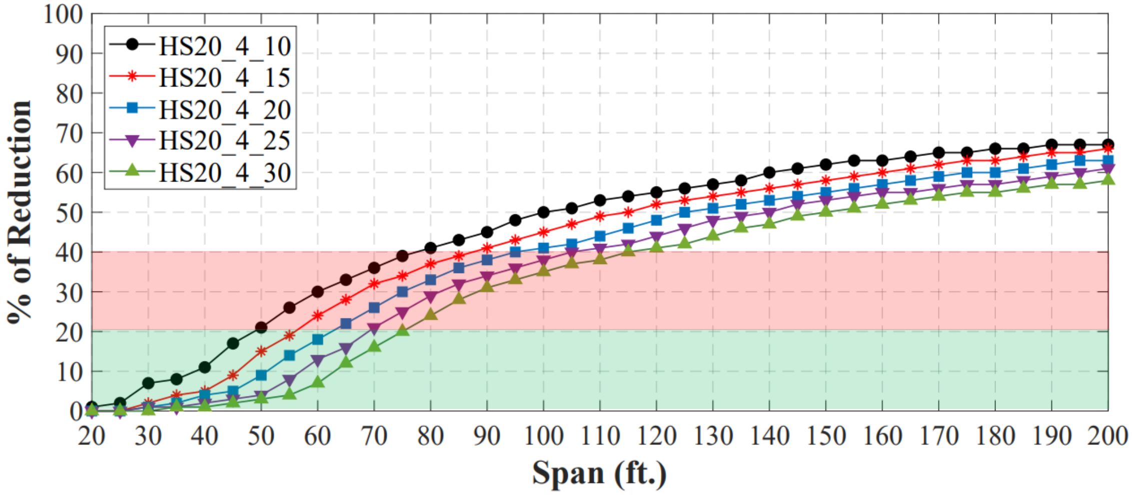

Figure 5.23 Reductions in shear force RFs for two-span bridges due to four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

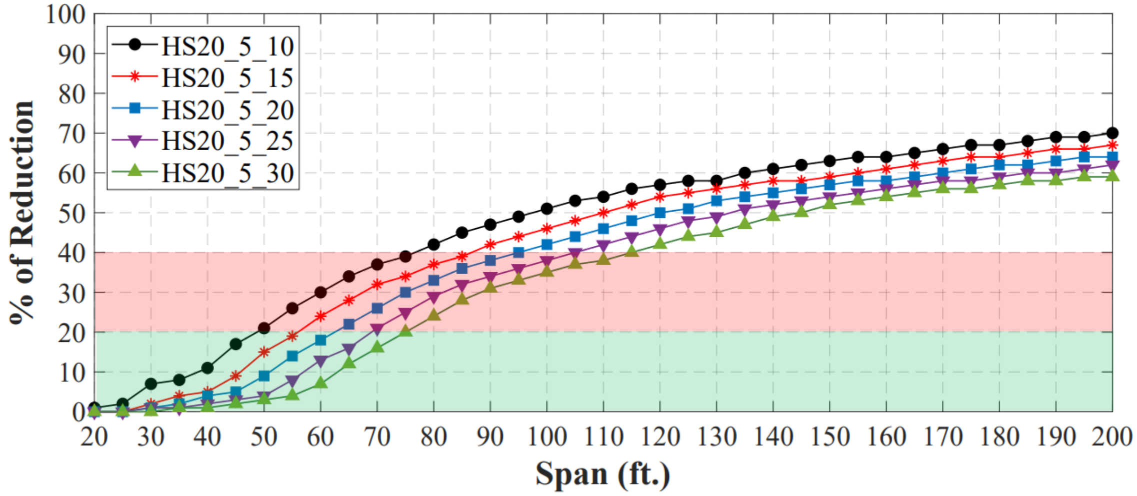

Figure 5.24 Reductions in shear force RFs for two-span bridges due to more than four platooned trucks at different headways (10, 15, 20, 25, and 30 ft.)

5.4. Case Study

The bridge cross-section A1, provided in the AASHTO MBE, was used to implement the results obtained in this work. The bridge was a 70-ft. simple span with the cross-section shown in figure 5.25. The bridge was analyzed, and the following properties were obtained:

- Moment Capacity = 3500 kip.ft.
- Shear Capacity = 400 kips
- Total Dead Loads for moment = 808.5 kip.ft.
- Total Dead Loads for shear = 46.2 kips
- Live Load Distribution Factor for the interior girder = 0.667.

The ASR, LRF, and LRFR load ratings were calculated for an interior girder for different truck platooning configurations. Figures 5.26 to 5.29 show load rating results for the 70-ft. simple span bridge under one, two, and three trucks.

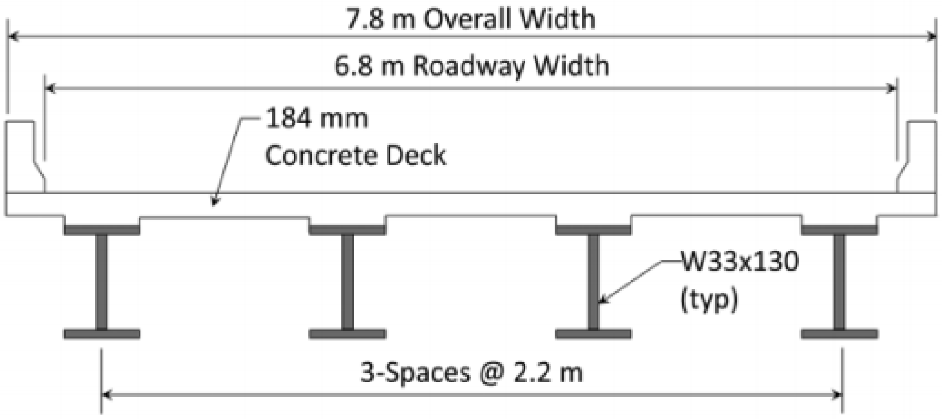

Figure 5.25 Cross-section of AASHTO MBE example bridge A1 (Yarnold, 2019)

As can be seen, the operating ASR/LFR for the interior girder was 1.3 for the moment and 2.97 for shear, based on the original design. The use of two trucks resulted in reductions in the bending moment RF of 18 percent for a 10-ft. headway, 11 percent for a 15-ft. headway, and 5 percent for a 20-ft. headway. In addition, there was no reduction in the bending moment RF for headways equal to or greater than 25 ft. The same reduction values can be obtained from the RF charts provided in this chapter. Figure 5.30 shows the reduction in bending moment RF for a simple span bridge under two trucks. The same correlations can be used for LRFR for moment and shear.

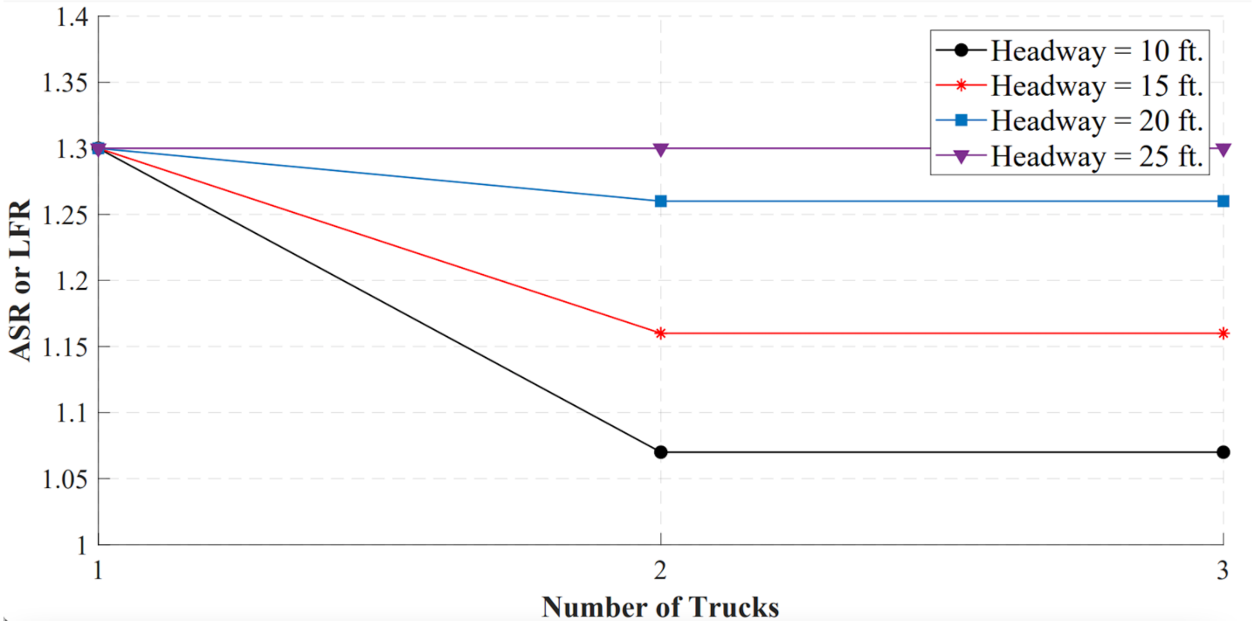

Figure 5.26 ASR\LFR for the moment of a 70-ft. simple span bridge under one, two, and three trucks

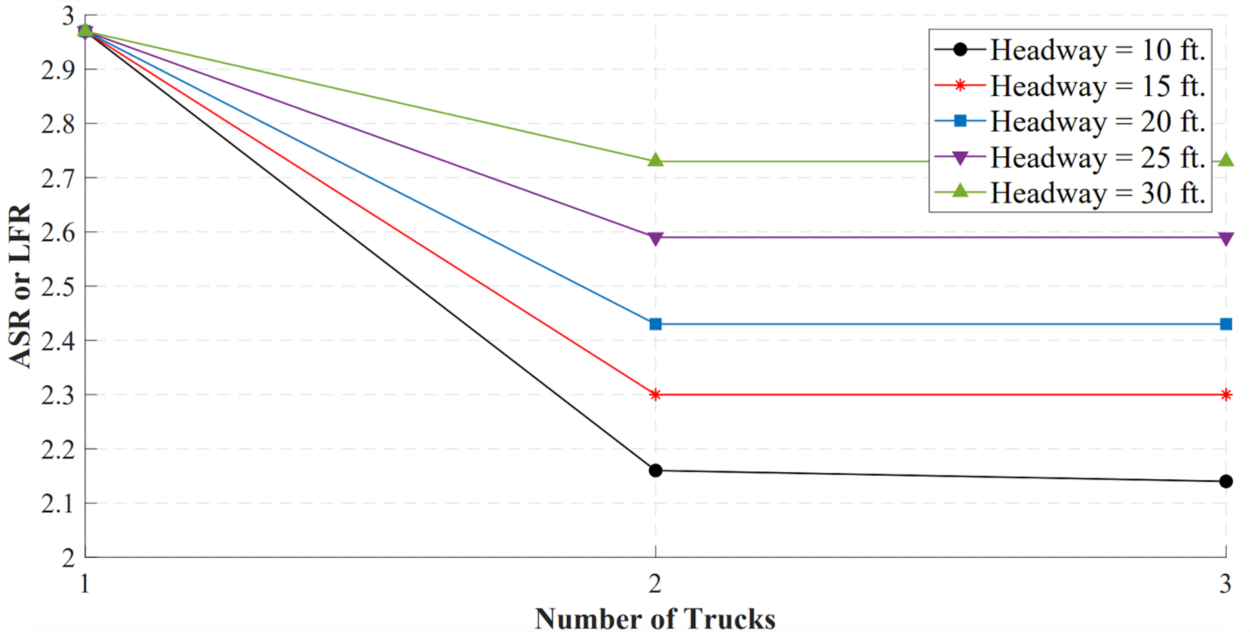

Figure 5.27 ASR\LFR for the shear of a 70-ft. simple span bridge under one, two, and three trucks

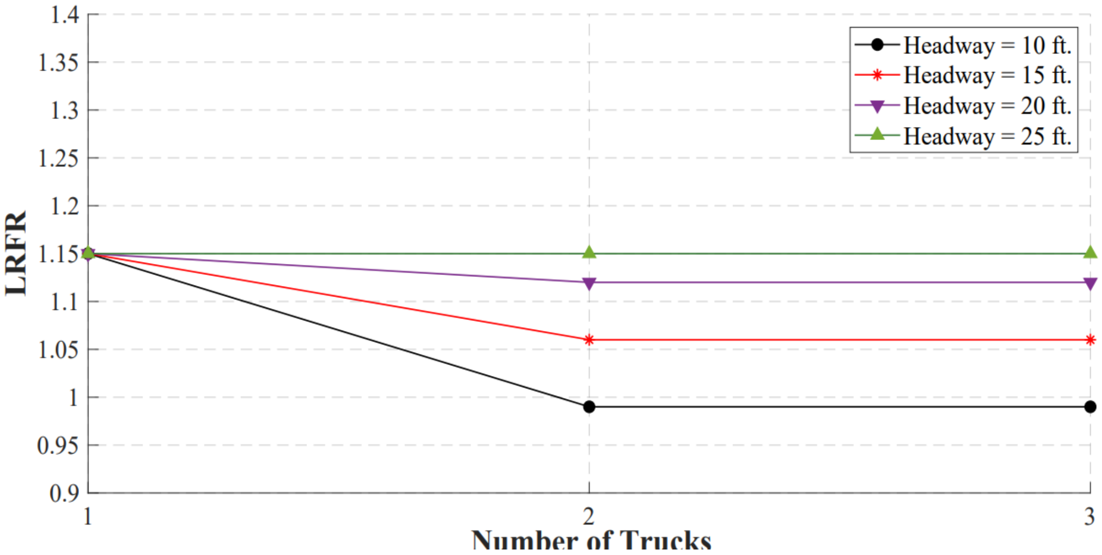

Figure 5.28 LRFR for the moment of a 70-ft. simple span bridge under one, two, and three trucks

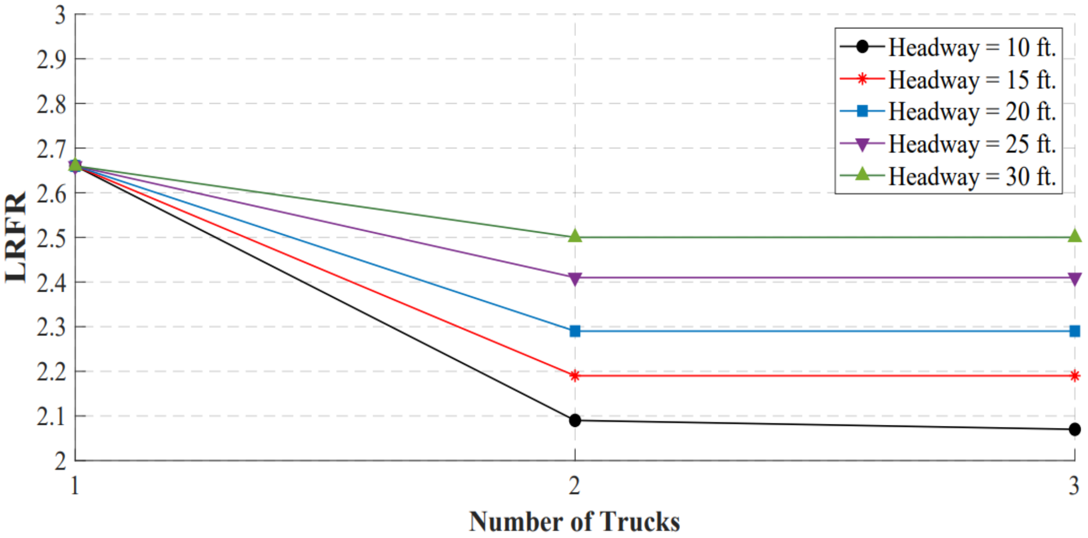

Figure 5.29 LRFR for the shear of a 70-ft. simple span bridge under one, two, and three trucks

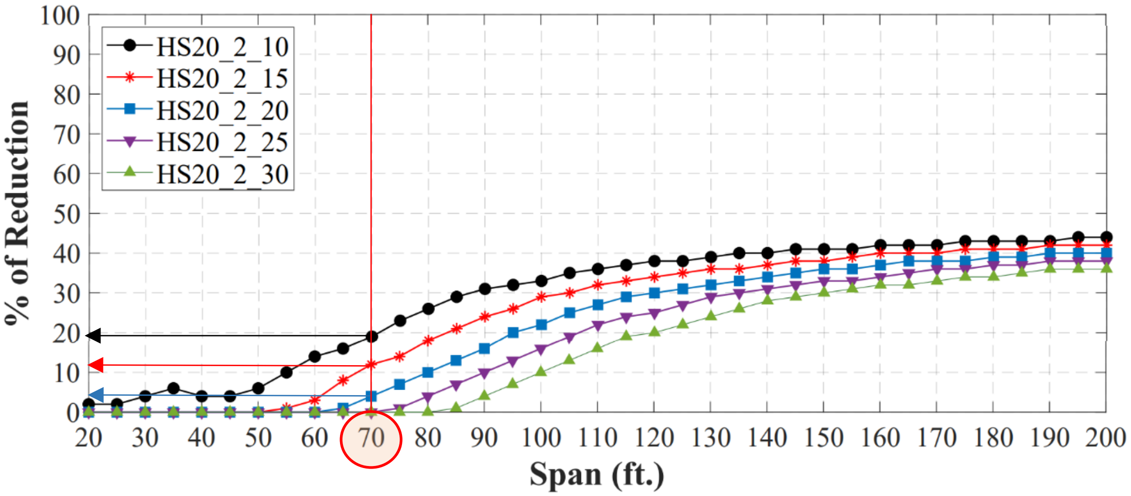

Figure 5.30 The reduction in a 70-ft. simple span bridge under two trucks

CHAPTER 6. CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1. Conclusions

The operational characteristics of freight shipments will significantly change after implementation of autonomous and connected trucks (ACTs). This change will have major impacts on mobility, safety, and infrastructure service life. Truck platooning is one of the truck arrangements that will soon become feasible with connected vehicle technology. It will enable trucks to be connected with themselves and the surrounding infrastructure. Although truck platooning will increase fuel efficiency and improve transportation services, the platooning configuration is expected to accelerate damage to the existing infrastructures. This damage, if accumulated, will cost the country billions of dollars to fix and will affect the mobility of people and goods. This research aimed to develop a well-defined framework to assess and data-driven solutions to address the influence of truck platoons on existing bridges in the Pacific Northwest to be ready for the implementation of ACTs and to preserve the current bridge inventory.

An extensive parametric study of 59,200 models considering a wide range of parameters was conducted. Four bridge cases were included: simple span, two-span, three-span, and four-span bridges. The effects of bridge continuity were demonstrated by the two-, three-, and four-span bridges. The spans varied from 20 ft. to 200 ft. (6 m to 60 m) with increments of 5 ft. (1.5 m). The HS-20 design truck was arranged, according to the parametric study, to form different platooning configurations with up to 20 trucks at headways varying from 10 to 30 ft.

The results were then used to provide guidelines for the optimum parameters for future application. SAP 2000 was used for the analysis, and the model was verified by using the results obtained from Sayed et al. (2020). A coded script was written with MATLAB to generate the input data files for SAP 2000 and analyze the numerous output results.

The specific conclusions that can be drawn from this study are as follows:

- An increase in span length allowed more trucks to be fully accommodated on the bridge simultaneously, which increased the bending moment.
- As the headway spacing decreased, the bending moment increased.
- Allowing two trucks to be fully accommodated on a simple span bridge simultaneously produced an increase in the maximum moment of up to 77 percent for 200-ft. spans, at a 10-ft. headway spacing, and this percentage decreased to 56 percent when the headway spacing increased to 30 ft.

- Allowing more than two trucks to be fully accommodated on a simple span bridge significantly increased the bending moment by as much as three times the single truck moment.
- Shear force results for simple span bridges showed the same trend as that of bending moments.
- For continuous spans, critical positive moments for long-span bridges (longer than 100 ft.) occurred when the maximum number of trucks was located on a single span. Therefore, continuous bridges with short and medium spans (shorter than 100 ft.) were not expected to experience a considerable increase in the positive moment because their spans could not accommodate many trucks at the same time.
- Critical negative moments for short and medium span bridges (up to 100 ft.) occurred when two adjacent spans were loaded simultaneously. Bridges with spans shorter than 75 ft. showed a significant increase in the negative bending moment in comparison to AASHTO's 90 percent design live load condition.
- In comparison to simple span bridges, continuous bridges were expected to experience a reduction in positive moments as a result of the development of negative moments. Also, the internal shear forces were expected to be higher than the maximum shear force in simple span bridges.
- The average reductions in positive moments were around 21 to 24 percent for two-span bridges, 18 to 22 percent for three-span bridges, and approximately 19 to 23 percent for four-span bridges.
- The linear regression models showed acceptable results, with an R^2 of more than 95 percent, while polynomial and exponential models showed great ability to predict the results, with an R^2 of more than 99 percent.
- Charts were developed to determine the percentage of bridge load rating reduction based on the number of trucks and the headway distance.

6.2. Future Work

The following considerations are proposed for future work:

- The effects of the multiple presence factor and the horizontal arrangement of platooning trucks.
- The dynamic response of bridges under truck platoons at different speeds.

- Implementation of the obtained results on existing bridges and the optimum configuration for each bridge.
- More details about trucks that are expected to use ACT technology and work under the platooning system.
- Comparison of the effects of AASHTO and several DOT trucks with the HS20 design truck.
- Reliability analysis and calibration of live load factors for the new load case.
- Collection of more WIM data to reduce unnecessary conservatism for adjacent load effects.

REFERENCES

Agarwal, A. C. (1978). Vehicle Weight Regulations across Canada: A Technical Review with Respect to the Capacity of Highway Systems.

Alam, A., Besselink, B., Turri, V., Mårtensson, J., & Johansson, K. H. (2015). Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency. IEEE Control Systems Magazine, 35(6), 34-56.

Bala Sivakumar, P. (2011). Recalibration of LRFR live load factors in the AASHTO manual for bridge evaluation. Washington, DC: National Cooperative Highway Research Program.

Barker, M. & Puckett, J. A. (2016). Assessment and evaluations of I-80 truck loads and their load effects. Wyoming. Department of Transportation.

Bergenhem, C., Shladover, S., Coelingh, E., Englund, C., & Tsugawa, S. (2012). Overview of platooning systems. Proceedings of the 19th ITS World Congress, Oct 22-26, Vienna, Austria (2012)

Bishop, R. (2017). Connected automated trucking: latest developments and outlook. 5th Annual Florida Automated Vehicles (FAV) Summit, 14-15.

Bonnet, C. & Fritz, H. (2000). Fuel consumption reduction in a platoon: Experimental results with two electronically coupled trucks at close spacing. SAE technical paper.

Browand, F., McArthur, J., & Radovich, C. (2004). Fuel saving achieved in the field test of two tandem trucks.

Chen, F., Balieu, R., & Kringos, N. (2016). Potential influences on long-term service performance of road infrastructure by automated vehicles. Transportation Research Record, 2550(1), 72-79.

Couto Braguim, T., Lou, P., & Nassif, H. (2021). Truck platooning to minimize load-induced fatigue in steel girder bridges. Transportation Research Record, 2675(4), 146-154.

DeVault, A., & Beitelman, T. (2017). Two-Truck Platooning. Load Effects of Two-Truck Platoons on Interstate and Turnpike Bridges in Florida.

Eilers, S., Mårtensson, J., Pettersson, H., Pillado, M., Gallegos, D., Tobar, M., Johansson, K. H., Ma, X., Friedrichs, T., & Borojeni, S. S. (2015). COMPANION--Towards Co-operative Platoon Management of Heavy-Duty Vehicles. 2015 IEEE 18th International Conference on Intelligent Transportation Systems.

Gaudet, B., & Eng, P. (2014). Technical Report Review of Cooperative Truck Platooning Systems.

Ghosn, M. (2000). Development of truck weight regulations using bridge reliability model. Journal of Bridge Engineering, 5(4), 293-303.

Gungor, O. E., Al-Qadi, I. L., Gamez, A., & Hernandez, J. A. (2016). In-situ validation of three-dimensional pavement finite element models. In The roles of accelerated pavement testing in pavement sustainability (pp. 145-159). Springer.

GUNGOR, O. E., SHE, R., AL-QADI, I. L. & OUYANG, Y. 2018. Optimization of lateral position of autonomous trucks. University of Michigan. Center for Connected and Automated Transportation.

Gungor, O. E., She, R., Al-Qadi, I. L., & Ouyang, Y. (2020). One for all: Decentralized optimization of lateral position of autonomous trucks in a platoon to improve roadway infrastructure sustainability. Transportation Research Part C: Emerging Technologies, 120, 102783.

Harman, D. (1985). Surveys of commercial vehicles weights 1975 to 1982.

Humphreys, H. L., Batterson, J., Bevly, D., & Schubert, R. (2016). An evaluation of the fuel economy benefits of a driver assistive truck platooning prototype using simulation (0148-7191).

Jacob, B., & de Chalendar, O. A. (2018). Truck platooning: Expected benefits and implementation conditions on highways. Heavy Vehicle Transportant Technology (HVTT) International Symposium

James, R., Noel, J., Furr, L., & Bonilla, F. (1985). Proposed new truck weight formula. Rep No. FHWA/RD-85/088, Federal Highway Administration, Washington, DC.

Kamranian, Z. (2018). Load Evaluation of the Hay River Bridge Under Different Platoons of Connected Trucks Graduate Studies.

Kulicki, J. M., Prucz, Z., Clancy, C. M., Mertz, D. R., & Nowak, A. S. (2007). Updating the calibration report for AASHTO LRFD code. Final Rep. for National Cooperative Highway Research Program (NCHRP), 186, 20-27.

Lammert, M. P., Duran, A., Diez, J., Burton, K., & Nicholson, A. (2014). Effect of platooning on fuel consumption of class 8 vehicles over a range of speeds, following distances, and mass (1946-3928).

Lu, X.-Y., & Shladover, S. E. (2011). Automated truck platoon control.

Michaelian, M., & Browand, F. (2001). Quantifying platoon fuel savings: 1999 field experiments. SAE transactions, 1401-1410.

Moses, F. (2001). Calibration of load factors for LRFR bridge evaluation.

Nowak, A. S. (1999). Calibration of LRFD bridge design code (0077-5614).

Nowak, A. S., & Collins, K. R. (2012). Reliability of structures. CRC press.

Nowak, A. S., Nassif, H., & DeFrain, L. (1993). Effect of truck loads on bridges. Journal of transportation engineering, 119(6), 853-867.

Robinson, T., Chan, E., & Coelingh, E. (2010). Operating platoons on public motorways: An introduction to the sartre platooning programme. 17th world congress on intelligent transport systems

Salama, H. K., Haider, S. W., & Chatti, K. (2007). Evaluation of New Mechanistic–Empirical Pavement Design Guide Rutting Models for Multiple-Axle Loads. Transportation Research Record, 2005(1), 112-123.

Sayed, S. M., Sunna, H. N., & Moore, P. R. (2020). Truck platooning impact on bridge preservation. Journal of performance of constructed facilities, 34(3), 04020029.

Sivakumar, B. (2007). Legal truck loads and AASHTO legal loads for posting (Vol. 575). Transportation Research Board.

Sivakumar, B., Ghosn, M., & Moses, F. (2011). Protocols for collecting and using traffic data in bridge design (Vol. 683). Transportation Research Board.

Smith, A. F., C. M. Horrell, J. J. Grossmann, J. R. Feldman, & A. R. Bruccoleri. (2012). U.S. Patent No. 8,100,461. Washington, DC: U.S. Patent and Trademark Office

Steelman, J. S., Puckett, J. A., Linzell, D. G., & Yang, B. (2021). Truck Platooning Effects on Girder Bridges.

Study, N. R. C. C. f. t. T. W., & Council, C. f. t. T. W. S. N. R. (1990). Truck weight limits: issues and options. Transportation Research Board.

Suzuki, Y. (2011). A new truck-routing approach for reducing fuel consumption and pollutants emission. Transportation Research Part D: Transport and Environment, 16(1), 73-77.

Teter, J., Cazzola, P., Gul, T., Mulholland, E., Le Feuvre, P., Bennett, S., Hugues, P., Lagarde, Z., Kraayvanger, V., & Bryant, T. (2017). The future of trucks: Implications for energy and the environment.

Thulaseedharan, N. P., & Yarnold, M. T. (2020). Prioritization of Texas prestressed concrete bridges for future truck platoon loading. Bridge Structures, 16(4), 155-167.

Tirado, C., Carrasco, C., Mares, J. M., Gharaibeh, N., Nazarian, S., & Bendaña, J. (2010). Process to estimate permit costs for movement of heavy trucks on flexible pavements. Transportation Research Record, 2154(1), 187-196.

Tohme, R., & Yarnold, M. (2020). Steel bridge load rating impacts owing to autonomous truck platoons. Transportation Research Record, 2674(2), 57-67.

Tsugawa, S. (2014). Results and issues of an automated truck platoon within the energy ITS project. 2014 IEEE Intelligent Vehicles Symposium Proceedings, Tsugawa, S., Jeschke, S., & Shladover, S. E. (2016). A review of truck platooning projects for energy savings. IEEE Transactions on Intelligent Vehicles, 1(1), 68-77.

Tsugawa, S., Kato, S., & Aoki, K. (2011). An automated truck platoon for energy saving. 2011 IEEE/RSJ international conference on intelligent robots and systems,

TxDOT/FHWA. (2017). Commercial truck platooning demon-station in Texas: Level 2 automation [Technical Report](FHWA/TX-17/0-6836-1). T. T. F. College Station.

U.S. Department of Transportation

Wassef. (2017). Parametric study & cost effects for the USDOT truck size & weight study vehicles 20-07/Task 390. Washington, DC: Transportation Research Board).

Yarnold, M. T., & Weidner, J. S. (2019). Truck platoon impacts on steel girder bridges. Journal of Bridge Engineering, 24(7), 06019003.

Zabat, M., Stabile, N., Farascaroli, S., & Browand, F. (1995). The aerodynamic performance of platoons: A final report.

APPENDIX A. SAMPLE OF THE INPUT DATA FILES

Program Control

Program Name	Version	Prog Level	LicenseOS	LicenseSC	LicenseHT	CurrUnits	SteelCode	ConcCode
Text	Text	Text	Yes/No	Yes/No	Yes/No	Text	Text	Text
SAP2000	21.2.0	Ultimate	Yes	Yes	No	Kip, ft, F	AISC 360-10	ACI 318-14

Vehicles Definition Table 1

TABLE: Vehicles 2 - General Vehicles 1 - General		
VehName	NumInter	StayInLane
Text	Unitless	Yes/No
HS20_1	3	No
HS20_2_10	6	No
HS20_2_11	6	No
HS20_2_12	6	No
HS20_2_13	6	No
HS20_2_14	6	No
HS20_2_15	6	No
HS20_2_16	6	No
HS20_2_17	6	No
HS20_2_18	6	No
HS20_2_19	6	No
HS20_2_20	6	No
HS20_2_21	6	No
HS20_2_22	6	No
HS20_2_23	6	No
HS20_2_24	6	No
HS20_2_25	6	No
HS20_2_26	6	No
HS20_2_27	6	No
HS20_2_28	6	No
HS20_2_29	6	No
HS20_2_30	6	No
HS20_3_10	9	No
HS20_3_11	9	No
HS20_3_12	9	No
HS20_3_13	9	No

Vehicles Definition Table 2

TABLE: Vehicles 3 - General Vehicles 2 - Loads				
VehName	**LoadType**	**InterUnif**	**InterAxle**	**InterMinD**
Text	Text	Kip/ft	Kip	ft
HS20_1	Fixed Length	0	32	0.1
HS20_1	Fixed Length	0	32	14
HS20_1	Fixed Length	0	8	14
HS20_2_10	Fixed Length	0	32	0.1
HS20_2_10	Fixed Length	0	32	14
HS20_2_10	Fixed Length	0	8	14
HS20_2_10	Fixed Length	0	32	10
HS20_2_10	Fixed Length	0	32	14
HS20_2_10	Fixed Length	0	8	14
HS20_3_10	Fixed Length	0	32	0.1
HS20_3_10	Fixed Length	0	32	14
HS20_3_10	Fixed Length	0	8	14
HS20_3_10	Fixed Length	0	32	10
HS20_3_10	Fixed Length	0	32	14
HS20_3_10	Fixed Length	0	8	14
HS20_3_10	Fixed Length	0	32	10
HS20_3_10	Fixed Length	0	32	14
HS20_3_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	0.1
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	10
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	10
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	10
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14

Vehicles Definition Table 3

TABLE: Vehicles 3 - General Vehicles 2 - Loads				
VehName	**LoadType**	**InterUnif**	**InterAxle**	**InterMinD**
Text	Text	Kip/ft	Kip	ft
HS20_1	Fixed Length	0	32	0.1
HS20_1	Fixed Length	0	32	14
HS20_1	Fixed Length	0	8	14
HS20_2_10	Fixed Length	0	32	0.1
HS20_2_10	Fixed Length	0	32	14
HS20_2_10	Fixed Length	0	8	14
HS20_2_10	Fixed Length	0	32	10
HS20_2_10	Fixed Length	0	32	14
HS20_2_10	Fixed Length	0	8	14
HS20_3_10	Fixed Length	0	32	0.1
HS20_3_10	Fixed Length	0	32	14
HS20_3_10	Fixed Length	0	8	14
HS20_3_10	Fixed Length	0	32	10
HS20_3_10	Fixed Length	0	32	14
HS20_3_10	Fixed Length	0	8	14
HS20_3_10	Fixed Length	0	32	10
HS20_3_10	Fixed Length	0	32	14
HS20_3_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	0.1
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	10
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	10
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14
HS20_4_10	Fixed Length	0	32	10
HS20_4_10	Fixed Length	0	32	14
HS20_4_10	Fixed Length	0	8	14

APPENDIX B. SIMPLE SPAN BRIDGE RESULTS

Maximum Bending Moment

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_1	1	0	160	627.68	1075.2	1523.84	1973.12	2422.56	2872.23	3321.92
HS20_2_10	2	10	162	659.68	1376.64	2265.6	3158.78	4054.4	4951.13	5848.8
HS20_2_11	2	11	160	641.28	1345.28	2233.2	3125.57	4020.8	4917.12	5814.6
HS20_2_12	2	12	160	636.48	1314.56	2200.8	3092.74	3987.2	4883.38	5780.4
HS20_2_13	2	13	160	632	1283.84	2168.64	3059.9	3953.76	4849.65	5746.32
HS20_2_14	2	14	160	627.68	1263.36	2136.96	3027.07	3920.64	4815.91	5712.48
HS20_2_15	2	15	160	627.68	1244.16	2105.28	2994.43	3887.52	4782.31	5678.64
HS20_2_16	2	16	160	627.68	1224.96	2073.6	2962.18	3854.4	4748.98	5644.8
HS20_2_17	2	17	160	627.68	1205.87	2042.16	2929.92	3821.44	4715.66	5611.08
HS20_2_18	2	18	160	627.68	1187.2	2011.2	2897.66	3788.8	4682.33	5577.6
HS20_2_19	2	19	160	627.68	1168.53	1980.24	2865.6	3756.16	4649.14	5544.12
HS20_2_20	2	20	160	627.68	1149.87	1949.28	2833.92	3723.52	4616.23	5510.64
HS20_2_21	2	21	160	627.68	1131.2	1918.56	2802.24	3691.04	4583.31	5477.28
HS20_2_22	2	22	160	627.68	1115.09	1888.32	2770.56	3658.88	4550.4	5444.16
HS20_2_23	2	23	160	627.68	1100.8	1858.08	2739.07	3626.72	4517.62	5411.04
HS20_2_24	2	24	160	627.68	1086.72	1827.84	2707.97	3594.56	4485.12	5377.92
HS20_2_25	2	25	160	627.68	1081.28	1797.84	2676.86	3562.56	4452.62	5344.92
HS20_2_26	2	26	160	627.68	1077.76	1768.32	2645.76	3530.88	4420.11	5312.16
HS20_2_27	2	27	160	627.68	1075.2	1738.8	2614.85	3499.2	4387.75	5279.4
HS20_2_28	2	28	160	627.68	1075.2	1709.28	2584.32	3467.52	4355.66	5246.64
HS20_2_29	2	29	160	627.68	1075.2	1680	2553.79	3436	4323.57	5214

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_2_30	2	30	160	627.68	1075.2	1661.12	2523.26	3404.8	4291.47	5181.6
HS20_3_10	3	10	162	659.68	1380.69	2424.64	3743.36	5091.68	6440.69	7789.76
HS20_3_11	3	11	160	641.28	1348.8	2372.88	3671.36	5019.68	6368.69	7717.76
HS20_3_12	3	12	160	636.48	1316.91	2321.12	3599.36	4947.68	6296.69	7645.76
HS20_3_13	3	13	160	632	1285.01	2269.36	3527.36	4875.68	6224.69	7573.76
HS20_3_14	3	14	160	627.68	1263.36	2217.6	3455.36	4803.68	6152.69	7501.76
HS20_3_15	3	15	160	627.68	1244.16	2166	3383.36	4731.68	6080.69	7429.76
HS20_3_16	3	16	160	627.68	1224.96	2114.4	3311.36	4659.68	6008.69	7357.76
HS20_3_17	3	17	160	627.68	1205.87	2062.8	3239.36	4587.68	5936.69	7285.76
HS20_3_18	3	18	160	627.68	1187.2	2011.2	3169.28	4515.68	5864.69	7213.76
HS20_3_19	3	19	160	627.68	1168.53	1980.24	3101.5	4443.68	5792.69	7141.76
HS20_3_20	3	20	160	627.68	1149.87	1949.28	3033.73	4371.68	5720.69	7069.76
HS20_3_21	3	21	160	627.68	1131.2	1918.56	2965.95	4299.68	5648.69	6997.76
HS20_3_22	3	22	160	627.68	1115.09	1888.32	2905.6	4227.68	5576.69	6925.76
HS20_3_23	3	23	160	627.68	1100.8	1858.08	2853.18	4155.68	5504.69	6853.76
HS20_3_24	3	24	160	627.68	1086.72	1827.84	2801.92	4083.68	5432.69	6781.76
HS20_3_25	3	25	160	627.68	1081.28	1797.84	2750.72	4011.68	5360.69	6709.76
HS20_3_26	3	26	160	627.68	1077.76	1768.32	2699.52	3939.68	5288.69	6637.76
HS20_3_27	3	27	160	627.68	1075.2	1738.8	2648.32	3867.68	5216.69	6565.76
HS20_3_28	3	28	160	627.68	1075.2	1709.28	2597.12	3795.68	5144.69	6493.76
HS20_3_29	3	29	160	627.68	1075.2	1680	2553.79	3723.68	5072.69	6421.76
HS20_3_30	3	30	160	627.68	1075.2	1661.12	2523.26	3652.05	5000.69	6349.76
HS20_4_10	4	10	162	659.68	1380.69	2435.84	3764.1	5372.8	7166.26	8961.6
HS20_4_11	4	11	160	641.28	1348.8	2376.96	3684.8	5233.6	7026.24	8821.2
HS20_4_12	4	12	160	636.48	1316.91	2321.12	3608.32	5121.71	6886.77	8680.8

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_4_13	4	13	160	632	1285.01	2269.36	3531.84	5010.24	6747.29	8540.64
HS20_4_14	4	14	160	627.68	1263.36	2217.6	3455.36	4898.77	6607.82	8400.96
HS20_4_15	4	15	160	627.68	1244.16	2166	3383.36	4787.31	6468.62	8261.28
HS20_4_16	4	16	160	627.68	1224.96	2114.4	3311.36	4680.32	6329.97	8121.6
HS20_4_17	4	17	160	627.68	1205.87	2062.8	3239.36	4595.2	6191.31	7982.16
HS20_4_18	4	18	160	627.68	1187.2	2011.2	3169.28	4515.68	6053.21	7843.2
HS20_4_19	4	19	160	627.68	1168.53	1980.24	3101.5	4443.68	5942.17	7704.24
HS20_4_20	4	20	160	627.68	1149.87	1949.28	3033.73	4371.68	5831.31	7565.28
HS20_4_21	4	21	160	627.68	1131.2	1918.56	2965.95	4299.68	5720.46	7426.56
HS20_4_22	4	22	160	627.68	1115.09	1888.32	2905.6	4227.68	5611.52	7288.32
HS20_4_23	4	23	160	627.68	1100.8	1858.08	2853.18	4155.68	5514.56	7150.08
HS20_4_24	4	24	160	627.68	1086.72	1827.84	2801.92	4083.68	5434.88	7011.84
HS20_4_25	4	25	160	627.68	1081.28	1797.84	2750.72	4011.68	5360.69	6875.76
HS20_4_26	4	26	160	627.68	1077.76	1768.32	2699.52	3939.68	5288.69	6764.96
HS20_4_27	4	27	160	627.68	1075.2	1738.8	2648.32	3867.68	5216.69	6654.16
HS20_4_28	4	28	160	627.68	1075.2	1709.28	2597.12	3795.68	5144.69	6543.36
HS20_4_29	4	29	160	627.68	1075.2	1680	2553.79	3723.68	5072.69	6440
HS20_4_30	4	30	160	627.68	1075.2	1661.12	2523.26	3652.05	5000.69	6354.56
HS20_5_10	5	10	162	659.68	1380.69	2435.84	3764.1	5377.07	7312.91	9521.6
HS20_5_11	5	11	160	641.28	1348.8	2376.96	3684.8	5236.8	7137.05	9305.6
HS20_5_12	5	12	160	636.48	1316.91	2321.12	3608.32	5122.13	6961.19	9089.6
HS20_5_13	5	13	160	632	1285.01	2269.36	3531.84	5010.45	6785.33	8873.6
HS20_5_14	5	14	160	627.68	1263.36	2217.6	3455.36	4898.77	6609.65	8661.12
HS20_5_15	5	15	160	627.68	1244.16	2166	3383.36	4787.31	6468.62	8453.44
HS20_5_16	5	16	160	627.68	1224.96	2114.4	3311.36	4680.32	6329.97	8258.56

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_5_17	5	17	160	627.68	1205.87	2062.8	3239.36	4595.2	6191.31	8082.96
HS20_5_18	5	18	160	627.68	1187.2	2011.2	3169.28	4515.68	6053.21	7907.52
HS20_5_19	5	19	160	627.68	1168.53	1980.24	3101.5	4443.68	5942.17	7732.32
HS20_5_20	5	20	160	627.68	1149.87	1949.28	3033.73	4371.68	5831.31	7565.28
HS20_5_21	5	21	160	627.68	1131.2	1918.56	2965.95	4299.68	5720.46	7426.56
HS20_5_22	5	22	160	627.68	1115.09	1888.32	2905.6	4227.68	5611.52	7288.32
HS20_5_23	5	23	160	627.68	1100.8	1858.08	2853.18	4155.68	5514.56	7150.08
HS20_5_24	5	24	160	627.68	1086.72	1827.84	2801.92	4083.68	5434.88	7011.84
HS20_5_25	5	25	160	627.68	1081.28	1797.84	2750.72	4011.68	5360.69	6875.76
HS20_5_26	5	26	160	627.68	1077.76	1768.32	2699.52	3939.68	5288.69	6764.96
HS20_5_27	5	27	160	627.68	1075.2	1738.8	2648.32	3867.68	5216.69	6654.16
HS20_5_28	5	28	160	627.68	1075.2	1709.28	2597.12	3795.68	5144.69	6543.36
HS20_5_29	5	29	160	627.68	1075.2	1680	2553.79	3723.68	5072.69	6440
HS20_5_30	5	30	160	627.68	1075.2	1661.12	2523.26	3652.05	5000.69	6354.56

Maximum Shear Force

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_1	1	0	41.6	58.56	63.04	65.28	66.624	67.52	68.16	68.64
HS20_2_10	2	10	41.6	66.88	89.6	103.2	111.36	116.8	120.686	123.6
HS20_2_11	2	11	41.6	66.08	88.64	102.48	110.784	116.32	120.274	123.24
HS20_2_12	2	12	41.6	65.28	87.68	101.76	110.208	115.84	119.863	122.88
HS20_2_13	2	13	41.6	64.48	86.72	101.04	109.632	115.36	119.451	122.52
HS20_2_14	2	14	41.6	63.68	85.76	100.32	109.056	114.88	119.04	122.16
HS20_2_15	2	15	41.6	63.04	84.8	99.6	108.48	114.4	118.629	121.8
HS20_2_16	2	16	41.6	62.4	83.84	98.88	107.904	113.92	118.217	121.44
HS20_2_17	2	17	41.6	61.76	82.88	98.16	107.328	113.44	117.806	121.08
HS20_2_18	2	18	41.6	61.12	81.92	97.44	106.752	112.96	117.394	120.72
HS20_2_19	2	19	41.6	60.48	80.96	96.72	106.176	112.48	116.983	120.36
HS20_2_20	2	20	41.6	59.84	80.107	96	105.6	112	116.571	120
HS20_2_21	2	21	41.6	59.2	79.253	95.28	105.024	111.52	116.16	119.64
HS20_2_22	2	22	41.6	58.56	78.4	94.56	104.448	111.04	115.749	119.28
HS20_2_23	2	23	41.6	58.56	77.547	93.84	103.872	110.56	115.337	118.92
HS20_2_24	2	24	41.6	58.56	76.693	93.12	103.296	110.08	114.926	118.56
HS20_2_25	2	25	41.6	58.56	75.84	92.4	102.72	109.6	114.514	118.2
HS20_2_26	2	26	41.6	58.56	74.987	91.68	102.144	109.12	114.103	117.84
HS20_2_27	2	27	41.6	58.56	74.133	90.96	101.568	108.64	113.691	117.48
HS20_2_28	2	28	41.6	58.56	73.28	90.24	100.992	108.16	113.28	117.12
HS20_2_29	2	29	41.6	58.56	72.427	89.52	100.416	107.68	112.869	116.76
HS20_2_30	2	30	41.6	58.56	71.573	88.8	99.84	107.2	112.457	116.4
HS20_3_10	3	10	41.6	66.88	90.453	114.72	134.208	147.84	157.577	164.88

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_3_11	3	11	41.6	66.08	89.28	112.56	132.48	146.4	156.343	163.8
HS20_3_12	3	12	41.6	65.28	88.107	110.4	130.752	144.96	155.109	162.72
HS20_3_13	3	13	41.6	64.48	86.933	108.24	129.024	143.52	153.874	161.64
HS20_3_14	3	14	41.6	63.68	85.76	106.08	127.296	142.08	152.64	160.56
HS20_3_15	3	15	41.6	63.04	84.8	104.08	125.568	140.64	151.406	159.48
HS20_3_16	3	16	41.6	62.4	83.84	102.72	123.84	139.2	150.171	158.4
HS20_3_17	3	17	41.6	61.76	82.88	101.36	122.112	137.76	148.937	157.32
HS20_3_18	3	18	41.6	61.12	81.92	100	120.384	136.32	147.703	156.24
HS20_3_19	3	19	41.6	60.48	80.96	98.64	118.656	134.88	146.469	155.16
HS20_3_20	3	20	41.6	59.84	80.107	97.28	116.928	133.44	145.234	154.08
HS20_3_21	3	21	41.6	59.2	79.253	95.92	115.264	132	144	153
HS20_3_22	3	22	41.6	58.56	78.4	94.56	113.664	130.56	142.766	151.92
HS20_3_23	3	23	41.6	58.56	77.547	93.84	112.064	129.12	141.531	150.84
HS20_3_24	3	24	41.6	58.56	76.693	93.12	110.464	127.68	140.297	149.76
HS20_3_25	3	25	41.6	58.56	75.84	92.4	108.864	126.24	139.063	148.68
HS20_3_26	3	26	41.6	58.56	74.987	91.68	107.264	124.8	137.829	147.6
HS20_3_27	3	27	41.6	58.56	74.133	90.96	105.664	123.36	136.594	146.52
HS20_3_28	3	28	41.6	58.56	73.28	90.24	104.32	121.92	135.36	145.44
HS20_3_29	3	29	41.6	58.56	72.427	89.52	103.232	120.48	134.126	144.36
HS20_3_30	3	30	41.6	58.56	71.573	88.8	102.144	119.04	132.891	143.28
HS20_4_10	4	10	41.6	66.88	90.453	114.72	137.792	160.853	178.834	192.48
HS20_4_11	4	11	41.6	66.08	89.28	112.56	135.104	157.973	176.366	190.32
HS20_4_12	4	12	41.6	65.28	88.107	110.4	132.416	155.093	173.897	188.16
HS20_4_13	4	13	41.6	64.48	86.933	108.24	129.728	152.213	171.429	186
HS20_4_14	4	14	41.6	63.68	85.76	106.08	127.296	149.333	168.96	183.84

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_4_15	4	15	41.6	63.04	84.8	104.08	125.568	146.613	166.491	181.68
HS20_4_16	4	16	41.6	62.4	83.84	102.72	123.84	143.893	164.023	179.52
HS20_4_17	4	17	41.6	61.76	82.88	101.36	122.112	141.173	161.554	177.36
HS20_4_18	4	18	41.6	61.12	81.92	100	120.384	138.88	159.086	175.2
HS20_4_19	4	19	41.6	60.48	80.96	98.64	118.656	136.8	156.617	173.04
HS20_4_20	4	20	41.6	59.84	80.107	97.28	116.928	134.72	154.149	170.88
HS20_4_21	4	21	41.6	59.2	79.253	95.92	115.264	132.64	151.68	168.72
HS20_4_22	4	22	41.6	58.56	78.4	94.56	113.664	130.56	149.349	166.56
HS20_4_23	4	23	41.6	58.56	77.547	93.84	112.064	129.12	147.017	164.4
HS20_4_24	4	24	41.6	58.56	76.693	93.12	110.464	127.68	144.686	162.24
HS20_4_25	4	25	41.6	58.56	75.84	92.4	108.864	126.24	142.354	160.08
HS20_4_26	4	26	41.6	58.56	74.987	91.68	107.264	124.8	140.206	157.92
HS20_4_27	4	27	41.6	58.56	74.133	90.96	105.664	123.36	138.423	155.76
HS20_4_28	4	28	41.6	58.56	73.28	90.24	104.32	121.92	136.64	153.6
HS20_4_29	4	29	41.6	58.56	72.427	89.52	103.232	120.48	134.857	151.44
HS20_4_30	4	30	41.6	58.56	71.573	88.8	102.144	119.04	133.074	149.36
HS20_5_10	5	10	41.6	66.88	90.453	114.72	137.792	161.493	185.417	206.4
HS20_5_11	5	11	41.6	66.08	89.28	112.56	135.104	158.4	181.303	202.8
HS20_5_12	5	12	41.6	65.28	88.107	110.4	132.416	155.307	177.189	199.2
HS20_5_13	5	13	41.6	64.48	86.933	108.24	129.728	152.213	173.623	195.6
HS20_5_14	5	14	41.6	63.68	85.76	106.08	127.296	149.333	170.24	192
HS20_5_15	5	15	41.6	63.04	84.8	104.08	125.568	146.613	167.04	188.4
HS20_5_16	5	16	41.6	62.4	83.84	102.72	123.84	143.893	164.023	184.96
HS20_5_17	5	17	41.6	61.76	82.88	101.36	122.112	141.173	161.554	181.52
HS20_5_18	5	18	41.6	61.12	81.92	100	120.384	138.88	159.086	178.08

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_5_19	5	19	41.6	60.48	80.96	98.64	118.656	136.8	156.617	174.96
HS20_5_20	5	20	41.6	59.84	80.107	97.28	116.928	134.72	154.149	172.16
HS20_5_21	5	21	41.6	59.2	79.253	95.92	115.264	132.64	151.68	169.36
HS20_5_22	5	22	41.6	58.56	78.4	94.56	113.664	130.56	149.349	166.56
HS20_5_23	5	23	41.6	58.56	77.547	93.84	112.064	129.12	147.017	164.4
HS20_5_24	5	24	41.6	58.56	76.693	93.12	110.464	127.68	144.686	162.24
HS20_5_25	5	25	41.6	58.56	75.84	92.4	108.864	126.24	142.354	160.08
HS20_5_26	5	26	41.6	58.56	74.987	91.68	107.264	124.8	140.206	157.92
HS20_5_27	5	27	41.6	58.56	74.133	90.96	105.664	123.36	138.423	155.76
HS20_5_28	5	28	41.6	58.56	73.28	90.24	104.32	121.92	136.64	153.6
HS20_5_29	5	29	41.6	58.56	72.427	89.52	103.232	120.48	134.857	151.44
HS20_5_30	5	30	41.6	58.56	71.573	88.8	102.144	119.04	133.074	149.36

APPENDIX C. TWO-SPAN BRIDGE RESULTS

Maximum Positive Bending Moment

			Span (ft)							
CODE	No. Trucks	Spacing (ft)	20	50	75	100	125	150	175	200
HS20_1	1	0	132.748	500.76	865.109	1233.84	1604.59	1976.26	2348.36	2720.81
HS20_2_10	2	10	135.934	526.05	1088.05	1784.99	2503.15	3231.2	3964.79	4702.07
HS20_2_11	2	11	133.979	516.502	1065.55	1759.19	2475.51	3202.31	3935.32	4671.87
HS20_2_12	2	12	132.748	512.246	1043.54	1733.69	2448.29	3173.69	3905.86	4641.67
HS20_2_13	2	13	132.748	508.197	1022.11	1708.73	2421.13	3145.58	3876.65	4611.6
HS20_2_14	2	14	132.748	504.148	1001.28	1684.18	2394.39	3117.47	3847.51	4581.94
HS20_2_15	2	15	132.748	502.405	980.928	1659.85	2367.79	3089.59	3818.66	4552.4
HS20_2_16	2	16	132.748	500.76	964.229	1635.93	2341.62	3061.98	3789.93	4522.93
HS20_2_17	2	17	132.748	500.76	950.947	1612.32	2315.87	3034.43	3761.64	4493.77
HS20_2_18	2	18	132.748	500.76	937.952	1589.04	2290.12	3007.14	3733.35	4464.63
HS20_2_19	2	19	132.748	500.76	926.3	1566.08	2264.87	2980.34	3705.31	4435.67
HS20_2_20	2	20	132.748	500.76	917.102	1543.47	2239.61	2953.69	3677.28	4406.99
HS20_2_21	2	21	132.748	500.76	908.133	1521.19	2214.85	2927.15	3649.62	4378.51
HS20_2_22	2	22	132.748	500.76	899.396	1499.39	2190.09	2900.92	3622.06	4350.11
HS20_2_23	2	23	132.748	500.76	890.896	1478.02	2165.93	2874.84	3594.78	4321.86
HS20_2_24	2	24	132.748	500.76	882.636	1456.96	2142.04	2848.88	3567.77	4293.8
HS20_2_25	2	25	132.748	500.76	875.223	1436.27	2118.38	2823.24	3540.77	4265.81
HS20_2_26	2	26	132.748	500.76	873.283	1415.91	2094.98	2797.94	3514.09	4238.08
HS20_2_27	2	27	132.748	500.76	871.403	1395.92	2071.83	2772.8	3487.41	4210.56
HS20_2_28	2	28	132.748	500.76	869.584	1376.26	2048.94	2747.91	3461.01	4183.05
HS20_2_29	2	29	132.748	500.76	867.826	1358.66	2026.31	2723.31	3434.85	4155.82
HS20_2_30	2	30	132.748	500.76	866.13	1342.63	2003.93	2698.77	3409.05	4128.89

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_3_10	3	10	135.934	526.05	1090.45	1879.74	2891.9	3957.33	5042.15	6136.94
HS20_3_11	3	11	133.979	516.502	1067.51	1828.38	2833.75	3896.51	4979.71	6073.22
HS20_3_12	3	12	132.748	512.246	1045	1781.87	2776.47	3836.15	4917.53	6009.54
HS20_3_13	3	13	132.748	508.197	1022.92	1739.83	2720.05	3776.25	4855.42	5946.11
HS20_3_14	3	14	132.748	504.148	1001.28	1700.16	2663.64	3716.47	4793.63	5882.97
HS20_3_15	3	15	132.748	502.405	980.928	1664.13	2608.88	3657.31	4732.32	5820.13
HS20_3_16	3	16	132.748	500.76	964.229	1637.71	2556.22	3598.16	4671.22	5757.35
HS20_3_17	3	17	132.748	500.76	950.947	1612.32	2504.19	3539.56	4610.49	5694.87
HS20_3_18	3	18	132.748	500.76	937.952	1589.04	2452.16	3481.16	4550.12	5632.97
HS20_3_19	3	19	132.748	500.76	926.3	1566.08	2400.77	3423.54	4489.75	5571.08
HS20_3_20	3	20	132.748	500.76	917.102	1543.47	2350.12	3366.01	4429.64	5509.54
HS20_3_21	3	21	132.748	500.76	908.133	1521.19	2299.74	3308.95	4370.13	5448.01
HS20_3_22	3	22	132.748	500.76	899.396	1499.39	2250.03	3252.18	4310.69	5386.79
HS20_3_23	3	23	132.748	500.76	890.896	1478.02	2202.38	3195.89	4251.51	5325.77
HS20_3_24	3	24	132.748	500.76	882.636	1456.96	2160.98	3139.6	4192.88	5265.17
HS20_3_25	3	25	132.748	500.76	875.223	1436.27	2124.09	3084.62	4134.46	5204.73
HS20_3_26	3	26	132.748	500.76	873.283	1415.91	2097.79	3032.05	4076.46	5144.59
HS20_3_27	3	27	132.748	500.76	871.403	1395.92	2071.83	2980.01	4018.75	5084.46
HS20_3_28	3	28	132.748	500.76	869.584	1376.26	2048.94	2928.54	3961.12	5024.72
HS20_3_29	3	29	132.748	500.76	867.826	1358.66	2026.31	2877.34	3903.76	4965.41
HS20_3_30	3	30	132.748	500.76	866.13	1342.63	2003.93	2826.69	3846.81	4906.34
HS20_4_10	4	10	135.934	526.05	1090.45	1879.74	2913.21	4161.88	5554.12	6978.26
HS20_4_11	4	11	133.979	516.502	1067.51	1830.33	2848.5	4060.95	5443.56	6863.38
HS20_4_12	4	12	132.748	512.246	1045	1785.7	2784.61	3961.42	5333.76	6749.21
HS20_4_13	4	13	132.748	508.197	1022.92	1741.61	2721.37	3863.56	5225.24	6635.92

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_4_14	4	14	132.748	504.148	1001.28	1700.16	2663.64	3766.92	5118.21	6523.4
HS20_4_15	4	15	132.748	502.405	980.928	1664.13	2608.88	3687.26	5012.13	6411.99
HS20_4_16	4	16	132.748	500.76	964.229	1637.71	2556.22	3617.55	4907.08	6301.56
HS20_4_17	4	17	132.748	500.76	950.947	1612.32	2504.19	3554.74	4803.58	6191.93
HS20_4_18	4	18	132.748	500.76	937.952	1589.04	2452.16	3492.34	4705.68	6083.38
HS20_4_19	4	19	132.748	500.76	926.3	1566.08	2400.77	3430.52	4609.79	5975.74
HS20_4_20	4	20	132.748	500.76	917.102	1543.47	2350.12	3368.84	4515.12	5869.38
HS20_4_21	4	21	132.748	500.76	908.133	1521.19	2299.74	3308.95	4421.5	5764.03
HS20_4_22	4	22	132.748	500.76	899.396	1499.39	2250.03	3252.18	4339.36	5659.4
HS20_4_23	4	23	132.748	500.76	890.896	1478.02	2202.38	3195.89	4270.61	5555.45
HS20_4_24	4	24	132.748	500.76	882.636	1456.96	2160.98	3139.6	4207.93	5456.15
HS20_4_25	4	25	132.748	500.76	875.223	1436.27	2124.09	3084.62	4145.4	5360.18
HS20_4_26	4	26	132.748	500.76	873.283	1415.91	2097.79	3032.05	4083.28	5265.05
HS20_4_27	4	27	132.748	500.76	871.403	1395.92	2071.83	2980.01	4021.58	5170.86
HS20_4_28	4	28	132.748	500.76	869.584	1376.26	2048.94	2928.54	3961.12	5077.23
HS20_4_29	4	29	132.748	500.76	867.826	1358.66	2026.31	2877.34	3903.76	4992.84
HS20_4_30	4	30	132.748	500.76	866.13	1342.63	2003.93	2826.69	3846.81	4924.49
HS20_5_10	5	10	135.934	526.05	1090.45	1879.74	2913.21	4162.03	5607.51	7320.56
HS20_5_11	5	11	133.979	516.502	1067.51	1830.33	2848.5	4060.95	5464.44	7148.97
HS20_5_12	5	12	132.748	512.246	1045	1785.7	2784.61	3961.42	5348.37	6978.51
HS20_5_13	5	13	132.748	508.197	1022.92	1741.61	2721.37	3863.56	5233.94	6810.27
HS20_5_14	5	14	132.748	504.148	1001.28	1700.16	2663.64	3766.92	5121.42	6646.38
HS20_5_15	5	15	132.748	502.405	980.928	1664.13	2608.88	3687.26	5012.13	6486.14
HS20_5_16	5	16	132.748	500.76	964.229	1637.71	2556.22	3617.55	4907.08	6327.79
HS20_5_17	5	17	132.748	500.76	950.947	1612.32	2504.19	3554.74	4803.58	6208.58

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_5_18	5	18	132.748	500.76	937.952	1589.04	2452.16	3492.34	4705.68	6094.66
HS20_5_19	5	19	132.748	500.76	926.3	1566.08	2400.77	3430.52	4609.79	5981.23
HS20_5_20	5	20	132.748	500.76	917.102	1543.47	2350.12	3368.84	4515.12	5869.72
HS20_5_21	5	21	132.748	500.76	908.133	1521.19	2299.74	3308.95	4421.5	5764.03
HS20_5_22	5	22	132.748	500.76	899.396	1499.39	2250.03	3252.18	4339.36	5659.4
HS20_5_23	5	23	132.748	500.76	890.896	1478.02	2202.38	3195.89	4270.61	5555.45
HS20_5_24	5	24	132.748	500.76	882.636	1456.96	2160.98	3139.6	4207.93	5456.15
HS20_5_25	5	25	132.748	500.76	875.223	1436.27	2124.09	3084.62	4145.4	5360.18
HS20_5_26	5	26	132.748	500.76	873.283	1415.91	2097.79	3032.05	4083.28	5265.05
HS20_5_27	5	27	132.748	500.76	871.403	1395.92	2071.83	2980.01	4021.58	5170.86
HS20_5_28	5	28	132.748	500.76	869.584	1376.26	2048.94	2928.54	3961.12	5077.23
HS20_5_29	5	29	132.748	500.76	867.826	1358.66	2026.31	2877.34	3903.76	4992.84
HS20_5_30	5	30	132.748	500.76	866.13	1342.63	2003.93	2826.69	3846.81	4924.49

Maximum Negative Bending Moment

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_1	1	0	-119.27	-296.06	-484.82	-666.35	-844.70	-1021.34	-1197.08	-1372.14
HS20_2_10	2	10	-125.35	-578.86	-810.06	-1116.98	-1514.01	-1895.37	-2267.23	-2632.93
HS20_2_11	2	11	-123.55	-579.43	-819.02	-1105.76	-1504.84	-1887.62	-2260.46	-2627.02
HS20_2_12	2	12	-121.66	-579.26	-827.07	-1094.39	-1495.50	-1879.71	-2253.65	-2620.96
HS20_2_13	2	13	-119.71	-580.61	-835.03	-1082.80	-1485.82	-1871.50	-2246.59	-2614.79
HS20_2_14	2	14	-119.27	-582.87	-845.37	-1070.86	-1476.05	-1863.24	-2239.40	-2608.38
HS20_2_15	2	15	-119.27	-584.70	-856.02	-1058.69	-1466.04	-1854.72	-2232.04	-2601.96
HS20_2_16	2	16	-119.27	-585.72	-865.99	-1046.40	-1455.71	-1845.97	-2224.44	-2595.30
HS20_2_17	2	17	-119.27	-586.34	-875.62	-1041.03	-1445.31	-1837.17	-2216.82	-2588.52
HS20_2_18	2	18	-119.27	-586.16	-884.58	-1055.65	-1434.66	-1828.06	-2208.93	-2581.61
HS20_2_19	2	19	-119.27	-585.60	-893.20	-1069.99	-1423.71	-1818.80	-2200.89	-2574.46
HS20_2_20	2	20	-119.27	-584.27	-901.17	-1083.79	-1412.68	-1809.42	-2192.75	-2567.32
HS20_2_21	2	21	-119.27	-582.57	-908.81	-1097.31	-1401.43	-1799.74	-2184.29	-2559.93
HS20_2_22	2	22	-119.27	-580.14	-915.81	-1110.29	-1389.87	-1789.97	-2175.81	-2552.41
HS20_2_23	2	23	-119.27	-577.35	-922.48	-1122.99	-1378.22	-1780.03	-2167.22	-2544.79
HS20_2_24	2	24	-119.27	-573.85	-928.52	-1135.17	-1366.38	-1769.80	-2158.31	-2536.93
HS20_2_25	2	25	-119.27	-570.01	-934.25	-1147.07	-1354.26	-1759.52	-2149.34	-2529.04
HS20_2_26	2	26	-119.27	-565.49	-939.35	-1158.45	-1341.96	-1749.04	-2140.23	-2520.95
HS20_2_27	2	27	-119.27	-560.64	-944.15	-1169.56	-1329.57	-1738.28	-2130.90	-2512.69
HS20_2_28	2	28	-119.27	-555.14	-948.35	-1180.15	-1330.48	-1727.47	-2121.43	-2504.37
HS20_2_29	2	29	-119.27	-549.33	-952.24	-1190.48	-1345.18	-1716.48	-2111.84	-2495.82
HS20_2_30	2	30	-119.27	-542.90	-955.53	-1200.30	-1359.45	-1705.21	-2102.06	-2487.18
HS20_3_10	3	10	-125.35	-627.39	-1187.95	-1587.31	-1870.07	-2487.17	-3091.35	-3676.06

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_3_11	3	11	-123.55	-614.76	-1179.25	-1594.62	-1887.68	-2457.56	-3065.28	-3653.04
HS20_3_12	3	12	-121.66	-601.85	-1169.16	-1600.82	-1904.19	-2427.31	-3038.73	-3629.45
HS20_3_13	3	13	-119.71	-598.84	-1157.72	-1605.73	-1919.63	-2396.38	-3011.70	-3605.28
HS20_3_14	3	14	-119.27	-594.68	-1145.37	-1609.36	-1933.91	-2364.86	-2983.90	-3580.70
HS20_3_15	3	15	-119.27	-593.77	-1133.63	-1611.74	-1947.04	-2332.74	-2955.62	-3555.52
HS20_3_16	3	16	-119.27	-591.70	-1120.97	-1612.89	-1959.03	-2299.93	-2926.76	-3529.78
HS20_3_17	3	17	-119.27	-589.53	-1107.12	-1612.84	-1969.91	-2266.66	-2897.30	-3503.52
HS20_3_18	3	18	-119.27	-586.22	-1092.13	-1611.59	-1979.69	-2258.61	-2867.32	-3476.83
HS20_3_19	3	19	-119.27	-585.60	-1076.02	-1609.26	-1988.37	-2276.68	-2836.77	-3449.52
HS20_3_20	3	20	-119.27	-584.27	-1058.86	-1605.98	-1995.98	-2293.91	-2805.65	-3421.66
HS20_3_21	3	21	-119.27	-582.57	-1041.12	-1601.58	-2002.56	-2310.17	-2774.02	-3393.41
HS20_3_22	3	22	-119.27	-580.14	-1022.36	-1596.09	-2008.26	-2325.46	-2741.90	-3364.66
HS20_3_23	3	23	-119.27	-577.35	-1003.74	-1589.51	-2012.92	-2339.80	-2709.17	-3335.29
HS20_3_24	3	24	-119.27	-573.85	-996.05	-1581.88	-2016.56	-2353.18	-2675.94	-3305.52
HS20_3_25	3	25	-119.27	-570.01	-989.04	-1573.21	-2019.19	-2365.62	-2644.38	-3275.19
HS20_3_26	3	26	-119.27	-565.49	-982.64	-1563.68	-2020.82	-2377.13	-2663.01	-3244.41
HS20_3_27	3	27	-119.27	-560.64	-976.02	-1553.30	-2021.48	-2387.92	-2680.79	-3213.17
HS20_3_28	3	28	-119.27	-555.14	-968.60	-1541.95	-2021.17	-2397.81	-2697.72	-3181.58
HS20_3_29	3	29	-119.27	-549.33	-969.37	-1529.66	-2020.17	-2406.80	-2713.81	-3149.26
HS20_3_30	3	30	-119.27	-542.90	-969.87	-1516.44	-2019.41	-2414.90	-2729.14	-3116.72
HS20_4_10	4	10	-125.35	-627.39	-1394.47	-2156.45	-2700.83	-3098.09	-3566.39	-4406.02
HS20_4_11	4	11	-123.55	-614.76	-1363.66	-2146.76	-2711.47	-3125.51	-3504.61	-4350.44
HS20_4_12	4	12	-121.66	-601.85	-1330.80	-2134.50	-2720.19	-3150.29	-3477.60	-4293.79
HS20_4_13	4	13	-119.71	-598.84	-1296.40	-2122.05	-2727.14	-3173.23	-3513.48	-4235.90

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_4_14	4	14	-119.27	-594.68	-1259.88	-2108.84	-2734.63	-3196.86	-3549.07	-4176.95
HS20_4_15	4	15	-119.27	-593.77	-1225.74	-2093.61	-2740.03	-3219.12	-3584.91	-4116.77
HS20_4_16	4	16	-119.27	-591.70	-1199.59	-2076.03	-2743.00	-3239.07	-3618.58	-4055.47
HS20_4_17	4	17	-119.27	-589.53	-1174.49	-2056.57	-2743.96	-3257.05	-3650.39	-3993.15
HS20_4_18	4	18	-119.27	-586.22	-1148.55	-2034.91	-2742.61	-3272.79	-3680.08	-4001.19
HS20_4_19	4	19	-119.27	-585.60	-1121.03	-2011.54	-2739.33	-3286.63	-3707.97	-4040.61
HS20_4_20	4	20	-119.27	-584.27	-1098.19	-1986.13	-2733.83	-3298.29	-3733.79	-4078.09
HS20_4_21	4	21	-119.27	-582.57	-1080.87	-1959.12	-2726.51	-3308.13	-3757.85	-4113.90
HS20_4_22	4	22	-119.27	-580.14	-1062.25	-1930.25	-2717.08	-3315.85	-3779.90	-4147.81
HS20_4_23	4	23	-119.27	-577.35	-1043.13	-1899.93	-2705.90	-3321.81	-3800.23	-4180.09
HS20_4_24	4	24	-119.27	-573.85	-1022.92	-1867.89	-2692.71	-3325.73	-3818.60	-4210.51
HS20_4_25	4	25	-119.27	-570.01	-1009.69	-1834.56	-2677.88	-3327.95	-3835.30	-4239.34
HS20_4_26	4	26	-119.27	-565.49	-1000.29	-1800.02	-2661.13	-3328.20	-3850.09	-4266.34
HS20_4_27	4	27	-119.27	-560.64	-990.65	-1766.94	-2642.84	-3326.81	-3863.26	-4291.79
HS20_4_28	4	28	-119.27	-555.14	-980.12	-1732.53	-2622.73	-3323.52	-3874.57	-4315.46
HS20_4_29	4	29	-119.27	-549.33	-969.37	-1697.05	-2601.17	-3318.66	-3884.31	-4337.61
HS20_4_30	4	30	-119.27	-542.90	-969.87	-1660.43	-2577.88	-3311.98	-3892.24	-4358.01
HS20_5_10	5	10	-125.35	-627.39	-1399.57	-2363.20	-3290.58	-3999.05	-4556.84	-5002.44
HS20_5_11	5	11	-123.55	-614.76	-1363.67	-2310.37	-3268.01	-4005.09	-4584.90	-5048.78
HS20_5_12	5	12	-121.66	-601.85	-1330.80	-2255.41	-3241.64	-4007.31	-4609.27	-5091.61
HS20_5_13	5	13	-119.71	-598.84	-1296.40	-2217.58	-3211.79	-4005.79	-4630.01	-5130.98
HS20_5_14	5	14	-119.27	-594.68	-1259.88	-2177.51	-3180.54	-4000.61	-4647.18	-5166.95
HS20_5_15	5	15	-119.27	-593.77	-1225.74	-2134.94	-3146.24	-3991.82	-4660.84	-5199.56
HS20_5_16	5	16	-119.27	-591.70	-1199.59	-2093.88	-3108.75	-3979.79	-4671.09	-5229.09

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_5_17	5	17	-119.27	-589.53	-1174.49	-2069.70	-3068.10	-3964.50	-4678.21	-5255.36
HS20_5_18	5	18	-119.27	-586.22	-1148.55	-2042.95	-3024.38	-3945.91	-4682.02	-5278.42
HS20_5_19	5	19	-119.27	-585.60	-1121.03	-2014.76	-2977.77	-3924.09	-4682.57	-5298.30
HS20_5_20	5	20	-119.27	-584.27	-1098.19	-1986.13	-2928.79	-3899.13	-4679.94	-5315.07
HS20_5_21	5	21	-119.27	-582.57	-1080.87	-1959.12	-2877.24	-3871.12	-4674.14	-5328.78
HS20_5_22	5	22	-119.27	-580.14	-1062.25	-1930.25	-2823.12	-3840.24	-4665.33	-5339.48
HS20_5_23	5	23	-119.27	-577.35	-1043.13	-1899.93	-2778.61	-3806.75	-4653.68	-5347.20
HS20_5_24	5	24	-119.27	-573.85	-1022.92	-1867.89	-2742.99	-3770.49	-4639.23	-5352.25
HS20_5_25	5	25	-119.27	-570.01	-1009.69	-1834.56	-2708.52	-3731.49	-4621.91	-5354.42
HS20_5_26	5	26	-119.27	-565.49	-1000.29	-1800.02	-2679.37	-3689.94	-4601.78	-5353.77
HS20_5_27	5	27	-119.27	-560.64	-990.65	-1766.94	-2656.14	-3645.98	-4578.92	-5350.28
HS20_5_28	5	28	-119.27	-555.14	-980.12	-1732.53	-2631.11	-3599.74	-4553.37	-5344.12
HS20_5_29	5	29	-119.27	-549.33	-969.37	-1697.05	-2604.53	-3551.27	-4525.21	-5335.29
HS20_5_30	5	30	-119.27	-542.90	-969.87	-1660.43	-2577.88	-3500.42	-4494.76	-5323.84

Maximum Shear Force Results

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_1	1	0	44.29	62.03	66.00	67.76	68.74	69.36	69.78	70.09
HS20_2_10	2	10	44.49	72.89	97.99	112.28	120.14	125.03	128.32	130.68
HS20_2_11	2	11	44.46	71.95	96.89	111.53	119.59	124.60	127.97	130.39
HS20_2_12	2	12	44.41	71.00	95.79	110.78	119.03	124.17	127.63	130.10
HS20_2_13	2	13	44.36	70.04	94.68	110.02	118.47	123.73	127.27	129.80
HS20_2_14	2	14	44.29	69.08	93.57	109.25	117.91	123.28	126.91	129.49
HS20_2_15	2	15	44.29	68.11	92.45	108.48	117.34	122.84	126.55	129.19
HS20_2_16	2	16	44.29	67.14	91.32	107.71	116.76	122.40	126.18	128.89
HS20_2_17	2	17	44.29	66.17	90.19	106.93	116.19	121.95	125.82	128.58
HS20_2_18	2	18	44.29	65.92	89.06	106.14	115.61	121.49	125.45	128.28
HS20_2_19	2	19	44.29	65.67	87.94	105.35	115.02	121.03	125.09	127.97
HS20_2_20	2	20	44.29	65.41	86.90	104.55	114.43	120.57	124.71	127.66
HS20_2_21	2	21	44.29	65.14	85.88	103.76	113.84	120.11	124.33	127.34
HS20_2_22	2	22	44.29	64.86	84.86	102.95	113.24	119.65	123.95	127.03
HS20_2_23	2	23	44.29	64.73	83.84	102.14	112.64	119.18	123.57	126.71
HS20_2_24	2	24	44.29	64.60	82.81	101.33	112.04	118.70	123.19	126.39
HS20_2_25	2	25	44.29	64.45	81.77	100.52	111.43	118.23	122.81	126.07
HS20_2_26	2	26	44.29	64.30	80.73	99.69	110.82	117.75	122.43	125.75
HS20_2_27	2	27	44.29	64.15	79.69	98.87	110.21	117.27	122.04	125.43
HS20_2_28	2	28	44.29	63.98	78.65	98.04	109.59	116.79	121.64	125.10
HS20_2_29	2	29	44.29	63.82	77.60	97.21	108.96	116.31	121.24	124.77
HS20_2_30	2	30	44.29	63.65	76.55	96.38	108.34	115.82	120.85	124.44
HS20_3_10	3	10	44.49	77.73	104.33	126.83	148.02	162.29	171.92	178.81

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_3_11	3	11	44.46	76.62	103.26	124.35	146.12	160.80	170.71	177.79
HS20_3_12	3	12	44.41	75.49	102.20	121.86	144.20	159.28	169.48	176.77
HS20_3_13	3	13	44.36	74.33	101.10	119.36	142.27	157.75	168.24	175.73
HS20_3_14	3	14	44.29	73.16	100.00	116.85	140.32	156.22	167.00	174.69
HS20_3_15	3	15	44.29	72.17	98.87	114.84	138.37	154.68	165.73	173.63
HS20_3_16	3	16	44.29	71.17	97.73	114.13	136.41	153.13	164.47	172.58
HS20_3_17	3	17	44.29	70.15	96.57	113.40	134.44	151.56	163.19	171.51
HS20_3_18	3	18	44.29	69.11	95.41	112.66	132.45	149.99	161.91	170.44
HS20_3_19	3	19	44.29	68.06	94.21	111.90	130.46	148.41	160.63	169.36
HS20_3_20	3	20	44.29	67.00	93.15	111.14	128.45	146.82	159.33	168.28
HS20_3_21	3	21	44.29	65.93	92.06	110.37	126.52	145.22	158.02	167.19
HS20_3_22	3	22	44.29	64.86	90.97	109.58	124.67	143.61	156.70	166.08
HS20_3_23	3	23	44.29	64.73	89.86	108.78	122.81	142.00	155.37	164.97
HS20_3_24	3	24	44.29	64.60	88.74	107.98	120.94	140.37	154.04	163.85
HS20_3_25	3	25	44.29	64.45	87.60	107.16	119.06	138.74	152.70	162.73
HS20_3_26	3	26	44.29	64.30	86.46	106.33	117.41	137.10	151.37	161.62
HS20_3_27	3	27	44.29	64.15	85.30	105.49	116.83	135.47	150.02	160.49
HS20_3_28	3	28	44.29	63.98	84.14	104.64	116.24	133.81	148.67	159.35
HS20_3_29	3	29	44.29	63.82	82.96	103.79	115.64	132.15	147.29	158.19
HS20_3_30	3	30	44.29	63.65	81.78	102.93	115.04	130.48	145.91	157.03
HS20_4_10	4	10	44.49	77.73	106.29	133.18	153.41	178.54	197.97	212.22
HS20_4_11	4	11	44.46	76.62	105.00	130.77	151.62	175.32	195.28	209.97
HS20_4_12	4	12	44.41	75.49	103.70	128.33	149.81	172.08	192.58	207.70
HS20_4_13	4	13	44.36	74.33	102.35	125.88	147.98	168.82	189.86	205.42
HS20_4_14	4	14	44.29	73.16	101.00	123.41	146.13	165.55	187.14	203.13

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_4_15	4	15	44.29	72.17	99.61	120.93	144.27	162.26	184.37	200.80
HS20_4_16	4	16	44.29	71.17	98.22	119.22	142.40	158.96	181.59	198.46
HS20_4_17	4	17	44.29	70.15	96.91	117.49	140.50	157.14	178.80	196.11
HS20_4_18	4	18	44.29	69.11	95.69	115.84	138.60	155.67	176.01	193.75
HS20_4_19	4	19	44.29	68.06	94.45	114.50	136.68	154.16	173.21	191.39
HS20_4_20	4	20	44.29	67.00	93.33	113.41	134.74	152.65	170.39	189.00
HS20_4_21	4	21	44.29	65.93	92.19	112.32	132.87	151.14	167.55	186.60
HS20_4_22	4	22	44.29	64.86	91.04	111.19	131.07	149.60	164.87	184.17
HS20_4_23	4	23	44.29	64.73	89.89	110.21	129.26	148.06	162.18	181.73
HS20_4_24	4	24	44.29	64.60	88.74	109.21	127.44	146.49	159.74	179.30
HS20_4_25	4	25	44.29	64.45	87.60	108.20	125.61	144.92	158.48	176.86
HS20_4_26	4	26	44.29	64.30	86.46	107.18	123.77	143.35	157.22	174.41
HS20_4_27	4	27	44.29	64.15	85.30	106.15	121.92	141.78	155.94	171.95
HS20_4_28	4	28	44.29	63.98	84.14	105.11	120.37	140.18	154.65	169.46
HS20_4_29	4	29	44.29	63.82	82.96	104.06	119.14	138.56	153.33	166.97
HS20_4_30	4	30	44.29	63.65	81.78	103.16	117.90	136.93	152.01	164.57
HS20_5_10	5	10	44.49	77.73	107.26	137.79	159.83	183.90	206.24	229.43
HS20_5_11	5	11	44.46	76.62	105.73	135.10	157.94	180.78	201.56	225.42
HS20_5_12	5	12	44.41	75.49	104.18	132.38	156.02	177.63	197.18	221.39
HS20_5_13	5	13	44.36	74.33	102.59	129.64	154.06	174.47	194.58	217.33
HS20_5_14	5	14	44.29	73.16	101.00	126.87	152.07	171.29	191.96	213.29
HS20_5_15	5	15	44.29	72.17	99.61	124.26	150.07	168.07	189.30	209.22
HS20_5_16	5	16	44.29	71.17	98.22	122.45	148.02	165.13	186.61	205.20
HS20_5_17	5	17	44.29	70.15	96.91	120.62	145.96	163.58	183.91	201.26
HS20_5_18	5	18	44.29	69.11	95.69	118.77	143.88	162.01	181.22	198.55

			Span (ft)							
CODE	**No. Trucks**	**Spacing (ft)**	**20**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
HS20_5_19	5	19	44.29	68.06	94.45	116.89	141.77	160.40	178.50	196.27
HS20_5_20	5	20	44.29	67.00	93.33	115.00	139.63	158.80	175.77	193.97
HS20_5_21	5	21	44.29	65.93	92.19	113.11	137.55	157.17	173.02	191.65
HS20_5_22	5	22	44.29	64.86	91.04	111.19	135.54	155.51	170.42	189.30
HS20_5_23	5	23	44.29	64.73	89.89	110.21	133.51	153.84	167.80	186.95
HS20_5_24	5	24	44.29	64.60	88.74	109.21	131.47	152.14	166.18	184.59
HS20_5_25	5	25	44.29	64.45	87.60	108.20	129.40	150.42	164.84	182.24
HS20_5_26	5	26	44.29	64.30	86.46	107.18	127.31	148.70	163.49	179.86
HS20_5_27	5	27	44.29	64.15	85.30	106.15	125.20	146.98	162.12	177.46
HS20_5_28	5	28	44.29	63.98	84.14	105.11	123.40	145.21	160.74	175.05
HS20_5_29	5	29	44.29	63.82	82.96	104.06	121.92	143.42	159.32	172.62
HS20_5_30	5	30	44.29	63.65	81.78	103.16	120.42	141.61	157.89	170.29

APPENDIX D. REGRESSION MODELS FOR MOMENTS

No. Trucks	Headway (ft.)	Linear Equation	R^2	Polynomial Equation	R^2	Exponential Equation	R^2
1	N/A	$y = 17.862x - 257.27$	0.9999	$y = 0.0026x^2 + 17.293x - 233.34$	0.9999		
2	10	$y = 33.294x - 945.58$	0.9939	$y = 0.0461x^2 + 23.149x - 519.05$	0.9982		
2	11	$y = 33.124x - 953.4$	0.9933	$y = 0.0483x^2 + 22.506x - 506.97$	0.9981	$y = 1.2482x^{1.6111}$	0.9940
2	12	$y = 32.941x - 959.21$	0.9928	$y = 0.0505x^2 + 21.823x - 491.76$	0.9981	$y = 1.225x^{1.6127}$	0.9944
2	13	$y = 32.755x - 964.46$	0.9921	$y = 0.0529x^2 + 21.125x - 475.45$	0.998	$y = 1.2099x^{1.613}$	0.9948
2	14	$y = 32.561x - 968.07$	0.9915	$y = 0.0551x^2 + 20.436x - 458.24$	0.998	$y = 1.1996x^{1.6126}$	0.9953
2	15	$y = 32.351x - 969.1$	0.9908	$y = 0.0575x^2 + 19.708x - 437.5$	0.9979	$y = 1.2052x^{1.6095}$	0.9957
2	16	$y = 32.141x - 970$	0.9901	$y = 0.0598x^2 + 18.985x - 416.84$	0.9979	$y = 1.211x^{1.6064}$	0.9962
2	17	$y = 31.923x - 969.27$	0.9894	$y = 0.062x^2 + 18.276x - 395.5$	0.9979	$y = 1.2209x^{1.6027}$	0.9966
2	18	$y = 31.703x - 968.05$	0.9887	$y = 0.0642x^2 + 17.577x - 374.13$	0.9979	$y = 1.232x^{1.5988}$	0.9970
2	19	$y = 31.481x - 966.49$	0.9879	$y = 0.0664x^2 + 16.882x - 352.68$	0.9979	$y = 1.2441x^{1.5948}$	0.9974
2	20	$y = 31.253x - 963.57$	0.9872	$y = 0.0684x^2 + 16.209x - 331.04$	0.9979	$y = 1.2594x^{1.5903}$	0.9977
2	21	$y = 31.024x - 960.33$	0.9864	$y = 0.0703x^2 + 15.548x - 309.62$	0.998	$y = 1.2753x^{1.5858}$	0.9980
2	22	$y = 30.792x - 956.37$	0.9856	$y = 0.0722x^2 + 14.9x - 288.17$	0.998	$y = 1.293x^{1.581}$	0.9982
2	23	$y = 30.557x - 951.68$	0.9849	$y = 0.074x^2 + 14.268x - 266.8$	0.998	$y = 1.3125x^{1.5761}$	0.9984
2	24	$y = 30.321x - 946.61$	0.9841	$y = 0.0757x^2 + 13.657x - 245.96$	0.9981	$y = 1.3326x^{1.5711}$	0.9986
2	25	$y = 30.081x - 940.59$	0.9834	$y = 0.0773x^2 + 13.066x - 225.18$	0.9982	$y = 1.355x^{1.5658}$	0.9987
2	26	$y = 29.841x - 934.32$	0.9826	$y = 0.0789x^2 + 12.486x - 204.63$	0.9982	$y = 1.3783x^{1.5605}$	0.9988
2	27	$y = 29.599x - 927.45$	0.9818	$y = 0.0803x^2 + 11.935x - 184.79$	0.9983	$y = 1.4026x^{1.5551}$	0.9988

No. Trucks	Headway (ft.)	Linear Equation	R^2	Polynomial Equation	R^2	Exponential Equation	R^2
2	28	$y = 29.353x - 919.76$	0.9811	$y = 0.0816x^2 + 11.41x - 165.32$	0.9984	$y = 1.4288x^{1.5496}$	0.9988
2	29	$y = 29.109x - 912.07$	0.9804	$y = 0.0828x^2 + 10.887x - 145.94$	0.9984	$y = 1.4558x^{1.544}$	0.9988
2	30	$y = 28.862x - 903.56$	0.9797	$y = 0.0839x^2 + 10.409x - 127.68$	0.9985	$y = 1.4839x^{1.5383}$	0.9987
3	10	$y = 44.811x - 1616.4$	0.9792	$y = 0.1291x^2 + 16.409x - 422.19$	0.9977	$y = 0.7076x^{1.7657}$	0.9971
3	11	$y = 44.348x - 1614.8$	0.9778	$y = 0.1328x^2 + 15.136x - 386.57$	0.9977	$y = 0.6894x^{1.7677}$	0.9975
3	12	$y = 43.869x - 1610.7$	0.9763	$y = 0.1365x^2 + 13.836x - 347.91$	0.9978	$y = 0.6847x^{1.7657}$	0.9978
3	13	$y = 43.384x - 1604.8$	0.9748	$y = 0.14x^2 + 12.584x - 309.85$	0.9979	$y = 0.6849x^{1.7622}$	0.9981
3	14	$y = 42.888x - 1597.1$	0.9733	$y = 0.1434x^2 + 11.349x - 271.07$	0.998	$y = 0.6879x^{1.758}$	0.9984
3	15	$y = 42.371x - 1585.5$	0.9717	$y = 0.1465x^2 + 10.144x - 230.47$	0.9981	$y = 0.7008x^{1.7509}$	0.9986
3	16	$y = 41.854x - 1573.4$	0.9701	$y = 0.1495x^2 + 8.9694x - 190.72$	0.9982	$y = 0.7142x^{1.7438}$	0.9987
3	17	$y = 41.325x - 1558.7$	0.9685	$y = 0.1521x^2 + 7.8597x - 151.69$	0.9984	$y = 0.7308x^{1.7359}$	0.9987
3	18	$y = 40.794x - 1543.3$	0.9669	$y = 0.1546x^2 + 6.7908x - 113.66$	0.9985	$y = 0.7486x^{1.7279}$	0.9986
3	19	$y = 40.259x - 1526.7$	0.9653	$y = 0.1567x^2 + 5.7826x - 77.16$	0.9986	$y = 0.7677x^{1.7196}$	0.9984
3	20	$y = 39.718x - 1508.5$	0.9638	$y = 0.1586x^2 + 4.8275x - 41.538$	0.9987	$y = 0.7893x^{1.7108}$	0.9982
3	21	$y = 39.176x - 1489.4$	0.9623	$y = 0.1601x^2 + 3.9465x - 8.1003$	0.9989	$y = 0.812x^{1.702}$	0.9979
3	22	$y = 38.631x - 1469.2$	0.9608	$y = 0.1615x^2 + 3.1027x + 24.585$	0.999	$y = 0.8366x^{1.6929}$	0.9974
3	23	$y = 38.084x - 1447.8$	0.9593	$y = 0.1625x^2 + 2.3385x + 55.087$	0.9991	$y = 0.863x^{1.6836}$	0.9970
3	24	$y = 37.536x - 1425.8$	0.9579	$y = 0.1632x^2 + 1.6225x + 84.153$	0.9992	$y = 0.8907x^{1.6742}$	0.9964
3	25	$y = 36.985x - 1402.5$	0.9566	$y = 0.1636x^2 + 0.9858x + 111.11$	0.9992	$y = 0.9206x^{1.6646}$	0.9958
3	26	$y = 36.436x - 1378.7$	0.9553	$y = 0.1638x^2 + 0.3939x + 136.68$	0.9993	$y = 0.9519x^{1.6549}$	0.9952

No. Trucks	**Headway (ft.)**	**Linear Equation**	**R^2**	**Polynomial Equation**	**R^2**	**Exponential Equation**	**R^2**
3	27	$y = 35.888x - 1354.1$	0.9542	$y = 0.1637x^2 - 0.1169x + 159.71$	0.9993	$y = 0.9847x^{1.6453}$	0.9945
3	28	$y = 35.338x - 1328.5$	0.9531	$y = 0.1632x^2 - 0.5616x + 180.93$	0.9993	$y = 1.0197x^{1.6354}$	0.9938
3	29	$y = 34.792x - 1302.8$	0.9520	$y = 0.1625x^2 - 0.9655x + 200.67$	0.9993	$y = 1.0561x^{1.6255}$	0.9930
3	30	$y = 34.247x - 1276.1$	0.9511	$y = 0.1615x^2 - 1.2757x + 217.51$	0.9992	$y = 1.0941x^{1.6157}$	0.9923
4	10	$y = 50.348x - 1993.1$	0.9633	$y = 0.2045x^2 + 5.3578x - 101.51$	0.9995	$y = 0.5692x^{1.8212}$	0.9995
4	11	$y = 49.384x - 1961.8$	0.9619	$y = 0.2048x^2 + 4.3225x - 67.149$	0.9996	$y = 0.5655x^{1.818}$	0.9995
4	12	$y = 48.419x - 1927.6$	0.9606	$y = 0.2046x^2 + 3.3975x - 34.642$	0.9997	$y = 0.5725x^{1.811}$	0.9994
4	13	$y = 47.462x - 1892.1$	0.9595	$y = 0.2039x^2 + 2.5982x - 5.8284$	0.9998	$y = 0.5834x^{1.8028}$	0.9992
4	14	$y = 46.51x - 1855$	0.9584	$y = 0.2027x^2 + 1.9113x + 20.144$	0.9998	$y = 0.5967x^{1.7939}$	0.9990
4	15	$y = 45.559x - 1814.5$	0.9575	$y = 0.2008x^2 + 1.3773x + 43.172$	0.9999	$y = 0.6183x^{1.7825}$	0.9987
4	16	$y = 44.632x - 1774.6$	0.9568	$y = 0.1986x^2 + 0.9422x + 62.403$	0.9999	$y = 0.6403x^{1.7712}$	0.9984
4	17	$y = 43.714x - 1733.2$	0.9562	$y = 0.1959x^2 + 0.6169x + 78.898$	0.9999	$y = 0.6652x^{1.7595}$	0.9981
4	18	$y = 42.817x - 1692.1$	0.9557	$y = 0.193x^2 + 0.3659x + 92.739$	0.9999	$y = 0.6913x^{1.7478}$	0.9978
4	19	$y = 41.946x - 1651.7$	0.9554	$y = 0.1898x^2 + 0.1921x + 103.86$	0.9999	$y = 0.7183x^{1.7362}$	0.9975
4	20	$y = 41.097x - 1611.3$	0.9551	$y = 0.1865x^2 + 0.0724x + 113.56$	0.9998	$y = 0.7476x^{1.7244}$	0.9971
4	21	$y = 40.274x - 1571.7$	0.9549	$y = 0.183x^2 + 0.0139x + 121.04$	0.9998	$y = 0.7776x^{1.7128}$	0.9968
4	22	$y = 39.479x - 1533.2$	0.9548	$y = 0.1797x^2 - 0.0474x + 128.67$	0.9997	$y = 0.809x^{1.7013}$	0.9965
4	23	$y = 38.716x - 1495.8$	0.9546	$y = 0.1764x^2 - 0.0939x + 135.93$	0.9997	$y = 0.8417x^{1.6898}$	0.9961
4	24	$y = 37.986x - 1460.2$	0.9544	$y = 0.1734x^2 - 0.1652x + 143.88$	0.9996	$y = 0.8749x^{1.6787}$	0.9957
4	25	$y = 37.289x - 1425.8$	0.9541	$y = 0.1707x^2 - 0.254x + 152.71$	0.9996	$y = 0.9095x^{1.6676}$	0.9953

No. Trucks	Headway (ft.)	Linear Equation	R^2	Polynomial Equation	R^2	Exponential Equation	R^2
4	26	$y = 36.635x - 1394.1$	0.9536	$y = 0.1686x^2 - 0.4465x + 165.04$	0.9995	$y = 0.9444x^{1.6569}$	0.9948
4	27	$y = 36.002x - 1363$	0.9531	$y = 0.1664x^2 - 0.616x + 176.64$	0.9994	$y = 0.9803x^{1.6464}$	0.9942
4	28	$y = 35.389x - 1332.5$	0.9526	$y = 0.1645x^2 - 0.7924x + 188.8$	0.9994	$y = 1.0177x^{1.6359}$	0.9937
4	29	$y = 34.81x - 1304.1$	0.9518	$y = 0.163x^2 - 1.0457x + 203.41$	0.9993	$y = 1.0553x^{1.6257}$	0.9930
4	30	$y = 34.251x - 1276.4$	0.9511	$y = 0.1616x^2 - 1.2947x + 218.16$	0.9992	$y = 1.0939x^{1.6157}$	0.9923