RESEARCH & DEVELOPMENT

Analysis of Truck Load Weight Distribution in North Carolina

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NCDOT Project 2012-10
FHWA/NC/2012-10
September 2012

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Prepared for:

North Carolina Department of Transportation
Structures Management Unit
Raleigh, NC 27699-1581

Final Report
Project: HWY 2012-10
September 30, 2012

Technical Report Documentation Page

Report No. **FHWA/NC/2012-10**	Government Accession No.	Recipient's Catalog No.
4. Title and Subtitle **Analysis of Truck Load Weight Distribution in North Carolina**		Report Date **September 30, 2012**
		Performing Organization Code
Author(s) **John R. Stone, Mervyn Kowalsky, Ron Hughes, C. Kelly Herrick, Brian Narron, and Wei Cao**		Performing Organization Report No.
Performing Organization Name and Address **North Carolina State University** **Department of Civil, Construction and Environmental Engineering** **208 Mann Hall** **Raleigh, NC 27695-7908**		Work Unit No. (TRAIS)
		Contract or Grant No.
Sponsoring Agency Name and Address **North Carolina Department of Transportation** **Structures Management Branch** **Raleigh, North Carolina 27699-1581**		Type of Report and Period Covered **Final Report** **July 2011 to September 2012**
		Sponsoring Agency Code **2012-10**
Supplementary Notes:		

Abstract

Superloads, or "super heavy" vehicles are a growing occurrence on North Carolina bridges and highways. Due to their non-typical weights and geometries, as well as the difficulties of verifying such values, additional information is needed to prevent damage to bridge superstructures and highway pavements. The NCDOT Problem Statement 2403 addresses the need for basic data and analysis on the relationship between estimated axle load distributions provided by truck operators and actual axle load distributions, as well as the impacts of superloads on North Carolina bridges and highways.

The research produced the following results: (1) Weight distributions of superloads acquired through field weighs and permits from project partners and other DOTs; (2) Estimates of pavement damage from superloads in terms of ESALs and equivalent number of 80 kip trucks. (3) Recommendations for PMU superload permit application analysis (4) Estimates of superloads' distribution of demands on bridge superstructures for selected superload types; (5) Recommendations regarding the current NCDOT permitting process for superloads crossing bridges; (6) An updated version of the NCDOT program, PERM6 capable of analyzing vehicles with up to 50 axles.

Key Words **Pavement Impacts, Bridge Impacts, Superstructure, Overweight Trucks, Superload, Super Heavy, Weight Distribution.**	Distribution Statement		
Security Classif. (of this report) Unclassified	Security Classif. (of this page) Unclassified	No. of Pages 263	Price

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ACKNOWLEDGEMENTS

The research team acknowledges the North Carolina Department of Transportation for supporting and funding this project. We extend our thanks to the NCDOT Research Project Steering Committee and NCDOT staff, and others who provided valuable advice and data for the project. They are:

Dan Holderman, PE (retired), Chair

Gregory Perfetti, PE, Chair

Henry Black, PE

William Clarke, PE

Tammy Denning, PE

Heath Gore, PE

Charles Hunt, PE

Mustan Kadibhai, PE

Don Idol, PE

Kevin Lacy, PE

Clark Morrison, PE

The authors appreciate the efforts of the officers of the North Carolina State Highway Patrol, who provided field measurements of truck weights for several configurations. The authors also recognize the time and effort of Mike Hoggard and the staff of Turner Transfer who helped organize field measurements of their super heavy trucks.

The authors also acknowledge and appreciate the educational funding from the Southeastern Transportation Center. Without this special funding components of the research may not have been completed.

ACRONYMS

Acronym	Meaning
AASHTO	American Association of State Highway and Transportation Officials
BMU	NCDOT Bridge Management Unit
FHWA	Federal Highway Administration
GA SHP	Georgia State Highway Patrol
GDOT	Georgia Department of Transportation
GVW	Gross Vehicle Weight
LFD	Load Factor Design
LRFD	Load and Resistance Factor Design
NCDOT	North Carolina Department of Transportation
NC SHP	North Carolina State Highway Patrol
NHS	National Highway System
OSOW	Oversize/Overweight Permit Department
PMU	NCDOT Pavement Management Unit
PPC	Prestressed Precast Concrete
SCDOT	South Carolina Department of Transportation
SLR	Span-Length Ratios
S.N.T.	Standard Normal Truck
TxDMV	Texas Department of Motor Vehicles
TxDOT	Texas Department of Transportation
VA DMV	Virginia Department of Motor Vehicles
VA DOT	Virginia Department of Transportation
WIM	Weigh-in-Motion

DEFINITIONS

Axle: a set of two (2) or four (4) interconnected tires

Axle-Line: a set of one (1) or more axles arranged laterally.

Duals: a set of two closely spaced tires on a truck or trailer.

Gooseneck: a trailer part which is generally a curved beam that resembles a goose's neck used to transfer load from one area of the trailer to another. Also referred to as a bridge.

Jeep: a drop-deck flatbed semitrailer with a fifth wheel designed to go between a truck-tractor and semitrailer for the purpose of distributing weight.

Lift Axle: an axle that can be lowered for the purpose of distributing weight and raised when not needed.

Outrigger: sets of tandem axles attached to a trailer with I-beams for the purpose of distributing weight.

Stinger Dolly: a platform consisting of a set of one (1) or more axles attached to the rear of a trailer for the purpose of distributing weight. It is also referred to as a booster axle assembly or a booster assembly.

EXECUTIVE SUMMARY

NCDOT Research Problem Statement 2403 addresses the need for basic data and analysis on the relationship between estimated axle load distributions provided by truck operators, actual axle load distributions, and the impacts of overweight "super heavy" commercial vehicles on North Carolina bridge superstructures and highways. Such vehicles can weigh over one million pounds and are often longer and wider than standard vehicles. Typically, these vehicles are extremely long or have a large number of axle-lines to distribute their payload's weight. The State Bridge Management Unit in collaboration with the Oversize/Overweight Permit Unit and the NC Highway Patrol sought verification of axle load data to substantiate the estimates provided by commercial operators. The NCSU research team has gathered data from a number of superloads through field weighings, case studies, and historical accounts. This data was used to analyze the effects of superloads on bridge superstructures and pavements in North Carolina. Below, an overview of each section of the research project is provided, along with relevant conclusions.

Introduction

North Carolina separates overweight permits into three main categories: Annual Permits, Single Trip Permits, and Superload Permits. A Superload Permit is required for every truck operating in North Carolina meeting any or all of the following guidelines:

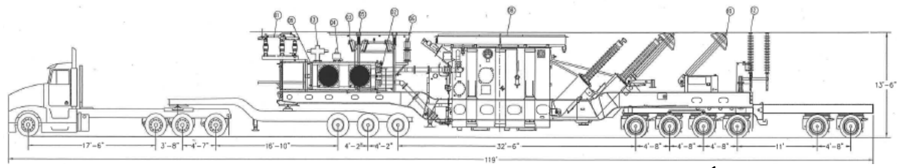
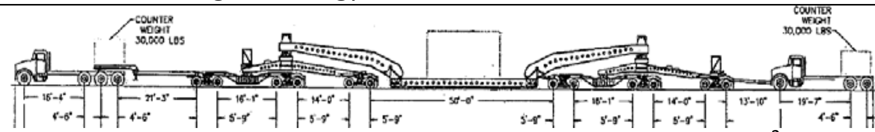
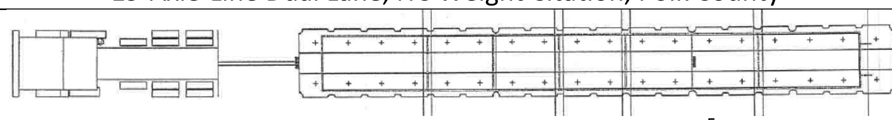
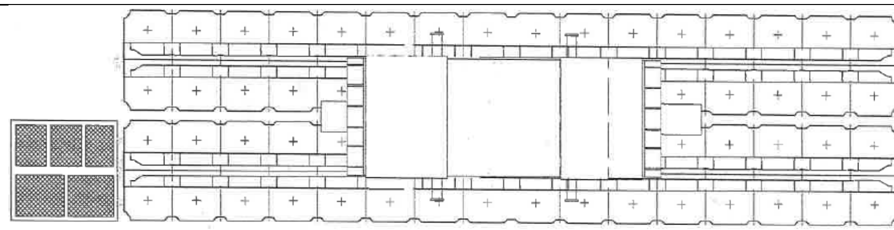
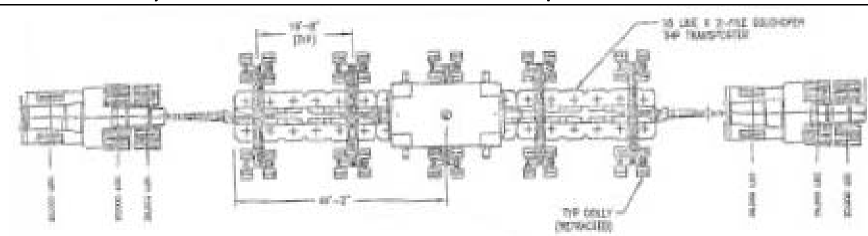
- Gross weight in excess of 132,000 lbs
- Steer axle weight in excess of 12,000 lbs
- Four- or more axle grouping weight in excess of 60,000 lbs
- Width in excess of 15 ft

A truck meeting these limits must submit a superload permit application as well as a vehicle schematic, showing axle spacing and axle weight distribution of the load to the Oversize/ Overweight Permit Unit (OSOW) at the NCDOT *(1)*. Also included in the superload permit application are the origin and destination of the load and the operator's planned route of travel, such that the NCDOT can analyze the proposed route for any constraints due to bridge loads, bridge clearances, etc. *(2)*.

Representative Vehicle Configurations

Commercial carriers that haul superloads use specialized equipment that varies greatly in length, width, height, and axle configuration in order to accommodate the irregular size and weight of non-divisible superloads. Therefore, a general classification system for superload truck configurations was developed to allow for trucks of similar configurations to be grouped together based on general truck characteristics and weight distribution methods. This classification system was developed by reviewing truck schematic drawings supplied by NCDOT, GDOT, Progress Energy, and Guy M. Turner and by reviewing equipment listings on websites of specialized carriers that operate in NC. Five main superload truck configurations were identified for this study, shown in Table 1 below. It should be noted that this classification system with these five general vehicle configurations is by no means meant to be exhaustive of all possible superload truck configurations. These configurations were identified as common superload configurations in NC and were selected for used in this study.

Table 1 Superload Truck Configurations

Config. Number	Config. Name	Example
1	Truck-Jeep-Trailer-Stinger	 Progress Energy 13 Axle Mobile Transformer[1]
2	Drop-Deck Gooseneck	 19-Axle-Line Dual Lane, NC Weight Citation, Polk County[2]
3	Singlewide Modular	 Crane Rental 21-Axle-Line Towed Goldhofer[5]
4	Doublewide Modular	 Guy M. Turner 16-Axle-Line Self-Propelled Goldhofer[16]
5	Modular With Outriggers	 Barnhart 24-Axle-Line Towed Goldhofer with Dollies[16]

Superload Weight Data and Distributions

Weight data was collected and analyzed for 20 superload trucks, with 14 for configuration 1, four for configuration 2, and two for configuration 3. The weight data for two configuration 1 trucks were collected in a field weigh, while the data for five trucks was supplied by the NC SHP through citation data, and data for the last seven configuration 1 trucks was supplied by GDOT. For configuration 2, the data for one truck was supplied by The NC SHP through a weight citation, the data for the other three trucks was supplied by GDOT through superload permits originating in the Port of Savannah. The data for the two configuration 3 trucks was collected in a field weigh.

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[1] Source: Progress Energy
[2] Source: NCDOT

Configuration 1

None of the fourteen examples of configuration 1 showed a uniform axle weight distribution. The 10-axle Progress Energy truck did not have a permit available for comparisons of estimated weight distributions to measured distributions. Of the remaining 13 examples for this configuration, nine estimated uniform axle weight distributions while four estimated non-uniform distributions. A summary table of the configuration 1 trucks is given in Table 2 below.

Table 2 Configuration 1 Summary

Truck	# of Axles	Uniform Estimate	# Overweight Axles	% Over Permit Axle Estimate		% Diff Gross Weight
				Maximum	Minimum	
PE Mobile Transformer	13	No	8	21.8	0.5	-0.4
NC 7/2007	9	Yes	1	15.7	--	-16.4
NC 6/2008	8	No	7	15	0	2.3
NC 7/2008	13	Yes	1	4.4	--	-8.1
NC 12/2008	13	Yes	9	4.3	0.3	0.1
NC 3/2011	13	Yes	1	16.7	--	-9.4
GA Truck 1	11	Yes	1	6.1	--	-5.2
GA Truck 2	11	No	1	1.7	--	-2.8
GA Truck 3	11	Yes	2	7.5	7	-14.6
GA Truck 4	13	Yes	0	--	--	-17.5
GA Truck 5	12	Yes	1	2.2	--	-8.3
GA Truck 6	13	Yes	2	4.6	2.5	-9
GA Truck 7	11	No	2	3.2	1.8	-8.8
Average	**12**	**--**	**2.8**	**6.4**		**-7.5**

The 13-axle mobile transformer had a load that comprised the entire body of, was permanently attached to the trailer, and was non-uniform in weight. This would explain why a non-uniform axle weight distribution was estimated for this truck. A Progress Energy official stated that the axle weight distribution was estimated by the trailer manufacturer and that they used these estimates when applying for a superload permit. It appears that there was no effort to overestimate the weights for the truck to provide a buffer for weight deviations from the permit. Also noted, was that the lift axle on the tractor was malfunctioning and it was difficult to get this axle to carry weight, causing other nearby axles to carry more weight. These two reasons would explain why this truck had eight overweight axles and the steering axle was 21.8% overweight. No information is known on the load type, size, or positioning for any of the other configuration 1 examples. However, in the GA data it appeared that there were similar lift axle problems as with the Progress Energy mobile transformer. This was not observable in the NC citation data because the NC SHP records axle group weights and not individual axle weights.

Of the thirteen examples, number of overweight axles ranged from 0 to 9, and percent overweight ranged from 0% to 21.8%. Only two of the trucks were observed to be over gross weight with the highest being 2.3% over estimated gross weight, with the rest of the trucks being below estimated gross weight. The average number of overweight axles for the data was 2.8, although this may be skewed slightly high because of the three trucks that had a large number of overweight axles. The median number of overweight axles for the sample group was 1. The average percent over permit estimate for axle weight was 6.4%. The sample trucks averaged 7.5% below estimated gross weight listed on the superload permit.

Configuration 2

For superload configuration 2, data was collected for four trucks: One dual-lane truck from an NC citation, and one single lane truck and two dual-lane trucks from GA permits. When the weight data was aggregated by axle-line, it was found that weights tend to distribute relatively uniformly across the trailer axle-lines. Although, observed in all the dual-lane example was that the first one or two trailer axle-lines generally carried more weight than the other trailer axle-lines. This was possibly due to the added weight of the coupling mechanism or weight from the counterweight on the tractor being transfer through the coupling and being carried by these axle-lines. Also noted was that the two GA examples with tractors with lift axles was that as with configuration 1, the lift axle generally carried a different amount of weight than the other axles in the same axle group. This could occur because the lift axle may not be designed to carry as much weight as a standard axle, or the operator may improperly set the height of the lift axle. When the weight data for the GA examples was aggregated by axle, the first two GA trucks showed a relatively uniform weight distribution while the last truck did not. In addition, the two GA dual-lane vehicles showed a tendency for the axles on one side to carry more weight than the axles on the other side. This may have been due to the loads on these trucks being located slightly off center or the trucks may have been weighed on a slight incline, shifting the center of gravity of the truck.

Only one of the GA examples and the NC citation example had carrier-estimated weight available for comparison to the measured weights. A summary table of the results of the comparison for these two trucks is provided in Table 3 below. The NC example had three axle-lines over the estimated weight, two trailer axle-lines, and a tractor steer axle. The GA example had one trailer axle-line over the estimated weight. The percent over the estimated axle-line weights ranged from 1.2% to 5.8%. The weight data for the NC example was only by axle-line while the GA example had weights given by axle. The GA example had five axles slightly above the estimated axle weights ranging from 1.0% to 3.4% over. Both of the examples had gross truck weights lower than estimated, which seems to indicate that the carriers overestimated weight to account for variations in weight distribution.

Table 3 Configuration 2 Summary

Truck		NC Citation	GA Permit #K0383872
Axle-lines	Number	19	22
	Number Over Estimates	3	1
	Max % Over Estimate	5.8	1.2
	Min % Over Estimate	2.8	--
Axles	Number	31	38
	Number Over Estimates	--	5
	Max % Over Estimate	--	3.4
	Min % Over Estimate	--	1.0
% Difference from Est. Gross Wt.		-8.0	-4.2

Configuration 3

Two examples of configuration 3 were weighed at the Progress Energy Shearon Harris power plant, an 11 axle-line truck-towed singlewide modular unit, and a 10 axle-line self-propelled singlewide modular unit. Guy M. Turner operated both units on the plant property and stated that since they were not operating on public roadways for these moves they were operating with more weight per axle than they would otherwise. They also stated that they were not as careful with the placement of the load on the units as they would have if they were operating on public roadways. Because of this, the recorded weights are not indicative of a superload that would operate on NC roads but are still useful for observing the weight distribution characteristics of configuration 3 units.

Each axle for a modular unit is hydraulically suspended and the hydraulics are linked into suspension groups to equalize hydraulic pressure and therefore axle load. Observed in both units was the ability of the hydraulic suspension to fairly evenly distribute weight to axles within linked suspension groups. Weights between suspension groups for both trucks showed longitudinal weight distribution discrepancies, with the front or rear suspension groups carrying significantly more weight than the other does. The 11 axle-line unit also showed weight distribution discrepancies laterally between suspension groups. Therefore, weight distribution between suspension groups seems highly dependent on the placement of the load on the trailer. To achieve uniform weight distribution the center of gravity of the load must be located over the center of the trailer.

Configurations 4 and 5

No data was able to be taken on configuration 4, doublewide modular, or configuration 5, modular with outriggers, trucks and alternate sources of data were also unavailable. During the study, there were plans to weigh a configuration 4 truck, estimated at over a million pounds, being operated by project partner Guy M. Turner in Greensboro, NC. This truck carried a generator for a power plant and moved 17 miles from a rail siding to the power plant. The NCDOT canceled this opportunity when the customer receiving the load expressed reservations and concerns over delays the weighing may cause. A case study was instead performed on this load by interviewing NCDOT engineers from that district involved in the move and is included in the pavement analysis chapter.

Configuration 4 and 5 trucks are very similar to configuration 3 trucks, both being comprised of the same type of modular units arranged in different ways. Configuration 4 trucks have modular units arranged laterally and longitudinally and configuration 5 trucks employ extra axle groups attached to the modular units with I-beams. Since all three of these configurations use the same modular units, it is thought that the weight distribution characteristics will be similar to those observed for configuration 3 trucks.

Conclusions Regarding Superload Configurations

None of the trucks for any observed configuration displayed uniform weight distribution. The configuration 2 trucks seemed to distribute weight the best having fairly uniform weight distributions. Configuration 1 trucks seemed to distribute weight the worst having irregular weight distributions. The two configuration 3 trucks showed good weight distribution ability within suspension groups but non-uniform distributions between suspension groups. It appears that of all of the configurations weight distribution is highly dependent on the location of the load on the truck. Most of the carriers for both of these configurations seemed to overestimate axle weights to compensate for variations in axle weight distribution.

Effects of Superloads on Bridge Superstructures

Data from weighings performed during the study and superload permits acquired from the State Oversize/Overweight Vehicle Unit was used to create seven representative superload vehicles. Figure 1 through Figure 5 display the basic superloads utilized in the study. More detailed figures and discussion can be found in the body of the structural section of the report. Two additional vehicles created represent the alternative configurations of Vehicle 2 and Vehicle 5. The NCSU team analyzed these seven superloads crossing 116 bridges with varying physical geometries and material properties. Additionally, the standard Load Factor Design bridge design HS-15 vehicle loading was modeled and included in the analyses for comparison to each superload.

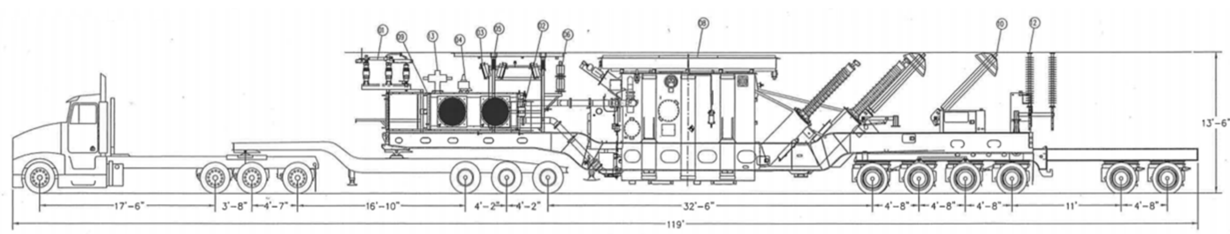

Figure 1 Vehicle 1: Combination Vehicle of Truck-Jeep-Trailer-Stinger.[3]

[3]Source: Progress Energy

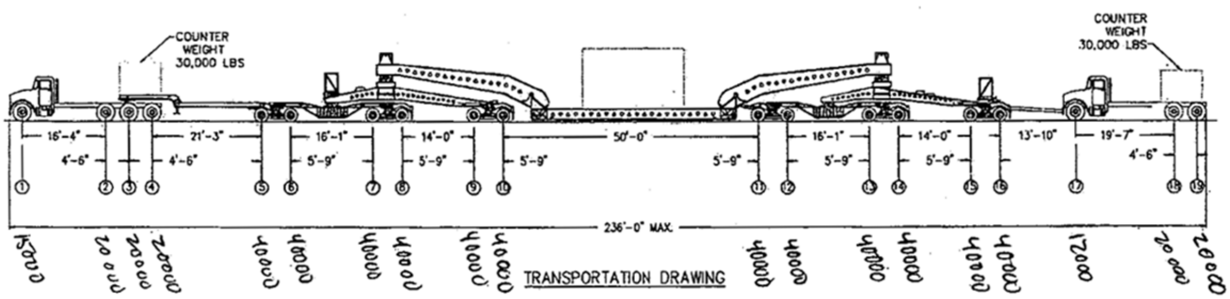

Figure 2 Vehicle 2a and Vehicle 2b: Drop-Deck Gooseneck with Expandable Axles-Lines.[4]

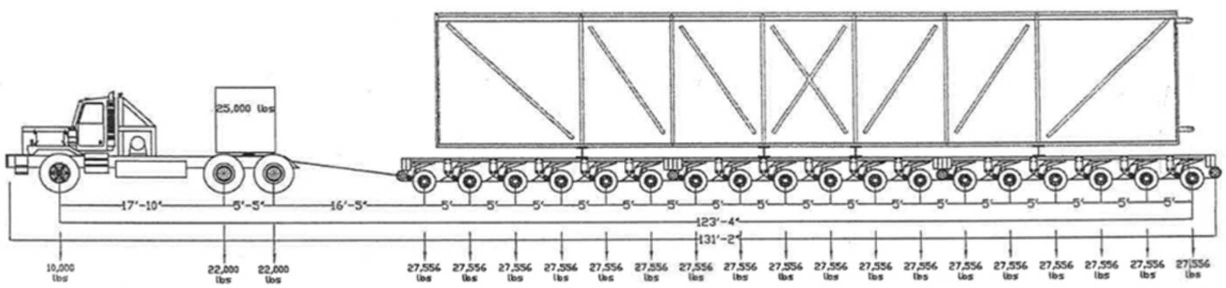

Figure 3 Vehicle 3: Singlewide Modular.[5]

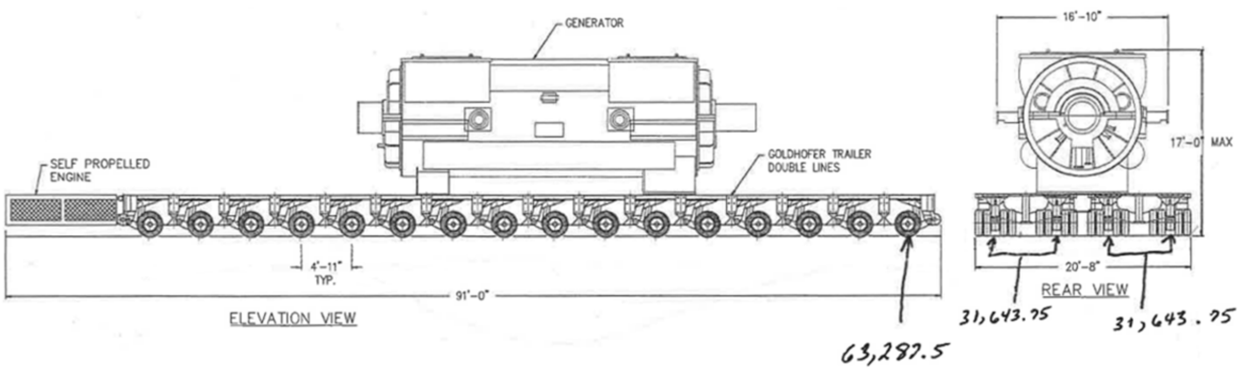

Figure 4 Vehicle 4: Doublewide Modular.[6]

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[4]Source: NCDOT OSOW.
[5]Source: NCDOT OSOW.
[6] Source: NCDOT OSOW

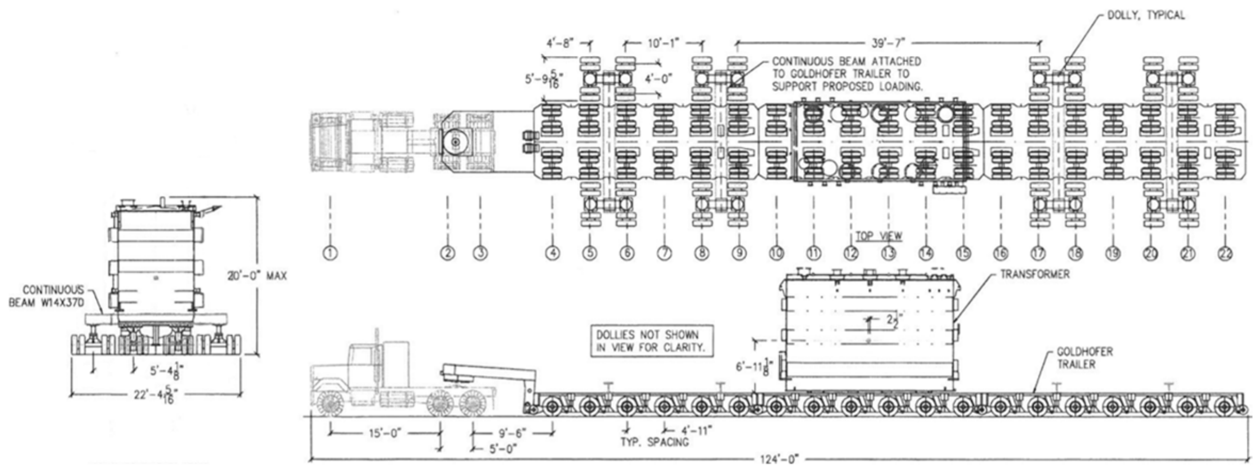

Figure 5 Vehicle 5a and Vehicle 5b: Modular with Optional Outrigger Dollies.[7]

Bridges were modeled using the plane-grillage method of analysis, which creates models consisting of a series of frame elements that approximates the bridge's response. Bridge parameters to be varied and their representative ranges were selected based on prior bridge studies and North Carolina bridge data. Bridges were created with a single parameter varied at a time, while all other parameters are held constant. Despite the results being not statistically representative for North Carolina bridges and some correlation between variables is possible, this sampling method provides reliable data for the superloads tested. Similarly, while the seven superload cases selected for analysis are not exhaustive of all types of superloads, they are commonly occurring trailer and vehicle arrangements and types.

From the analyses of the bridge models, moment envelopes for the maximum moment occurring during the passage for each superload and the HS vehicle were calculated for a range of points on the bridge superstructure. The maximum positive moments were calculated between spans, while the maximum negative moments were calculated over each bridge bent (if the bridge had multiple spans). These values were calculated for external girders and the girder closest to the bridge centerline. Results were also gathered for "transition" girders, or girders adjacent to the external girders.

Figure 6 contains an example of a graph displaying these results for an external, transition, and internal girder on three two-lane bridges with a span-length ratio (SLR) of 1-2-1. The bridges' SLR of 1-2-1 indicates the ratio of bridge lengths for which results are displayed. A maximum span length of 100 and a span-length ratio of 1:2:1 would have four spans with lengths 50 ft, 100 ft, and 50 ft. The x-axis displays the longest span length of the bridge being analyzed, and the y-axis displays the maximum moment experienced for the given location on the bridge. Note that the demands displayed are per 100 kip of GVW, and can be scaled directly to match superloads with similar axle layouts due to the elastic nature of the analysis performed.

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[7] Source: NCDOT OSOW

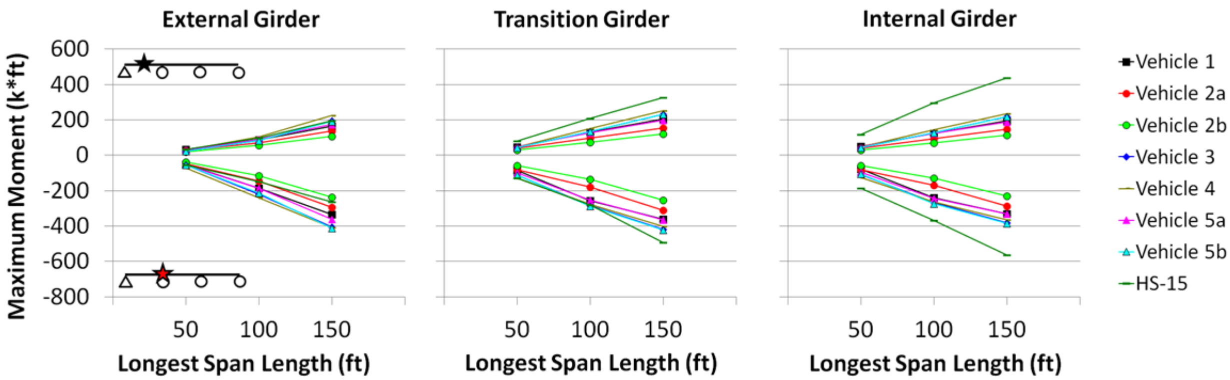

Figure 6 Moment Demands for Two-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths

Following the typical NCDOT permitting process, each superload was rated with an HS-equivalent rating, which is the weight of the HS-truck in tons that would generate an equivalent demand. These results from the NCSU team's analyses are displayed in a similar manner to the moments, located in the appendices of the report.

In order to provide an estimate on the conservatism of the current NCDOT method of analysis, HS-equivalent ratings were also calculated using the NCDOT program PERM6. A ratio comparing the plane-grillage HS-equivalent rating to those calculated using PERM6 was generated for each data-point. The resulting factor is a measure of conservatism when comparing the two methods. Figure 7 is an example of the conservatism ratios for a set of one span, two-lane bridges with varying girder spacings. Conservatism ratios above +1.0 or below -1.0 mean that the NCDOT method conservatively over-estimates demands and ratios below 1 mean the NCDOT method under-estimates demands in comparison to the refined plane-grillage method.

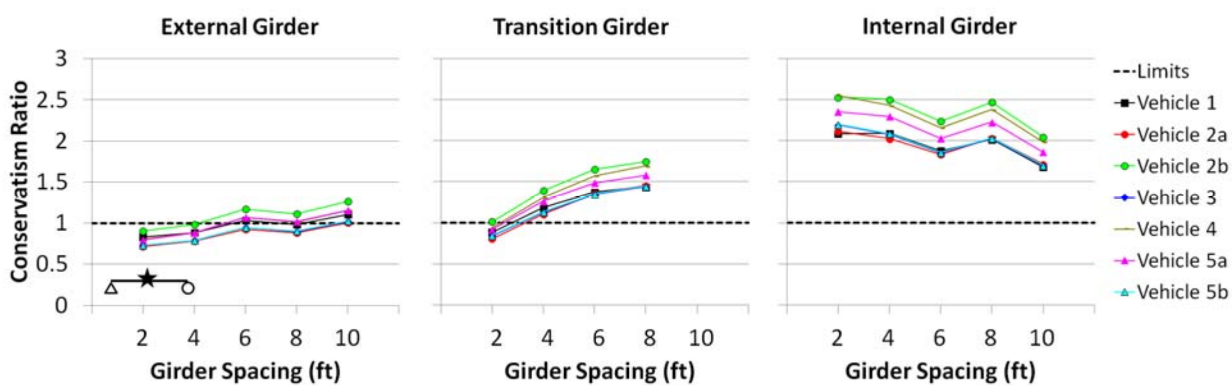

Figure 7 Conservatism Ratios of Two-Lane Bridges with Varying Girder Spacing.

More detailed analysis results are available in the body of the report, as well as details regarding each individual set of analyses. Conclusions drawn from the analyses are provided below.

Effects of Superloads on Pavements

In this report a four part pavement impact analysis was used, (1) The AASHTO ESAL conversion factors were used to convert the superloads into number of equivalent 18-kip single axles as an initial simple analysis. (2) LVECD was selected for the pavement response modeling and analysis. Developed at NCSU, this program was initially written for analyzing pavement response and performance (including thermal cracking, fatigue cracking, and rutting) under traffic loading of normal trucks. It was then modified to accommodate the special geometric configurations of the overload trucks while keeping the algorithms and assumptions the same as for normal trucks. The goal of this portion of the analysis was to convert a superload truck to an equivalent number of the standard 18-kip single axles, based on the concept of equivalent damage (either fatigue or permanent deformation) caused to the pavement. (3) The wheel load charts developed by Jooste and Fernando with the PALS software were used to determine the risk of immediate damage from a superload due to rapid shear failure. (4) A case study was performed for a route that a one-million pound configuration 4, doublewide modular, superload. This vehicle was unable to be weighed during the study, as noted in chapter 2, and no other weight data was found for this configuration. Therefore, to compensate for this lack of weight data for analysis an interview was conducted with the NCDOT inspector, Gary Darden, who inspected the route before and after the superload move and a case study written.

Five vehicles were selected for use in the pavement analysis portion of this study, one representative vehicle for each of the five superload configurations. Figure 8 through Figure 12 display the basic superloads utilized in the study. More detailed figures and discussion can be found in the body of CHAPTER 4 the report and schematics are supplied for reference in APPENDIX C of this report.

Figure 8 Truck-1: Progress Energy Mobile Transformer Truck.

Figure 9 Truck-2: 19 Axle-Line Dual-Lane Transporter.[8]

[8] Picture Source: NC SHP

Figure 10 Truck-3: 11 Axle-Line Singlewide Modular, Shearon Harris Plant.[9]

Figure 11 Truck-4: 16 Axle-Line Self-Propelled Doublewide Modular.[10]

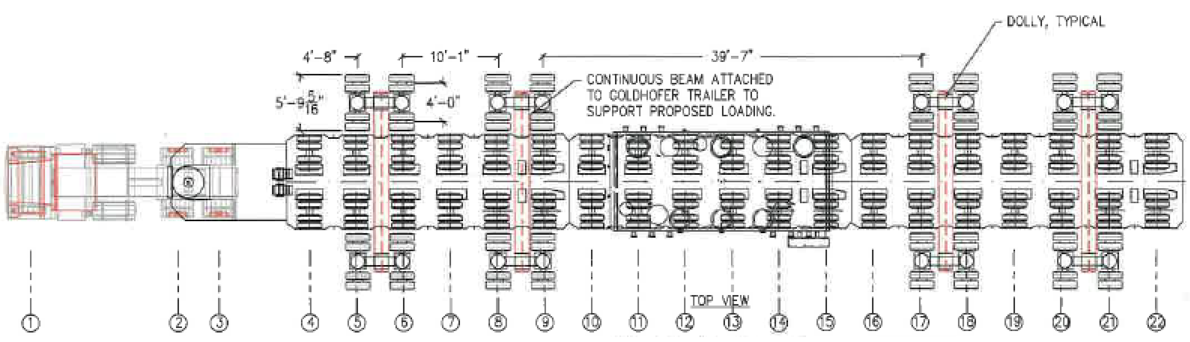

Figure 12 Truck-5: 22 Axle-Line Singlewide Modular with Outriggers.[11]

As a reference for comparison in the pavement impact analysis, a standard legal 80,000-pound tractor-trailer was also analyzed. The "standard normal truck" is considered a five-axle

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[9] Photo courtesy of Progress Energy
[10] Picture Source: NCDOT
[11] Source: NCDOT

truck with a steer axle weighing 12,000 pounds, a tandem axle weighing 32,000 pounds, and another tandem axle weighing 36,000 pounds.

The pavement analysis tool LVECD, developed in-house, was utilized to obtain the strain response of pavement to the overload trucks. In the framework of LVECD, asphalt concrete is treated as a linear viscoelastic material, while base and subgrade are considered as linear elastic. Given the length of the overload trucks and the resulting computational issues, all axle lines were grouped into several axle groups and then one axle group was used at a time in the strain response analysis. When the strain response was obtained, the strain profile at a depth of interest caused by each axle line in an axle group corresponding to the moment of the strain peak was extracted and then used to calculate the damage. For fatigue analysis, the transverse tensile strain at the bottom of asphalt layer was used to generate the damage profile across the pavement width. For rutting analysis, first, the vertical compressive strain was computed at the mid-depth of each sublayer of asphalt materials and then the rut depth coefficient (proportional to rut depth) profile across the pavement width was produced by summing up all the contributions from each sublayer. Finally, by comparing the fatigue damage and rut depth coefficient due to trucks to those caused by the standard 18-kip axle through both maximum and area-based methods, the fatigue/rut ESALs for each truck was found.

With the analysis by LVECD, it was determined that the AASHTO equivalency factors for converting axle loads to ESALs were inadequate for use with superloads. The AASHTO factors consistently underestimated ESALs when compared to ESALs calculated using LVECD modeling. The AASHTO ESAL method cannot manage the nonstandard axle configurations of superloads and therefore cannot account for the complex stress interactions within the pavement structure. As a result, the AASHTO ESAL method cannot be recommended for use by the PMU for analysis of superload permit applications.

In the LVECD analysis, it was shown that ESALs for both damage types increased when based on area of damage rather than the point of maximum damage. Superload trucks, to accommodate extra axles and wheels, are commonly wider than normal trucks and therefore cause damage to a wider portion of the pavement structure, indicated by the ESALs based on area. Although, damage to the pavement structure at a point would be more indicative to damage within the normal wheel paths, indicated by ESALs based on maximum, are of more concern since wheel paths are subject to a greater frequency and level of stresses caused by traffic loading. ESALs based on fatigue are higher than ESALs based on permanent deformation for every truck when based on point of maximum damage. This indicates that NC roads are at a higher risk over the long term for fatigue cracking damage from superload passes.

There does not seem to be a direct correlation between the truck gross weight and the ESAL. This is reasonably due to the arrangement of increased number of tires in most axle lines, which helps better distribute the truck weight and thus reduce the damage caused to the pavement. Thus, tire load is of greater concern for pavement damage than gross weight. Although, as seen by the ESAL estimates based on areas, superloads with higher gross weights generally cause more damage to the pavement structure as a whole because they have more contact points over a larger area than lesser weight trucks. Number of equivalent standard normal trucks based on the point of maximum damage for fatigue and permanent deformation are lower than those based on gross weight. This suggests that every superload vehicle type analyzed causes less damage per pound of gross weight than a standard normal truck does when based on point of maximum damage.

The ESALs calculated using LVECD show that for truck-1, truck-2, and truck-3, the ESALs based on measured weights are close to or less than ESALs based on estimated weights. Therefore, for superload permit approval, it seems that using carrier estimates would provide a reasonable basis for analysis for the PMU.

The charts developed by Jooste and Fernando for TxDOT were used to determine maximum wheel loads for superload trucks to reduce the risk of rapid shear failure of pavements. It was determined that with a weak pavement structure, steer axles pose a higher risk of pavement damage since these axles generally carry higher wheel loads due to only having two tires. Although, ignoring steer axles, it was determined that only truck-3, the singlewide modular, posed a significant risk for damaging the pavement due to uneven weight distribution.

The case study showed that over 100 runs of various superload trucks along a single route caused no visible damage to the pavement surface. This indicates that the route had sufficient strength to support the superloads without damage.

Also noted in the literature review was the finding that superloads pose a significant risk to new seal coats. It is recommended that the PMU adopt the TxDOT policy of not allowing superloads to use roads that have seal coats younger than 5 weeks if other routing is possible. If other routing is not possible then the carrier should be required to mat the road to protect the seal coat from damage.

Recommendations

Chapter 2 of this report constitutes the documentation of measured axle weight distributions for the twenty superload trucks found in this report. It appears that for all of the configurations weight distribution is highly dependent on the location of the load on the truck. In order to meet permit requirements most of the carriers for these configurations seemed to overestimate axle weights to compensate for variations in axle weight distribution.

It is recommended that the NCDOT consider forming a partnership with the NC SHP to create a database of citations for superload permitted trucks. A database of citations would provide needed weight data for future research projects and could help provide NCDOT a resource for determining trends in violation types for superload permits. A database would alert NCDOT to companies that frequently violate superload permits, such that the DOT could work with those companies to bring them back into compliance and help protect NC's transportation infrastructure.

Furthermore, a policy change should be considered that would allow NCDOT BMU, at their discretion, to request that a superload truck be weighed before a permit is issued, as in SC and TX. This would require a partnership with the NC SHP, to complete a requested weighing before a superload could be issued a permit. A policy change such as this would require research to determine tolerances from estimated axle weights that could be allowed that would not require a new bridge study be completed, such that loads would not be unnecessarily delayed. The proposed change would allow BMU to have a better piece of mind when approving superloads that are approaching bridge safety limits and better protect NC's infrastructure.

The NCSU team recommends several changes regarding the current permitting process for superloads crossing bridges:

- Where a superload is wider than a standard lane, current NCDOT practice entails analyzing only one lane's width of the vehicle. It is recommended that the entire superload be analyzed, to lessen any chances of underestimating moment demands.
- Where possible, superloads should be limited to travelling the centerline of a bridge to prevent overloading external girders.
- If a superload is wide enough to have axles extend over the external girders, it is recommended that the superload be re-routed along a wider bridge, or a more detailed analysis performed to prevent overloading external girders.
- When a superload vehicle has optional wheel-dollies or expandable axles that extend their axle-line width (and distributed their load over a wider area), it is recommended that they be required to do so when crossing a bridge. In cases where this extra width places wheels over the external girders, The NCSU team defers judgment to the discretion of NCDOT OSOW as to how to proceed.

Additionally, it is recommended that additional research be performed with a wider range of superload vehicles and a set of representative bridges to allow for the statistical quantification of the validity of NCDOT's current permitting process.

The NCDOT software, PERM6, has been expanded to allow for vehicles with up to 50 axles. This will likely become necessary as superload vehicles continue to grow in size to accommodate increased payload weights. The program functions the same as its predecessor, with an increased capacity.

Recommendations have been made regarding the current superload permit approval process for the NCDOT PMU:

- AASHTO equivalency factors for converting axle loads to ESALs were inadequate for use with superloads and thus should not be used by PMU.
- ESALs based on measured weights are close to or less than ESALs based on estimated weights. Therefore, for superload permit approval, using carrier estimates would provide a reasonable basis for analysis.
- The charts developed by Jooste and Fernando for TxDOT to determine maximum wheel loads for superload trucks to reduce the risk of rapid shear failure of pavements should be used in the PMU superload application approval process.
- It is recommended that the PMU adopt the TxDOT policy of not allowing superloads to use roads that have seal coats younger than five weeks if other routing is possible. If other routing is not possible then the carrier should be required to mat the road to protect the seal coat from damage.

The pavement analysis of this study focused on a single pavement structure with a set of assumed material properties for modeling. Further research is recommended to assess the impacts of superloads on several different pavement structures and to determine the sensitivity of pavement impact predictions to material properties. Furthermore, field-testing is needed to measure pavement responses under a superload truck to verify modeling predictions.

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CHAPTER 1. INTRODUCTION

This chapter will introduce the research project starting with the background and definition of need for the project. This will be followed by a literature review defining “superload” and giving an overview of permitting requirements and procedures for NC and several peer states. Next, the scope and objectives of the study will be discussed, including the selected vehicle configurations. Finally, an overview of the organization of the report is covered.

1.1 Background and Definition of Need

NCDOT Research Problem Statement No. 2403 addresses the need for basic data and analysis on the relationship between the axle load distributions of commercial vehicles with different axle configurations that are required to obtain a superload permit to operate on state highways. The distance between axles and/or axle combinations and the overall number of axles are critical in terms of mediating the impact of the weight on structures and pavements. Permit applicants commonly assume the weight of the load to be equally distributed across the bed of the trailer to each axle, even in instances where the load is confined to a limited portion of the trailer and/or the load is not a uniform mass. Such estimates strongly depend on the assumed stiffness, geometry, and lateral and longitudinal orientation of the truck as it moves. In North Carolina without an overweight permit axle group weights are allowed as follows: single axles up to 20,000 lbs, tandem axles up to 38,000 lbs, and tridem axles up to 48,000 lbs. With these allowances in mind, overweight permitted loads are generally accommodated by slightly higher axle group weights and the addition of more axles to an increasingly long vehicle as shown in Figure 13 to Figure 17.

Figure 13 Progress Energy Portable Transformer.

Figure 14 Guy M. Turner Dual-Lane Drop-Deck Gooseneck.

Figure 15 Guy M. Turner Truck-Towed Singlewide Modular.[12]

Figure 16 Guy M. Turner Self-propelled Doublewide Modular.[13]

Figure 17 Guy M. Turner Self-Propelled Modular with Outriggers.[14]

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[12] Picture courtesy of Progress Energy
[13] Picture Source: NCDOT

Currently, the gross weight limit on Interstate highways (without a special permit) is 80,000 pounds. Super heavy trucks with weights up to 1 million pounds far exceed typical truck weights, and NCDOT Bridge Management engineers have concerns about the super heavy trucks exceeding the design limits of bridge structures. Bridges with deficiency ratings may be particularly at risk. Bridge data for North Carolina indicates that approximately 5.2% of National Highway System (NHS) bridges and 14.2% of non-NHS bridges are classified as structurally deficient. An additional 13.3% of NHS bridges and 14.5% of non-NHS bridges are functionally obsolete *(1)*. There is also concern about the long term, "hidden" distress of super heavy vehicles on pavements.

Besides exceeding design specifications on bridges, super heavy vehicles that may use the same roads up to 50 times going to the same construction site (Goldsboro power plant) may cause significant impacts on the ultimate life of the highway pavement and its ride quality. Typically, 50 to 100 super heavy vehicles travel on North Carolina highways each month.

Unit managers of the State Bridge Management Unit, the Overweight/Oversize Permitting Unit, and an officer of the NC State Highway Patrol Size and Weight Enforcement Unit say that the major concern with regard Research Idea 2403 is the increasing number of "superloads" on North Carolina highways. These non-divisible loads may exceed one million pounds, and they are transported by the types of vehicles shown in Figure 13 to Figure 17.

The State Bridge Management Unit is particularly concerned about the accuracy of the estimates of axles loads provided by trucking companies when they apply for overweight permits. NCDOT wishes to confirm the companies' estimates by using scales to acquire field measurements of actual load distributions. NCDOT is concerned that current methods used by companies for calculating individual axle weights underestimate actual weights, thereby resulting in damage to bridges.

Problem Statement 2403 thus questions whether company permit estimates of individual axle weights can be accurately determined by dividing the known total weight of the trailer and load by the number of axles shown in a permit application. Fieldwork and research were completed to directly assess the validity of this assumption, especially in the case of non-symmetric, non-homogeneous loads.

Besides the "static" case of load distribution when the super heavy vehicles are stationary or moving slowly, the Bridge Management Unit is also concerned about the "dynamic" case of load distribution when the vehicles are changing speed and direction. The dynamic case will occur, for example, when the a vehicle starts up, when the vehicle changes the traction forces and geometry of the independently controlled axles, when the load and its center of gravity shift relative to the trailer, when the vehicle changes direction on turns, and when the vehicle crosses bridges including short "jumper" or "carrier" bridges over buried utilities and culverts. Due to complications of collecting dynamic loading axle weight data this was deemed to be out of scope for this project and will not be addressed.

As a result of this research regarding the load distribution of super heavy vehicles and the resulting forces on pavements and bridges, the NCDOT will be able to move forward with confidence when permits are authorized and issued.

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[14] Picture Source: http://www.guymturner.com

1.2 Literature Review

1.2.1 Superload Definition and Current Permitting Process

The Federal Highway Administration defines legal truck axle weight limits for the National System of Interstate and Defense Highways as:

- 80,000 pound Gross Weight
- 20,000 pound Single Axle Weight
- 34,000 pound Tandem Axle Weight (17,000 pounds per axle)
- Axle spacing adheres to the bridge weight formula

However, a truck is allowed to exceed these limits with a permit if it is carrying a load that is non-divisible. To be considered a non-divisible load it must meet FHWA guidelines such that the load cannot be dismantled in eight man-hours or such a reduction would destroy the value of the load. The FHWA gives little guidance on the permitting of overweight trucks, leaving it to individual states to regulate trucks that must exceed these normal limits *(4)*. Bilal in *A Synthesis of Overweight Truck Permitting*, found that while legal truck weights are consistent among states due to federal regulations, weight limits for overweight trucks and permitting procedures greatly vary between states. He notes that terms such as superload can have drastically different definitions between states. For example, superload means 120,000 pounds in Indiana and 170,000 pounds in Wisconsin *(5)*.

North Carolina separates overweight permits into three main categories: Annual Permits, Single Trip Permits, and Superload Permits. A Superload Permit is required for every truck operating in North Carolina meeting any or all of the following guidelines:

- Gross weight in excess of 132,000 lbs
- Steer axle weight in excess of 12,000 lbs
- Four- or more axle grouping weight in excess of 60,000 lbs
- Width in excess of 15 ft

A truck meeting these limits must submit a superload permit application as well as a vehicle schematic, showing axle spacing and axle weight distribution of the load to the Oversize/ Overweight Permit Unit (OSOW) at the NCDOT *(1)*. Also included in the superload permit application are the origin and destination of the load and the operator's planned route of travel, such that the NCDOT can analyze the proposed route for any constraints due to bridge loads, bridge clearances, etc. *(2)*.

Once the superload permit application has been submitted OSOW processes the applications in the order received. A summary flow chart of NC OSOW permit processing procedures is provided in Figure 18 on page 6. Initially, OSOW checks applications for completeness, accuracy, and that axle weights are within acceptable ranges. Then it is determined if bridge and pavement studies are required and if so a study request is sent to the respective departments. A bridge study for the proposed route is required for any truck exceeding 160,000 pounds gross weight, 20,000 pounds on any individual axle in a tri-axle group, or crossing any bridge not pre-approved. A list of non-inventoried structures, such as culverts, for the proposed route is required to be obtained from district engineers and sent to the Bridge Management Unit (BMU) for review if the truck exceeds 350,000 pounds gross weight, 26,000 pounds on any individual axle, or is requested by the BMU. A pavement study for the proposed route is required from the Pavement Management Unit (PMU) if requirements are met for a list of non-inventoried structures. After the BMU and PMU have analyzed the proposed route and submitted results from their respective studies, the restrictions from the studies are coordinated, the application is checked to make sure it is otherwise acceptable and is either approved or not approved *(6)*.

Comparatively, the peer states of South Carolina, Georgia, Virginia, and Texas have different superload definitions and procedures than North Carolina. South Carolina separates overweight permits into eight categories and requires a superload permit for trucks weighing over 130,000 pounds *(7)*. Georgia separates overweight permits into two main categories single trip and annual permits. Georgia defines two superload permits, a superload single and a superload plus. The superload single applies to trucks weighing between 150,001 pounds and 180,000 pounds and does not require a bridge analysis. The superload plus applies to trucks weighing over 180,000 pounds and requires a bridge analysis *(8)*. Virginia has a more complex definition of superload requiring a superload single trip or blanket permit for any truck exceeding the requirements for a general single trip or blanket permit. The allowed gross and axle weights are based on the number and spacing of axles. Therefore, the weight at which a superload permit is required depends on the number and spacing of axles *(9)*. Texas uses the term “super heavy” instead of superload, and requires a super heavy permit for any truck shorter than 95 feet and weighing over 200,000 pounds or longer than 95 feet and weighing over 254,300 pounds. Interestingly, Texas requires the super heavy permit applicant to hire a TxDOT approved, independent engineer to conduct a bridge analysis for the requested route *(10)*. A comparison of superload permit requirements by state is shown in Table 4 on page 7.

1.2.2 <u>Monitoring Overweight Permitted Trucks</u>

Besides different definitions of superloads, states also have different procedures to monitor superload permitted trucks. In NC, the monitoring of superload permitted trucks for permit compliance is handled by NC law enforcement, such as the NC SHP. South Carolina reserves the right to require weigh tickets to verify weights supplied on the permit application *(7)*. In a telephone interview with the SC OSOW department, it was noted that they rarely require weight tickets and generally rely on carrier estimates for analysis. Officials at GDOT and the GA Highway Patrol stated that any superload originating in a Georgia port must be weighed by the Highway Patrol before it is allowed to travel. Virginia, like NC, relies on random checks by state police to monitor and enforce superload permit compliance *(9)*. In Texas, TxDOT reserves the right to require that the truck be weighed at the discretion of their Bridge Department *(10)*.

Barron, Jessup, and Casavant reviewed citations for trucks violating overweight permits in Washington State occurring between November 1, 1991 and October 31, 1992. During this period, 189,360 overweight permits were issued and 721 permit violations were recorded. At an estimated capture rate of 10 percent, Barron, Jessup, and Casavant projected that there were 7,210 trucks violating overweight permits within a year. Special Motor Vehicle Permits (SMVP) are issued for non-divisible loads and accounted for 77 percent of the permits issued, but only 15 percent of the violations. The most common violation for the SMVP was exceeding permitted axle weight, which they attribute to the non-divisible nature of the load and the inability of a carrier to estimate axle weights. The average excess axle weight was calculated at 4950 pounds. They surmise that SMVP violations, though lower in number as compared to other overweight permit types, cause a higher percentage of damage to roadways due to heavier axle loads *(11)*.

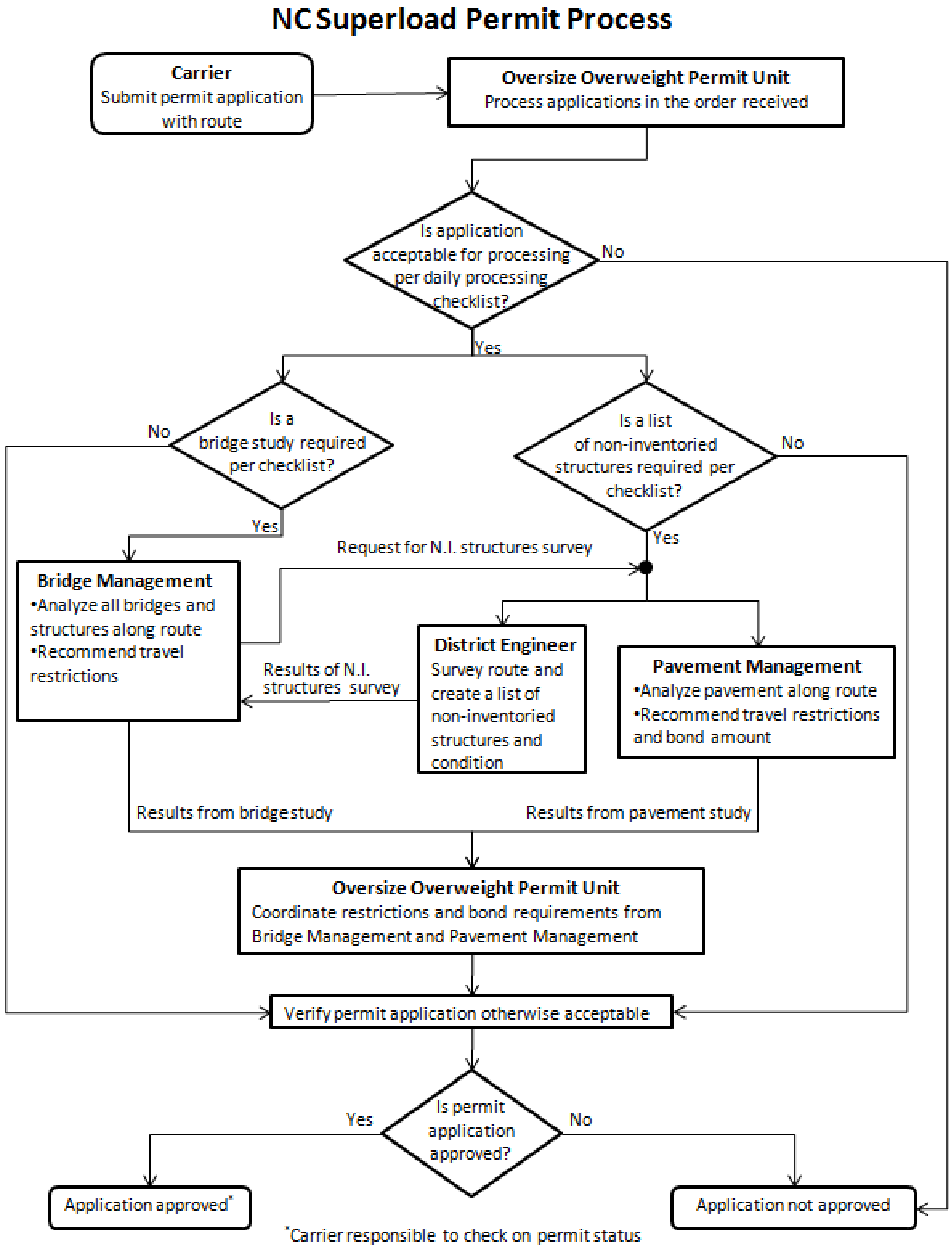


Figure 18 NC Superload Permit Process.

Table 4 Superload Comparison by State

State	Permit Type	Superload Weight	Single Use	Bridge Analysis	Bond/Insurance Required	Weight Checked
NC	Superload	≥132,000 lbs	Yes	Yes	At the Discretion of NCDOT; Carrier responsible for all damages	Random by state troopers
SC	Superload	≥130,000 lbs	Yes	Yes	At the discretion of SCDOT; Required on all loads >180,000 lbs	At the discretion of SCDOT Weigh tickets can be required on State approved scale with state rep observing
GA	Superload Single	≥150,001 & ≤180,000 lbs	Yes	No	Yes, ≥ $300,000	Weighed by GA State HP before movement allowed if originate in port
	Superload Plus	>180,000 lbs	Yes	Yes		
VA	Superload Single	Exceeding Single use permit weight table	Yes	Yes	Liable for damages	Random by state troopers
	Superload Blanket	Exceeding Blanket permit weight table	No	Yes		
TX	Super Heavy	>200,000 lbs if < 95ft; else >254,300 lbs	Yes	Yes, by private engineer hired by applicant	Yes, $10,000	Required at the discretion of TxDOT Bridge Division

Jeff Honfanger et al. review procedures used to monitor permitted overweight trucks in Europe *(11)*. Notably, Slovenia uses portable bridge Weigh-In-Motion units (SiWIM) to monitor "special transport" vehicles (i.e. overweight vehicles that require a permit). These units are used to collect axle loading and axle spacing information to calibrate influence lines for a more accurate analysis of bridges used by special transports. The SiWIM systems are also used to remotely check permit compliance and movements of overweight trucks. Honfanger explains the significance of this technology.

> *The accuracy and portability of bridge WIM systems have the potential to cost effectively generate significantly more field-based weight and load data for pavement, bridge, and asset management than is now generated in the United States. In addition, the unique data applications (i.e., special transport certification and verification) demonstrated in Europe may have merit. Using this technology Slovenia found that greater than 70 percent of the special transports had at least one violation and of those 47 percent were found to be in violation of the allowed permit weights.*

A similar report, *Effective Use of Weigh-In-Motion Data: The Netherlands Case Study*, released by the Federal Highway Administration in 2007, remarks on the use of WIMs in the Netherlands to monitor permitted overweight vehicles. The Transport Inspectorate in the Netherlands uses WIM+VID units that incorporate weigh-in-motion and video units to remotely monitor special transport vehicles and ensure they are operating in compliance with their permits. Using this system the Transport Inspectorate estimates that 40 percent of permitted trucks are in violation of their permits. The system makes it possible to identify carriers that are routinely in violation, which allows the Transport Inspectorate to contact the carriers and help them prevent future violations *(13)*.

1.3 Research Scope and Objectives

1.3.1 Scope

This project focuses on super heavy trucks with a GVW greater than 132,000 points, which are classified as superloads according to NCDOT practice. Five superload truck configurations have been selected for this study and are defined and detailed in section 1.4. Due to time limitations for the project and limited availability of opportunities to collect first-hand field measured weight data on the selected superload truck configurations, data was supplemented with alternative sources of field measured weight data such as the NC SHP and GDOT. Collecting weight data on the dynamic loading conditions of these trucks was deemed out of the project scope; therefore, this study will only address static loading conditions.

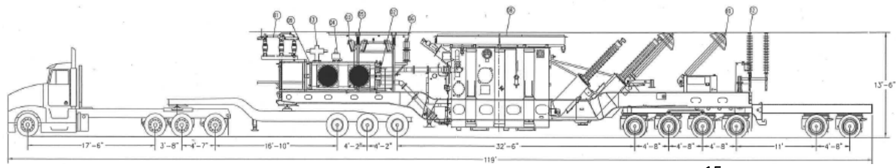
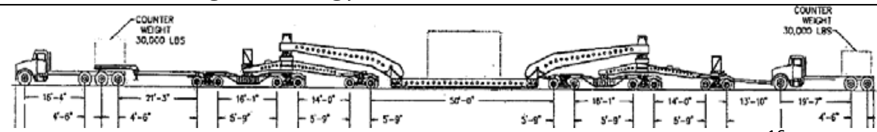
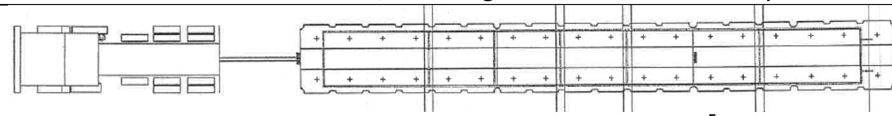
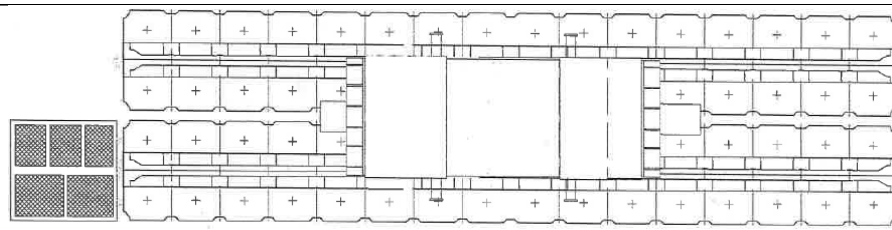
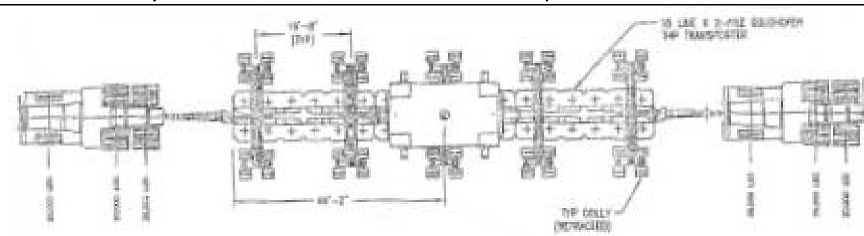
1.3.2 Objectives

The primary objective of this project is (1) to collect axle load measurements of super heavy vehicles and to validate company estimates of axle loads presented to NCDOT with overweight vehicle permit applications. Secondary goals of the project are: (2) to apply standard AASHTO design practices to superloads and prestressed precast concrete (PPC) slab-on-girder bridge superstructures, to generalize superload demands and to evaluate the accuracy of NCDOT BMU's current superload vetting process for bridge superstructures; and (3) to estimate the impacts of super heavy vehicles on long term pavement performance.

1.4 Representative Vehicle Configurations

Commercial carriers that haul superloads use specialized equipment that varies greatly in length, width, height, and axle configuration in order to accommodate the irregular size and weight of non-divisible superloads. Therefore, a general classification system for superload truck configurations was developed to allow for trucks of similar configurations to be grouped together based on general truck characteristics and weight distribution methods. This classification system was developed by reviewing truck schematic drawings supplied by NCDOT, GDOT, Progress Energy, and Guy M. Turner and by reviewing equipment listings on websites of specialized carriers that operate in NC. Five main superload truck configurations were identified for this study, shown in Table 5 on page 9. It should be noted that this classification system with these five general vehicle configurations is by no means meant to be exhaustive of all possible superload truck configurations. These configurations were identified as common superload configurations in NC and were selected for this study.

Table 5 Superload Truck Configurations

Config. Number	Config. Name	Example
1	Truck-Jeep-Trailer-Stinger	 Progress Energy 13 Axle Mobile Transformer[15]
2	Drop-Deck Gooseneck	 19-Axle-Line Dual Lane, NC Weight Citation, Polk County[16]
3	Singlewide Modular	 Crane Rental 21-Axle-Line Towed Goldhofer[5]
4	Doublewide Modular	 Guy M. Turner 16-Axle-Line Self-Propelled Goldhofer[16]
5	Modular With Outriggers	 Barnhart 24-Axle-Line Towed Goldhofer with Dollies[16]

1.4.1 <u>Configuration 1: Truck-Jeep-Trailer-Stinger</u>

This configuration most closely resembles a standard tractor-trailer and consists of a truck-tractor, a jeep, a semitrailer, and/or a stinger dolly. The jeep and the stinger dolly are optional for this configuration resulting in four possible unit combinations for this classification.

- *Truck-Jeep-Trailer-Stinger*
- *Truck-Jeep-Trailer*
- *Truck-Trailer-Stinger*
- *Truck-Trailer*

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[15] Source: Progress Energy
[16] Source: NCDOT

This configuration most commonly has only one axle per axle-line, while number of axles, axle spacing, length, and width vary for each truck.

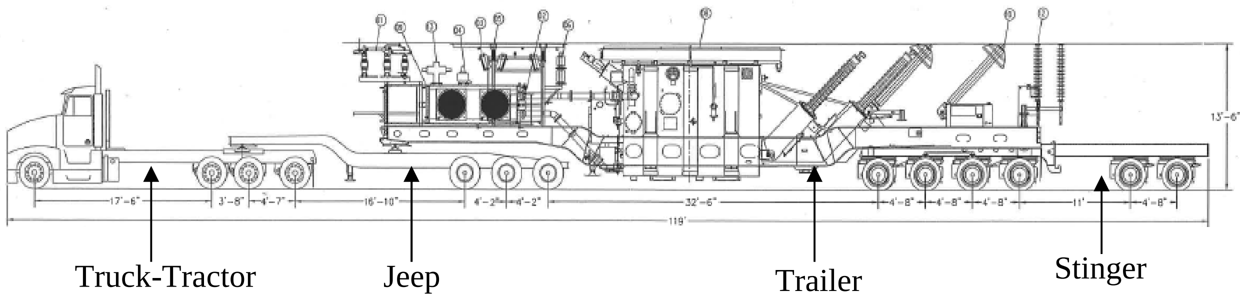

Figure 19 Configuration 1 Truck Components.

1.4.2 Configuration 2: Drop-Deck Gooseneck

This configuration consists of a trailer with drop-deck load platform suspended between sets of axle groups. Weight is distributed from the load platform to the axle groups through a series of gooseneck bridges. This configuration has one or more truck-tractors acting as “pull trucks” and can have one or more truck-tractors acting as “push trucks.”

There are two main categories for this configuration: a “dual-lane” configuration and a “single-lane” configuration. The dual-lane configuration has axle-lines consisting of two axles where the lateral space between axles can typically be hydraulically adjusted, as shown in Figure 20. The single lane configuration has axle-lines consisting of only one axle with a fixed width.

The number of truck-tractors propelling the unit, number of axles, axle spacing, length, and width vary per individual truck configuration.

Figure 20 Example of Configuration 2 Dual-Lane Adjustable Axle-Line Width Trailer.

1.4.3 Configuration 3: Singlewide Modular

This configuration consists of a trailer comprised of modular units that can be attached together longitudinally. Each axle is hydraulically suspended and axles are grouped together to form three or four-point suspension groups. The height of individual axles can be adjusted to keep the unit level. It can be towed and/or pushed by a truck-tractor or be self-propelled. Each modular unit has two axles per axle-line. This configuration generally has equally spaced axle-lines, though the number of axles and length vary per individual truck configuration.

Figure 21 Example of Hydraulic Axle Suspension.[17]

1.4.4   Configuration 4: Doublewide Modular

This configuration consists of a trailer comprised of modular units that can be attached together longitudinally and laterally. Each axle is hydraulically suspended and axles are grouped together to form three or four point suspension groups. The height of individual axles can be adjusted to keep the unit level. It can be towed and/or pushed by a truck-tractor or self-propelled. Each individual modular unit has two axles per axle-line and thus with a doublewide configuration there are four axles per axle-line. This configuration generally has equally spaced axle-lines, though the number of axles and overall vehicle length vary per individual truck configuration.

Figure 22 Example of Axle Height Adjustment over a Jumper Bridge.[18]

1.4.5   Configuration 5: Modular with Outriggers

This configuration consists of a trailer comprised of modular units that can be attached together longitudinally with extra tandem axles attached to the unit with I-beams. Each axle is hydraulically suspended and axles are grouped together to form three or four point suspension groups. The height of individual axles can be adjusted to keep the unit level. It can be towed and/or pushed by a truck-tractor or be self-propelled. Each individual modular unit has two axles per axle-line except for the axle-lines where outriggers are positioned; these axles-lines typically

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[17] Picture Source: Progress Energy
[18] Picture Source: NCDOT

have four axles per axle-line. This configuration generally has equally spaced axle-lines, though the number of axles and overall vehicle length may vary per individual truck configuration.

Figure 23 Example of an Outrigger Attached to a Modular Unit.[19]

1.5 Report Organization

CHAPTER 1 of this report defines the NCDOT needs and issues related to the research problem, the research scope, and objectives. Current policies defining superload trucks and their permit procedures in NC and several peer states are also discussed. Definitions of the superload truck configurations selected for this study are also provided.

CHAPTER 2 of this report provides an overview of weight distribution technology and data collection methods. The weight distribution data, its source, and a discussion of its limitations are presented for each truck as well as an analysis of the observed weight distribution.

CHAPTER 3 of this report reviews literature relevant to the effects of superloads on bridge superstructures, discusses the analysis method used, and provides results. Finally, conclusions are presented and recommendations are made regarding NCDOT's current permitting process for superloads crossing bridges.

CHAPTER 4 of this report reviews applicable superload pavement impact literature and covers the pavement impact approach and analysis for an example truck for each superload configuration. Finally, conclusions are presented and recommendations are made regarding supplementing NCDOT PMU's current approval process for superload applications.

The following section includes explanations of tasks included in the project proposal and where they are addressed in this document.

Task 1: Conduct a kick-off meeting of all stakeholders to review the research objectives, refine the tasks, confirm expectations, discuss potential problems, and define the detailed schedule.

- The meeting with NCDOT BMU, OSOW, and PMU resulted in the discussion and revision of the proposed project. The attendees discussed avenues for acquiring superload data and later investigated the NCSU team. The results of the kick-off meeting are reflected throughout the report.

[19] Picture Source: http://www.guymturner.com

Task 2: Review relevant literature regarding: case study impacts of oversize/overweight trucks on bridges and pavements with special emphasis on super heavy vehicles; and methods of weighing superload vehicles. Review the current NCDOT permitting process and AASHTO LFD analysis guidelines.

- There is no single chapter that contains all the literature reviews for this research. Instead, each chapter contains its own applicable literature review.

Task 3: Select representative superload vehicle configurations, such as, hauling rig axle configurations and spacings, and that are defined by the available permit data.

- This task is addressed in Chapter 1, section 1.4.
- A general superload vehicle configuration classification system was created for this study based on general weight distribution methods and truck styles.
- This study focuses on five superload configurations identified.

Task 4: Design a replicable process of measuring a range of representative loads on one or more of vehicle configurations.

- This task is addressed in Chapter 2, section 2.2.
- Due to limited opportunities to collect firsthand data, the data was supplemented with previously recorded weight data provided by the NC SHP and GDOT.
- NC SHP methods were used for weighing two Progress Energy superloads, closely corresponding to methods used in the supplemental data from the NC SHP and GDOT.
- A method of weighing outside wheel groups only was used for weighing two Guy M. Turner singlewide modular units. Each wheel group across each axle was not weighed due to safety concerns of placing and reading scales under these low units.

Task 4a: Analyze collected weight data with respect to carrier-estimated weights supplied on superload permits.

- This task is addressed in Chapter 2, section 2.3.
- Weight data was collected for a total of 20 superload trucks: 14 examples of configuration 1, four examples of configuration 2, and two examples of configuration 3. There was no data available or weighing opportunities for configuration 4 or 5 trucks during the project.

Task 5: Use current AASHTO design guidelines to analyze a vehicle load meant to model the effects of exclusion vehicles (which are heavy, overloaded vehicles consistent with the subject of this proposal and compare these demands with those of the selected representative superloads.

- This task is addressed in Chapter 3 of this report.
- Weight data for five basic superload types with two alternative arrangements were analyzed crossing plane-grillage models of 116 prestressed precast concrete girder bridges of various physical geometries and material properties. Single span bridges varied a large number of properties while multiple span bridges focused on the effects of multiple spans and their ratio of span lengths. One and two lane bridges were created and analyzed for each case.
- Results include moment demands for critical points on the bridge: positive moments between bridge bents, and negative moments over bents. These values were gathered across selected girders.

- From the moment demands, maximum HS-equivalent ratings were calculated for each superload vehicle's crossing of each bridge model. Ratios of conservatism were created to compare the more accurate plane-grillage models' results to the HS-equivalent ratings predicted by the current NCDOT program, PERM6.

Task 6: Assess pavement distress of super heavy vehicles and comparison to mechanistic-empirical design software estimates or estimates from other methods.

- This task is addressed in Chapter 4 of this report.
- Pavement impacts were estimated for an example truck from each superload configuration type in terms of ESALs and equivalent number of standard 80-kip trucks.
- Finally, conclusions and recommendations for the NCDOT PMU are made

Task 7: Document the project with quarterly reports and the final report.

- This report constitutes the final documentation of the project.

CHAPTER 2. SUPERLOAD WEIGHT DISTRIBUTION

This chapter will cover the weight distribution characteristics for the five superload configurations identified for use in this study. The organization of this chapter is as follows: a discussion of the background and problem, a discussion of the scope and objectives, a literature review of weight distribution technology, a discussion of weight data collection methods and sources, presentation of data and analysis of weight distribution characteristics, and lastly conclusions drawn from the data.

2.1 Background and Problem Definition

NCDOT Research Problem Statement No. 2403 addresses the need for basic data and analysis on the relationship between the axle load distributions of commercial vehicles with different axle configurations that are required to obtain a superload permit to operate on North Carolina highways. The distance between axles and/or axle combinations and the overall number of axles are critical in terms of mediating the impact of the weight on structures and pavements. Permit applicants commonly assume the weight of the load to be equally distributed across the bed of the trailer to each axle, even in instances where the load is confined to a limited portion of the trailer and/or the load is not a uniform mass. Such estimates strongly depend on the assumed stiffness, geometry, and lateral and longitudinal orientation of the truck as it moves.

The State Bridge Management Unit is particularly concerned about the accuracy of the estimates of axles loads provided by trucking companies when they apply for overweight permits. NCDOT wishes to validate the companies' estimates by using scales to acquire field measurements of actual load distributions. NCDOT is concerned that current methods for calculating individual axle weights underestimate actual weights, thereby resulting in damage to bridges. Thus, NCDOT questions whether or not estimates of individual axle weights can be accurately determined by simply dividing the known weight of the trailer plus load by the number of axles. Fieldwork and research were completed to directly verify (or not) this assumption, especially in the case of non-symmetric, non-homogeneous loads.

2.2 Objectives and Scope

This chapter will focus on super heavy trucks that meet the NC gross weight requirement for trucks to be classified as superloads, gross weight in excess of 132,000 pounds. Five superload truck configurations were selected for this study and are defined and detailed in section 1.4. Due to time limitations for the project and limited availability of opportunities to collect first hand field measured weight data on some superload truck configurations, the data was supplemented with alternative sources of field measured weight data such as the NC SHP and GDOT. The objective of this chapter is to collect axle load measurements of super heavy vehicles and to validate company estimates of axle loads presented to NCDOT with overweight vehicle permit applications

2.3 Literature Review: Weight Distribution Technology

This section will review applicable literature for weight distribution technology for the specialized equipment discussed in the previous section. For simplicity, configurations 1 and 2 will be discussed together and configurations 3, 4, and 5 will be discussed together due to similarities in weight distribution technology employed in these configurations.

2.3.1 Configuration 1 and 2

One form of technology used for weight distribution with these configurations is a lift axle on one or more of the truck-tractors. This is an extra axle located either in front of or behind the drive axles that has the ability to be lowered when extra weight distribution is required due to a heavy load. Hendrickson, an industry leader in lift axles, states on their website that a lift axle is generally mechanically lowered using compressed air. This type of axle may be manually controlled by the driver or employ a kit to automatically equalize weight with adjacent axles. The weight capacity of a lift axle depends on its design (14). Koehne and Mahoney, in a report for the Washington State Department of Transportation, note that most lift axles are controlled by the driver and improper deployment can cause the axle to carry too much weight and be overloaded or not enough weight overloading adjacent axles. They also comment that uneven terrain can cause the weight distribution to change (15).

Another technology used for weight distribution is air ride suspension. Our project partner Guy M. Turner, Inc. utilizes several trailers manufactured by Trail King Industries and a review of Trail King's trailer literature reveals that their specialized heavy haul trailers have air ride suspensions. The air ride suspension on some of the trucks can be raised and lowered to help keep the load level, which helps maintain equal load distribution (16). O'Connell, Abbo, and Hedrick, in their paper *Analyses of Moving Dynamic Loads on Highway Pavements: Part I – Vehicle Response,* explain that air ride suspensions for multi-axle groups have connections between air bags that helps maintain equal loading of the axles in that group. They also found in their research that air ride suspensions were the least damaging type of suspension to pavements (17).

Configuration 1 trucks often employ a stinger dolly, or booster axle assembly, which is a frame with one or more axles that attaches to the back of a trailer to further distribute weight. Design of these assemblies varies but most commonly, weight transfer to the stinger assembly is achieved using hydraulics or mechanical air (18).

Configuration 2 trucks employ the use of hydraulic leveling at the front and rear goosenecks, with hydraulic "hatboxes." These hatboxes are located between the main gooseneck from the load platform and the bridges between the axle groups (16). Keeping the load level is essential to weight distribution in these specialized trucks. The doublewide version of configuration 1 also employs axle-lines that have an adjustable width. The adjustment is achieved using tubular frames and hydraulics that can slide the axles in an axle-line in or out (16). The use of adjustable axle-line widths allows the truck to change its footprint and spread out the contact points with the pavement or bridge.

2.3.2 Configuration 3, 4, and 5

These configurations employ the use of modular units that can be assembled in a variety of ways to form a range of shapes. Our project partner Guy M. Turner, Inc., said that the leader in the industry for modular trailers is a company in Germany, Goldhofer AG. Literature available on their website was reviewed and a follow up letter was sent to their United States representative, Stefan Kohler, for further explanation of the methods employed for weight distribution for their modular units.

Literature available from Goldhofer shows their modular units to have a frame with a box-shaped center beam with crossbeams for high rigidity and a reinforced loading deck with a high bending moment to handle concentrated loads. The modular units are attached using a bolt-plate coupling system. Each axle is hydraulically suspended and the height of individual axles can be adjusted to maintain a level loading surface over uneven terrain and keep the center of gravity of the load over the center of the trailer, see Figure 24 and Figure 25. The hydraulics of the axles can be coupled together in groups to maintain equal load distribution (19).

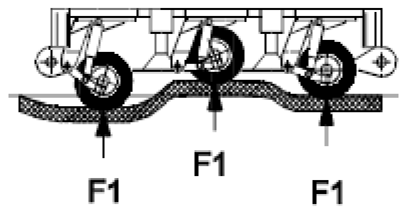

Figure 24 Longitudinal Axle Compensation.[20]

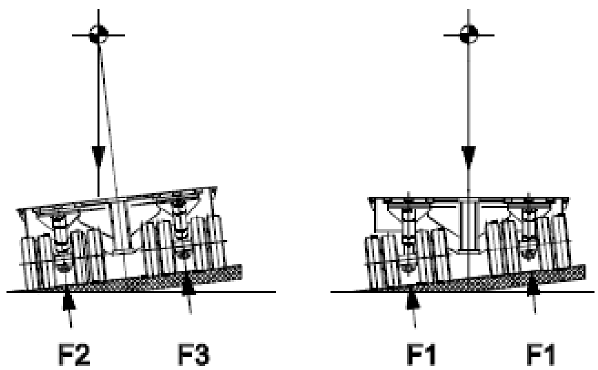

Figure 25 Lateral Axle Compensation.[20]

The NCSU team contacted Stefan Kohler with Goldhofer, and he further explained how Goldhofer modular units maintain an equal load distribution to each axle. He said that the weight is primarily distributed using the hydraulic suspension of each axle. The hydraulic cylinders can be linked causing the hydraulic pressure (and load) for each cylinder to equalize. However, he points out that linking every cylinder would lead to a single point and therefore be equivalent to trying to balance a plate on a sphere, see Figure 26, below. This would be highly unstable, so a three or four point suspension triangle or rectangle is preferred. The axles are separated into three or four groups with the hydraulics of each axle in a group linked. Any more than four groups would lead to forces and loads in the trailer which are not calculable. Goldhofer recommends using a three-point suspension for easier operation.

[20] Source: (20).

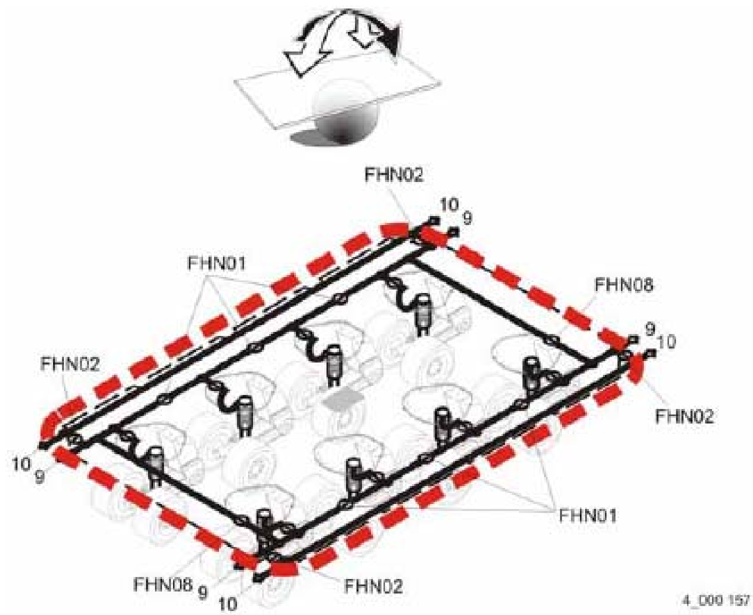

Figure 26 All Hydraulic Cylinders Linked.[21]

Kohler said that in a three-point suspension arrangement, the hydraulics form three support circuits that give the vehicle the stability behavior similar to that of balancing a plate on three spheres. As long as the center of gravity of the load is within the surface created by the support circuits the load cannot tilt. For an equal weight distribution to each axle with this type of set up it is essential that the center of gravity of the load be placed directly over the center of rigidity of the trailer. If the center of gravity of the load is offset, it will cause an unequal distribution of weight to the axles. Four-point suspension set-ups are also possible, but due to the possibility of torsion forming between groups, they are not recommended.

Kohler also points out that Goldhofer modular units employ a stiff center spine and mechanical couplings between units to ensure sufficient mechanical stability to transfer load. He notes that Goldhofer provides technical specifications for each unit and that the modular units must be used within their specified ratings. Longer module groupings cause larger bending moments in the center spine. For compact loads, the stiffness of the center spine can often be the limiting factor in capacity for a unit.

2.4 Data Collection Methodology

To collect field weight data for superload trucks the team partnered with the NC SHP. The NC SHP has a systematic process of using portable PAT scales shown in Figure 27 below, for weighing conventional tractor-trailer trucks with axles of four tires each. The portable scales used by the NC SHP have a maximum capacity of 20,000 pounds each, and they measure loads in increments of 20 pounds with an error of ± 2%. They are tested and calibrated at least every six months by a trained scale technician. The tires of a conventional truck have a relatively large diameter and troopers place scales under each tire or pair of tires. The SHP conducted an internal study of best practices for weighing trucks using portable scales in cooperation with the NC Department of Agriculture. This study is unpublished, but the NC SHP provided the research

[21] Image Courtesy Goldhofer AG

team a copy for review. In the study, four trucks with different axle grouping configurations were weighed on a permanent platform scale, a mobile scale, and PAT wheel load scales. The platform scale is considered the most accurate and the weights from different methods of using the portable scales were compared to the platform scale. The NC SHP has found the following method is the most accurate for weighing trucks with portable scales.

For single and tandem axle groupings, the entire group is weighed at one time. For tridem and greater axle groupings the SHP uses a "rocking" method - one side of the group is weighed and then the other side of the group is weighed (21). It is unclear if the results of this study can be extrapolated to the non-standard configurations of superload trucks in this study. Despite this uncertainty, NC SHP applied their standard procedures at the Garner Progress Energy field visit to weigh two transformer trucks. These procedures were also used when checking permitted weights and issuing citations on the highway, though for citations it is NC SHP policy to round weights down to the nearest 100 pounds due to possible scale variances.

Figure 27 PAT Scale Used by NC SHP.

Modular superload trucks (Configurations 3, 4, and 5) can have as many as four axles in a line laterally across a trailer. There may also be more than 18 lines of axles carrying relatively small diameter tires. Because it is dangerous to crawl under a low super load truck to place and read scales, scales were only placed and read on the outer pair of tires. Depending on the drive unit (towed, not self-propelled), the front line of axles may also be readable. This weighing method was also used for the two Guy M. Turner Goldhofer units at Shearon Harris power plant. The NC SHP was not able to assist with these weighings and the Haynie scales used were provided by Guy M. Turner. The accuracy and calibration of these scales is unknown.

Due to complications with arranging to weigh trucks in the field, supplemental weight data was assembled from several other sources (GDOT and NC SHP citations) that use weighing procedures similar to those described above.

GDOT provided a spreadsheet of seven superloads weighed by the GA SHP. The spreadsheet included permitted and measured axle weights and axle spacings. A sample truck schematic was sent to show the typical truck configurations in the spreadsheet but schematics for each truck were not available. GDOT said that their policy at the Port of Savannah requires permitted superload trucks to be weighed before leaving the Port. GDOT provided several superload permits for trucks originating at the Port of Savannah. The trucks were weighed by the GA SHP before the permit was issued; therefore, the permits reflected actual axle weights.

The NC SHP provided a citation of a superload truck that was weighed due to a permit violation. This data was cross-referenced with the superload permit from NCDOT. The NC SHP also provided a spreadsheet of the weight data from weight citations for ten superload trucks. Only five of these were used for analysis in this study because permits could not be found for four of the citations and without the permits, the truck configurations could not be determined. One of the remaining six citations was eliminated because of a transcription error that invalidated the data.

2.5 Weight Distribution Data and Analysis

This section will review the weight data gathered and analysis for each superload configuration. It is organized by superload configuration and will cover the data source, limitations of the data, and subsequent analysis.

2.5.1 Configuration 1: Truck-Jeep-Trailer-Stinger

The superload configuration 1, truck-jeep-trailer-stinger style trucks, is the closest configuration to a standard tractor-trailer. Such configuration 1 trucks have a lower weight capacity than any other superload truck configuration, and they are generally used to carry the lower weight range of superloads from approximately 132,000 up to 260,000 pounds. Data was gathered for 14 configuration 1 trucks from various sources. Weight data was collected on two trucks owned by Progress Energy through field weighs at the Garner Progress Energy facility with the cooperation of the NC SHP. NC SHP also provided citation weight data for five trucks. Weight data for the final seven trucks of this configuration was provided by GDOT. The data and subsequent analysis for each of these trucks will be discussed below.

2.5.1.1 Progress Energy Portable Transformers

In March 2012, the NCSU team was invited to Progress Energy's Garner facility to weigh two portable transformers used throughout the state during emergencies and for equipment maintenance. The first truck was a 10-axle truck-jeep-trailer configuration and the second was a 13-axle truck-jeep-trailer-stinger configuration. Both trucks were weighed by the NC SHP using their standard methods. A previously used superload permit was obtained for the 13-axle transformer truck for comparison to the measured weights, but a permit example for the 10-axle truck was unavailable. Each truck was weighed twice, once weighing axle groups of three or more at one time and then once using the SHP's standard weighing practice of "rocking" axle groupings of three or more. The trucks were weighed on site at the Garner Progress Energy facility on a relatively level paved surface.

Figure 28 Progress Energy 10-Axle Portable Transformer.

The 10-axle portable transformer, shown in Figure 28 above, had a malfunction with the lift axle (axle 2) during the weighing. There was difficulty in keeping the lift axle engaged, which led to the axle carrying significantly less weight than the adjacent drive axles (axles 3 and 4). This affects the weight distribution observed. Also, no permit was available for this truck, leading to a limited analysis without estimated weights for comparison. Included on page 21 is a table containing the two weighing trials and a graph of the weights. Trial 2 is thought to be the most accurate, having been performed using NC SHP standard methods.

As can be seen in Figure 29 on page 22, the weight distribution of the 10-axle transformer is not uniform. This is likely due to the non-uniform transformer's load being unevenly distributed along the length of the trailer. The weight in a single axle group seems to be relatively uniform on this truck. Axles 5, 6, and 7 had a range of 1120 and 1560 pounds for trials 1 and 2 respectively and axles 8, 9, and 10 had a range of 1200 and 400 pounds for trials 1 and 2 respectively. The axle group containing axles 2, 3, and 4 had a range of 4940 and 7320 pounds for trials 1 and 2, respectively. As previously mentioned, the lift axle (axle 2) was malfunctioning; therefore, likely reducing the load it was carrying. This helps to explain the high range for axle weights in this axle group. The weight carried by axle groups increases from front to back on the truck, following the shape of the transformer. This raises the question as to whether the trailer is "distributing" the load, or simply "carrying" the load placed above a respective axle group.

Table 6 Progress Energy 10-Axle Transformer Weight Data

Trial 1	
Weigh Entire Axle group	
Axle	Measured Weight (lbs)
1	10,160
2	7,960
3	12,600
4	12,900
5	16,280
6	15,160
7	15,320
8	20,380
9	19,180
10	19,800
Gross	149,740

Trial 2	
Rocking Truck Left to Right	
Axle	Measured Weight (lbs)
1	10,160
2	6,840
3	14,160
4	13,680
5	17,300
6	15,740
7	15,900
8	19,980
9	19,580
10	19,760
Gross	153,100

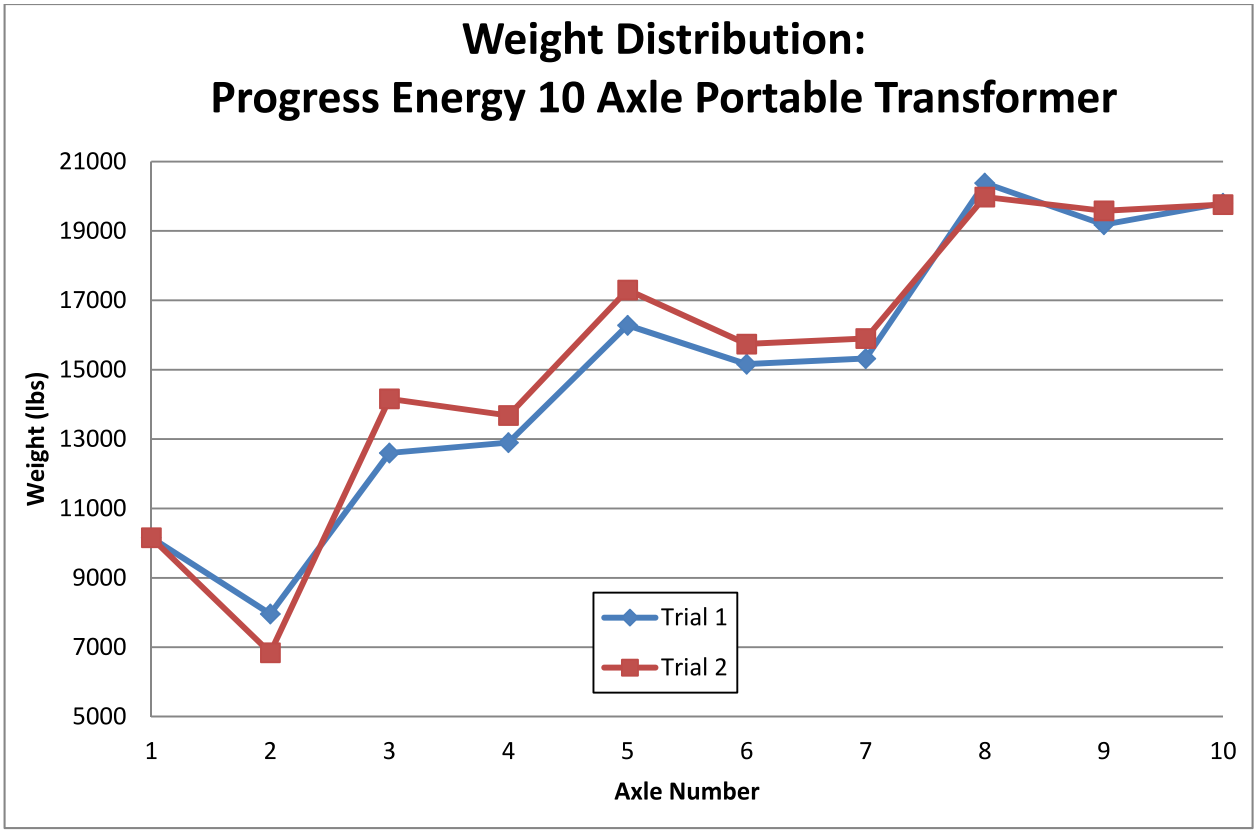

Figure 29 Progress Energy 10-Axle Transformer Weight Distribution.

The 13-axle portable transformer, shown below in Figure 30 and Figure 31, had a malfunction with the lift axle (axle 2) during the weighing. There was difficulty in keeping the lift axle engaged, which led to the axle carrying significantly less weight than the adjacent drive axles (axles 3 and 4). This affects the weight distribution observed.

Figure 30 Progress Energy 13-Axle Portable Transformer.

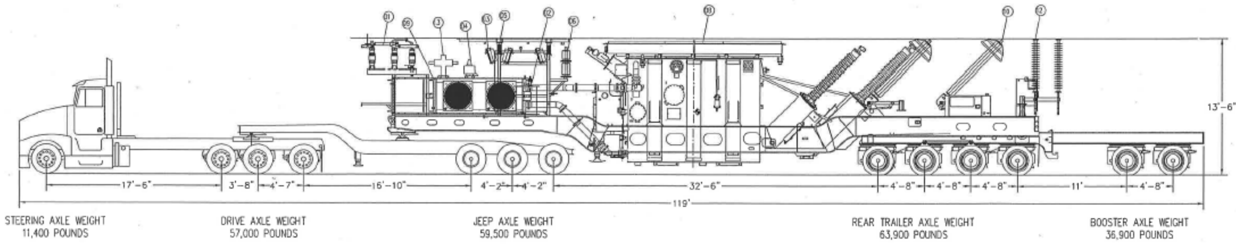

Figure 31 Progress Energy 13-Axle Portable Transformer Schematic.[22]

To analyze the weight data of the 13-axle transformer the measured weights were compared to the permit weights in a table for each trial and then both trials were graphed with the permit weights, shown below.

Table 7 13-Axle Transformer Weight Data, Trial 1

Trial 1: Weigh Entire Axle group					
Axle	Axle-Line Spacing From #13 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference from Permit	
1	113.08	11400	13880	2480	21.8
2	95.58	19000	12180	-6820	-35.9
3	91.92	19000	21020	2020	10.6
4	87.33	19000	20540	1540	8.1
5	70.50	19834	20160	326	1.6
6	66.33	19833	18640	-1193	-6.0
7	62.17	19833	17980	-1853	-9.3
8	29.67	15975	16920	945	5.9
9	25.00	15975	16160	185	1.2
10	20.33	15975	15780	-195	-1.2
11	15.67	15975	17040	1065	6.7
12	4.67	18450	18540	90	0.5
13	0.00	18450	17680	-770	-4.2
Gross		228700	226520	-2180	-1.0

[22] Source: Progress Energy

Table 8 13-Axle Transformer, Trial 2

Trial 2: Rocking Truck Left to Right					
Axle	Axle-Line Spacing From #13 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference from Permit	
1	113.08	11400	13880	2480	21.8
2	95.58	19000	11800	-7200	-37.9
3	91.92	19000	21540	2540	13.4
4	87.33	19000	20720	1720	9.1
5	70.50	19834	21300	1466	7.4
6	66.33	19833	19020	-813	-4.1
7	62.17	19833	17520	-2313	-11.7
8	29.67	15975	16920	945	5.9
9	25.00	15975	16160	185	1.2
10	20.33	15975	15720	-255	-1.6
11	15.67	15975	17040	1065	6.7
12	4.67	18450	18540	90	0.5
13	0.00	18450	17680	-770	-4.2
Gross		228700	227840	-860	-0.4

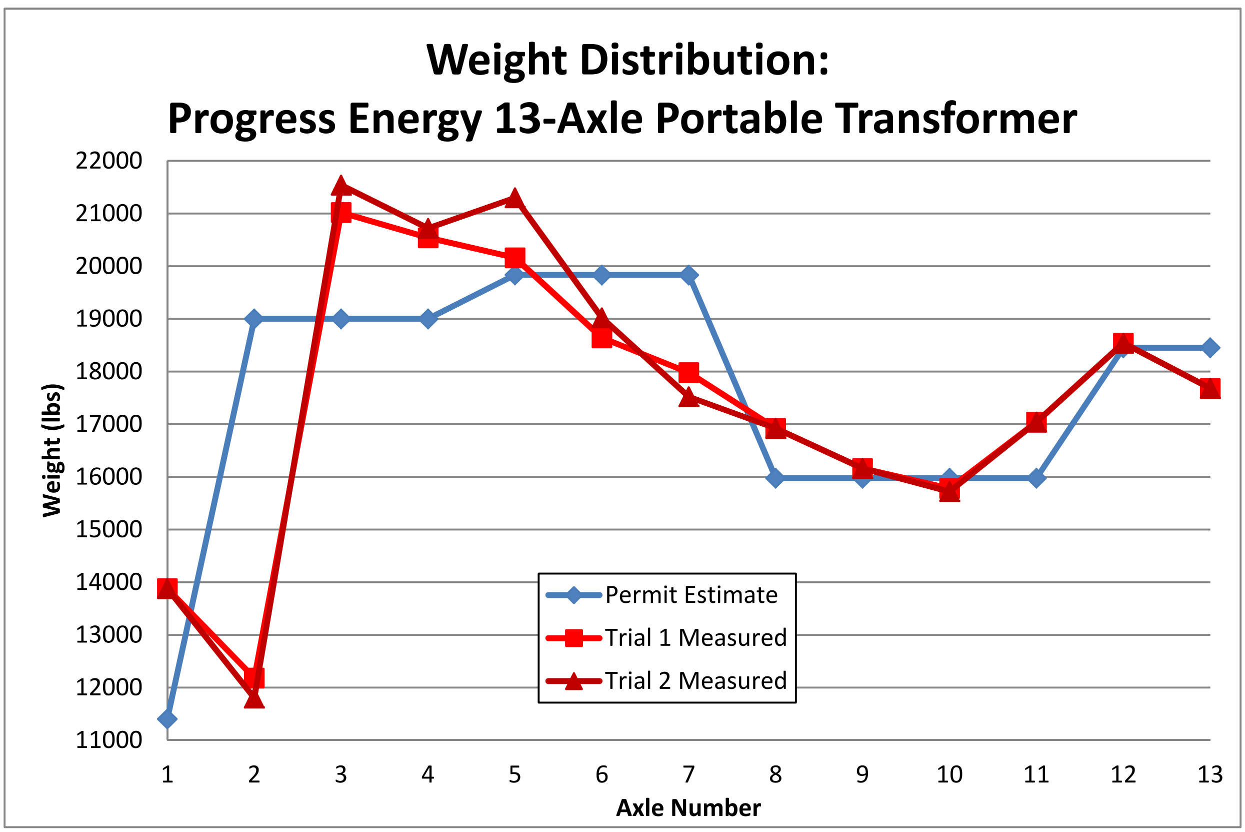

Figure 32 Weight Distribution: 13-Axle Transformer.

As can be seen in Figure 32 above, the weight distribution is not uniform, though the permit does not assume a uniform weight distribution. This is probably due to the fact that the transformer is the exact size of the trailer and does not have a uniform weight, thus the center of gravity of the transformer cannot be centered over the center of gravity of the trailer. According to a Progress Energy official, the estimated weights on the permit were supplied by the trailer manufacturer. The manufacturer assumed that all axles in an axle grouping would carry the same weight and that weight differences would occur drastically between axle groups. The data contradicts this assertion, since the axle weights vary nearly linearly from one axle to the next, rather than a series of constant "stepped" weights constant for a given axle group. There are eight overweight axles for both trials, ranging from 90 to 2480 pounds (0.5% to 21.8%) over the permitted axle weight. For both trials, axle 2 was greater than 35% underweight, which likely occurred due to the mechanical problems experienced. Both trials had gross vehicle weights approximately 1% under the permitted gross weight.

Results from both transformer-trailer trucks seem to indicate that a truck-jeep-trailer-singer configuration will not distribute weight uniformly if the weight of the load is not uniform and the load is the size of the trailer. For the 13-axle transformer, the measured gross weight and the estimated permit weight were almost identical indicating that the carrier did not overestimate axle weights for the superload permit to provide additional leeway for variance in weight distribution.

2.5.1.2 North Carolina State Highway Patrol Citations

The NC SHP supplied weight data taken from citations for five superload permitted trucks. The superload permit number for each was included and used to retrieve the permit with estimated weights from the Oversize/Overweight Permit department of the NCDOT. Although the permits were still on file, the truck schematic supplied by the carrier was no longer on file as these are not retained as long as the permit. Therefore, truck configurations were determined by comparing the axle spacings to those of known configurations. It was determined that all the citations provided were for trucks resembling configuration 1, truck-jeep-trailer-stinger. Since the other configurations generally have more than one axle per axle-line, the permit axle weights of the citations were also noted and found to be approximately 20,000 pounds. This weight seems to indicate each truck has one axle per axle-line, suggesting that all the citations were for configuration 1 trucks. However, without truck schematics the exact configurations are open to question.

It should be noted that for citations the NC SHP rounds weights down to the nearest 100 pounds. Additionally, axle weights are measured and recorded in groups, such as a tandem or tridem axle group. Therefore, for analysis the weight of an axle group was assumed to divide equally between the axles in that group. As a result, the analysis will focus on weight distributions between axle groups.

Citation 1 is a 9-axle truck, thought to be a truck-jeep-trailer-stinger configuration from July 2007. From axle spacings given on the superload permit it appears to be a truck-tractor with three axles pulling a two-axle jeep and a two-axle trailer with a two-axle stinger.

Table 9 9-Axle Truck-Jeep-Trailer-Stinger 7/2007

Axle	Axle Spacing From # 9 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	104.17	13,000	15,040	2,040	15.7
2	83.67	22,000	16,170	-5,830	-26.5
3	79.17	22,000	16,170	-5,830	-26.5
4	65.83	22,000	16,550	-5,450	-24.8
5	60.83	22,000	16,550	-5,450	-24.8
6	24.50	22,000	18,880	-3,120	-14.2
7	19.50	22,000	18,880	-3,120	-14.2
8	5.00	22,000	19,850	-2,150	-9.8
9	0.00	22,000	19,850	-2,150	-9.8
Gross		189,000	157,940	-31,060	-16.4

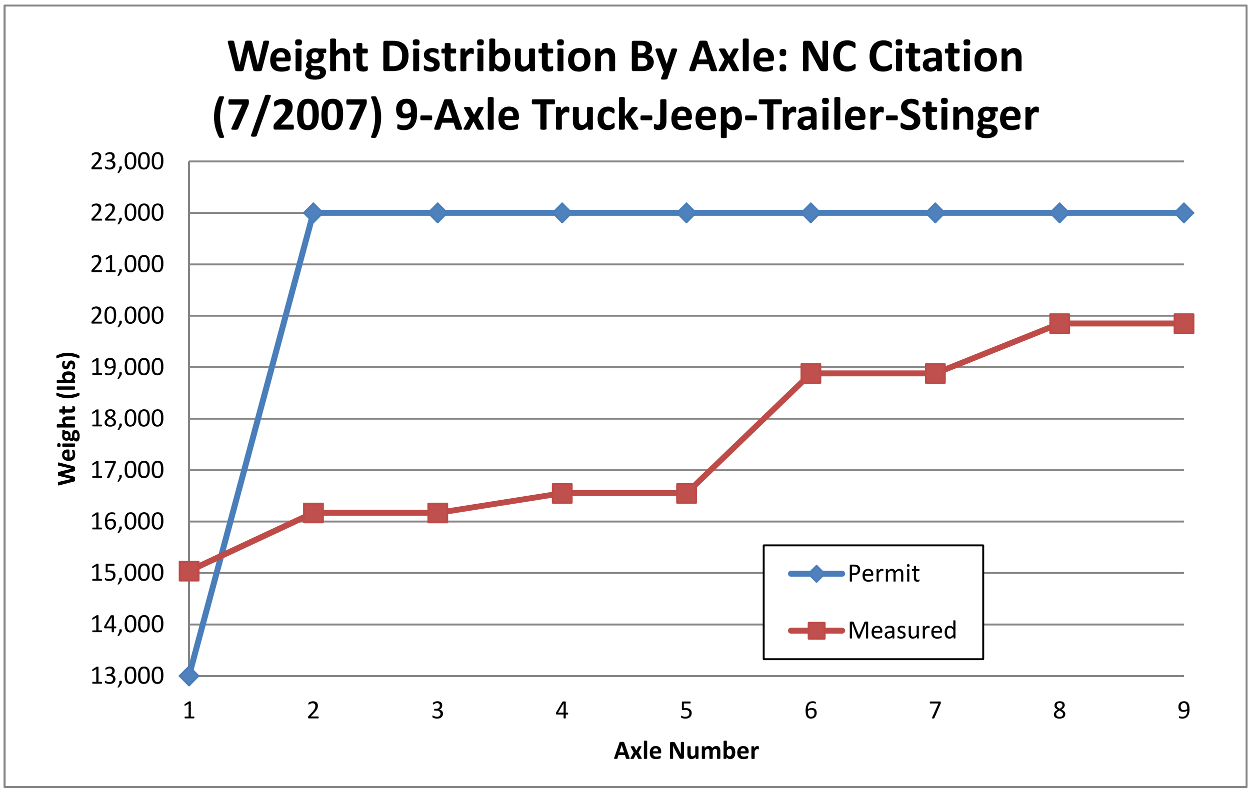

Figure 33 Weight Distribution 9-Axle Truck-Jeep-Trailer-Stinger 7/2007.

As can be seen in Figure 33 above, the axle weight distribution is not equal for this truck. The steer axle is the only overweight axle at 2,040 pounds (15.7%) over the permit weight. All the other axles are significantly underweight, ranging from 2,150 to 5,830 pounds (9.8% to 26.5%) under permit weight. The gross weight of the truck is 31,060 pounds (16.4%) below permit weight. Axles 2 through 5 have relatively equal weights, varying by only 380 pounds, while there is a significant weight increase for axles 6 through 9. Without more information on the load and its positioning on the truck, it is not possible to determine a reason for the rear axles carrying more weight. Overall, it seems that the carrier overestimated the axle weight when applying for the superload permit but miscalculated on the steering axle.

Citation 2 is for an 8-axle truck from June 2008 that matches typical characteristics for a truck-trailer-stinger configuration. From axle spacings given on the superload permit it appears to be a truck-tractor with four axles pulling a three-axle trailer with a single-axle stinger.

Table 10 8-Axle Truck-Trailer-Stinger 6/2008

Axle	Axle Spacing From #8 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	83.92	12,000	12,200	200	1.7
2	68.92	18,000	20,693	2,693	15.0
3	64.42	20,000	20,693	693	3.5
4	59.92	20,000	20,693	693	3.5
5	23.08	20,000	20,007	7	0.0
6	18.58	20,000	20,007	7	0.0
7	14.08	20,000	20,007	7	0.0
8	0.00	19,000	18,200	-800	-4.2
Gross		149,000	152,500	3,500	2.3

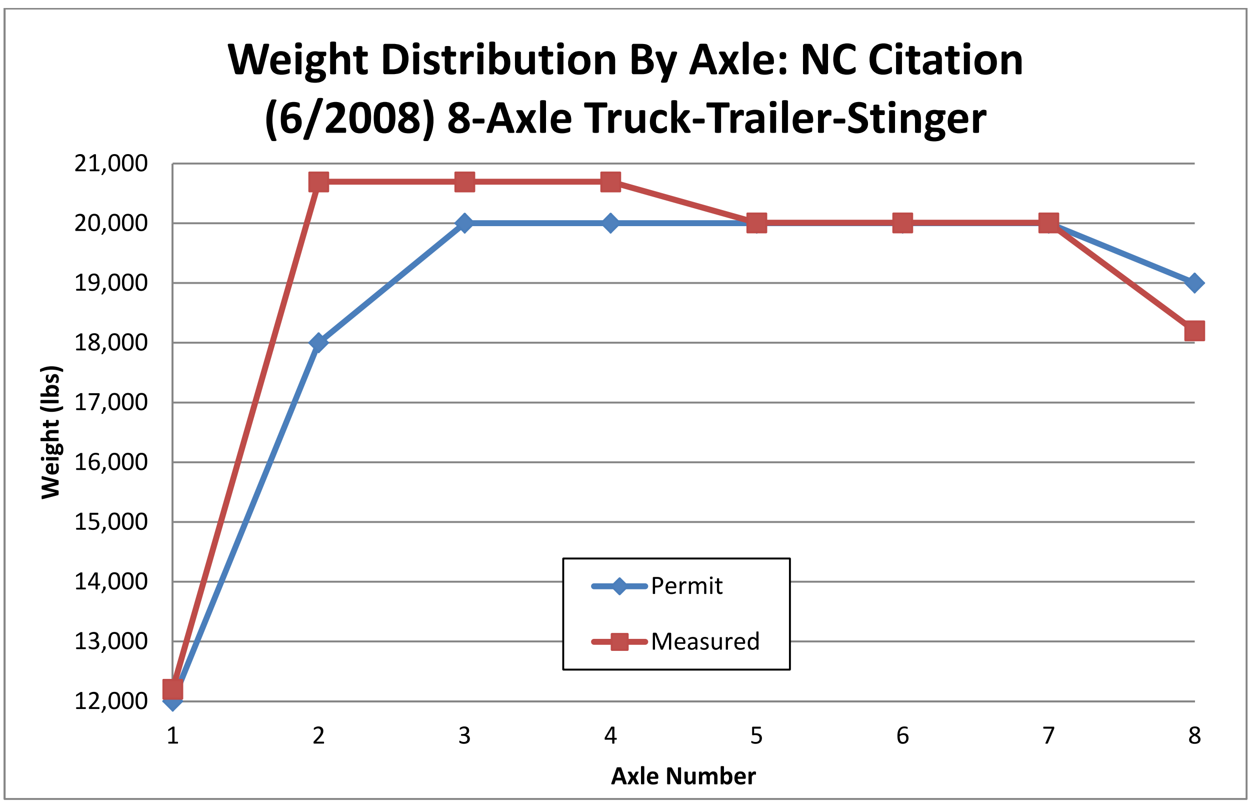

Figure 34 Weight Distribution 8-Axle Truck-Trailer-Stinger 6/2008.

This truck had seven overweight axles. This truck is one of the few examples observed over gross weight being 3,500 pounds (2.3%) over permit gross weight. The steering axle (axle 1) was 200 pounds (1.7%) over permit weight. Axle 2 may be a lift axle not designed to carry as much weight as a standard drive axle, which would explain why the carrier specified a lower weight for that axle compared to axles 2 and 3. Since the NC SHP weighs and records axle group weights for citations, the exact weight of this axle is unknown, but the entire axle group, axles 2, 3, and 4 are overweight. Axles 3 and 4 are only 693 pounds (3.5%) over their permitted weight. Axles 5, 6, and 7 are at permit weight being only 7 pounds overweight, though with a superload permit in NC there is no allowance for being over the permitted weight, especially after rounding down to the nearest 100 pounds to account for scale inaccuracies. The stinger axle (axle 8) is the only underweight axle being 800 pounds (4.2%) under permit weight. This truck shows a relatively uniform weight distribution across the truck drive axles and trailer axles varying by only 686 pounds. Since most of the axles were overweight it seems that the carrier did not attempt to overestimate the axle weight when applying for a permit. An alternate explanation could be that the carrier was misinformed of the weight of the load by their customer.

Citation 3 from July 2008 is a 13-axle truck, with physical characteristics of a truck-jeep-trailer-stinger configuration. From axle spacings given on the superload permit it appears to be a truck-tractor with four axles pulling a three-axle jeep and a three-axle trailer with a three-axle stinger.

Table 11 13-Axle Truck-Jeep-Trailer-Stinger 7/2008

Axle	Axle Spacing From #13 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	111.67	11,000	11,480	480	4.4
2	98.17	15,600	14,873	-727	-4.7
3	93.67	15,600	14,873	-727	-4.7
4	89.17	15,600	14,873	-727	-4.7
5	75.08	15,600	14,767	-833	-5.3
6	70.58	15,600	14,767	-833	-5.3
7	66.08	15,600	14,767	-833	-5.3
8	32.08	15,600	13,713	-1,887	-12.1
9	27.58	15,600	13,713	-1,887	-12.1
10	23.08	15,600	13,713	-1,887	-12.1
11	9.00	15,600	13,533	-2,067	-13.2
12	4.50	15,600	13,533	-2,067	-13.2
13	0.00	15,600	13,533	-2,067	-13.2
Gross		198,200	182,140	-16,060	-8.1

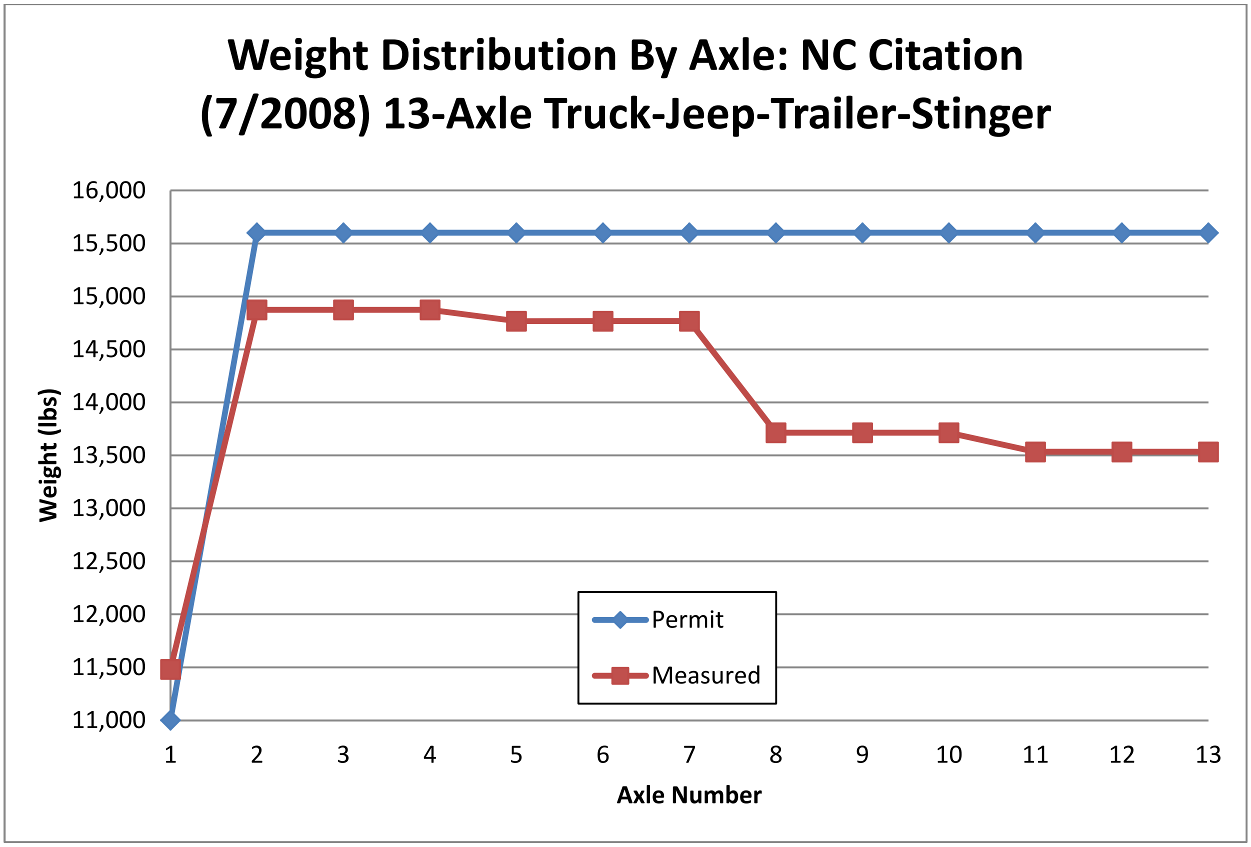

Figure 35 Weight Distribution 13-Axle Truck-Jeep-Trailer-Stinger 7/2008.

As can be seen above this truck had only the steer axle overweight, being 480 pounds (4.4%) over permit weight. The remainder of the axles ranged from 727 to 2,067 pounds or 4.7% to 13.2% underweight. The axle group containing axles 2, 3, and 4 weights are almost equal to those of the axle group containing axles 5, 6, and 7, varying by only 106 pounds. Similarly, the last two axle groups, axles 8, 9, and 10, and 11, 12, and 13, have almost equal weights, varying only by 180 pounds. However, the weights between these two sets of axle groups vary by approximately 1,000 pounds. Without information on the load and its position on the trailer, it is difficult to determine a reason for this discrepancy. With all but the first axle being significantly underweight it seems the carrier overestimated the axle weights when applying for the superload permit.

Citation 4 is a 13-axle truck from December 2008 that matches typical characteristics for a truck-jeep-trailer-stinger configuration. From axle spacings given on the superload permit it appears to be a truck-tractor with four axles pulling a three-axle jeep and a three-axle trailer with a three-axle stinger.

Table 12 13-Axle Truck-Jeep-Trailer-Stinger 12/2008

Axle	Axle Spacing From #13 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	129.33	18,000	14,800	-3,200	-17.8
2	109.67	20,000	20,067	67	0.3
3	105.17	20,000	20,067	67	0.3
4	100.67	20,000	20,067	67	0.3
5	85.17	20,000	19,467	-533	-2.7
6	80.67	20,000	19,467	-533	-2.7
7	76.17	20,000	19,467	-533	-2.7
8	33.50	20,000	20,867	867	4.3
9	29.00	20,000	20,867	867	4.3
10	24.50	20,000	20,867	867	4.3
11	9.00	20,000	20,767	767	3.8
12	4.50	20,000	20,767	767	3.8
13	0.00	20,000	20,767	767	3.8
Gross		258,000	258,300	300	0.1

This truck has nine axles, axles 2 through 4 and 8 through 13, over the allowed permit weight. The steering axle 3,200 pounds (17.8%) under the permit weight, also the axle group comprising axles 5 through 7 was 533 pounds (2.7%) under the permit weight per axle. The axle group containing axles 2 through 4 was only slightly overweight, being 67 pounds (0.3%) over the permit weight per axle. As noted before, NC does not allow any leeway for axles over the superload permit weight. The axle group for axles 8 through 10 was 867 pounds (4.3%) over permit weight. Finally, the last axle group for of axles 11, 12, and 13 was 767 pounds (3.8%) over the allowed permit weight. The entire gross weight of the truck was slightly overweight at 300 pounds (0.1%) over the allowed permit weight.

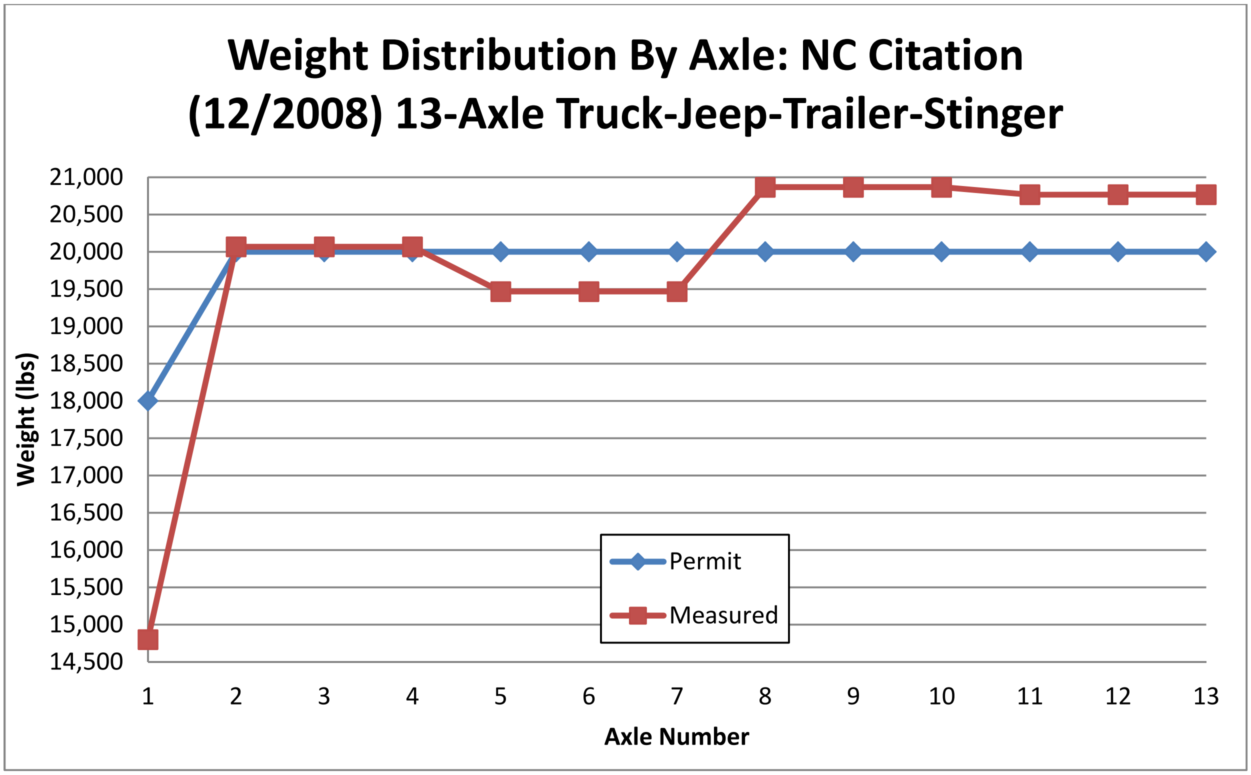

Figure 36 Weight Distribution 13-Axle Truck-Jeep-Trailer-Stinger 12/2008.

As illustrated in Figure 36 above, the first two axle groups have relatively uniform weight distribution - the axle weights vary by only 600 pounds. Similarly, the last two axle groups have a relatively uniform weight distribution, varying by only 100 pounds. However, as seen with the last truck there is a significant increase in weight from the first two axle groups to the last two axle groups. In this case the increase in axle weights is approximately 1,400 pounds. Without more information on the load and its positioning on the trailer, it is difficult to determine the reason for this weight variation. The carrier does not seem to have overestimated axle weights when applying for the superload permit. This is possibly because the carrier was operating the truck relatively close to its weight capacity. Or, it could be due to the carrier being misinformed of the weight of the load and therefore miscalculated the gross weight of the truck.

Citation 5 from March 2011 is a 13-axle truck that matches typical characteristics for a truck-jeep-trailer-stinger configuration. From axle spacings given on the superload permit it appears to be a truck-tractor with four axles pulling a three-axle jeep and a three-axle trailer with a three-axle stinger.

Table 13 13-Axle Truck-Jeep-Trailer-Stinger 3/2011

Axle	Axle Spacing From #13 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	130.17	12,000	14,000	2,000	16.7
2	114.00	20,000	18,433	-1,567	-7.8
3	109.50	20,000	18,433	-1,567	-7.8
4	105.00	20,000	18,433	-1,567	-7.8
5	89.50	20,000	17,700	-2,300	-11.5
6	85.00	20,000	17,700	-2,300	-11.5
7	80.50	20,000	17,700	-2,300	-11.5
8	32.50	20,000	18,600	-1,400	-7.0
9	28.00	20,000	18,600	-1,400	-7.0
10	23.50	20,000	18,600	-1,400	-7.0
11	9.00	20,000	16,733	-3,267	-16.3
12	4.50	20,000	16,733	-3,267	-16.3
13	0.00	20,000	16,733	-3,267	-16.3
Gross		252,000	228,400	-23,600	-9.4

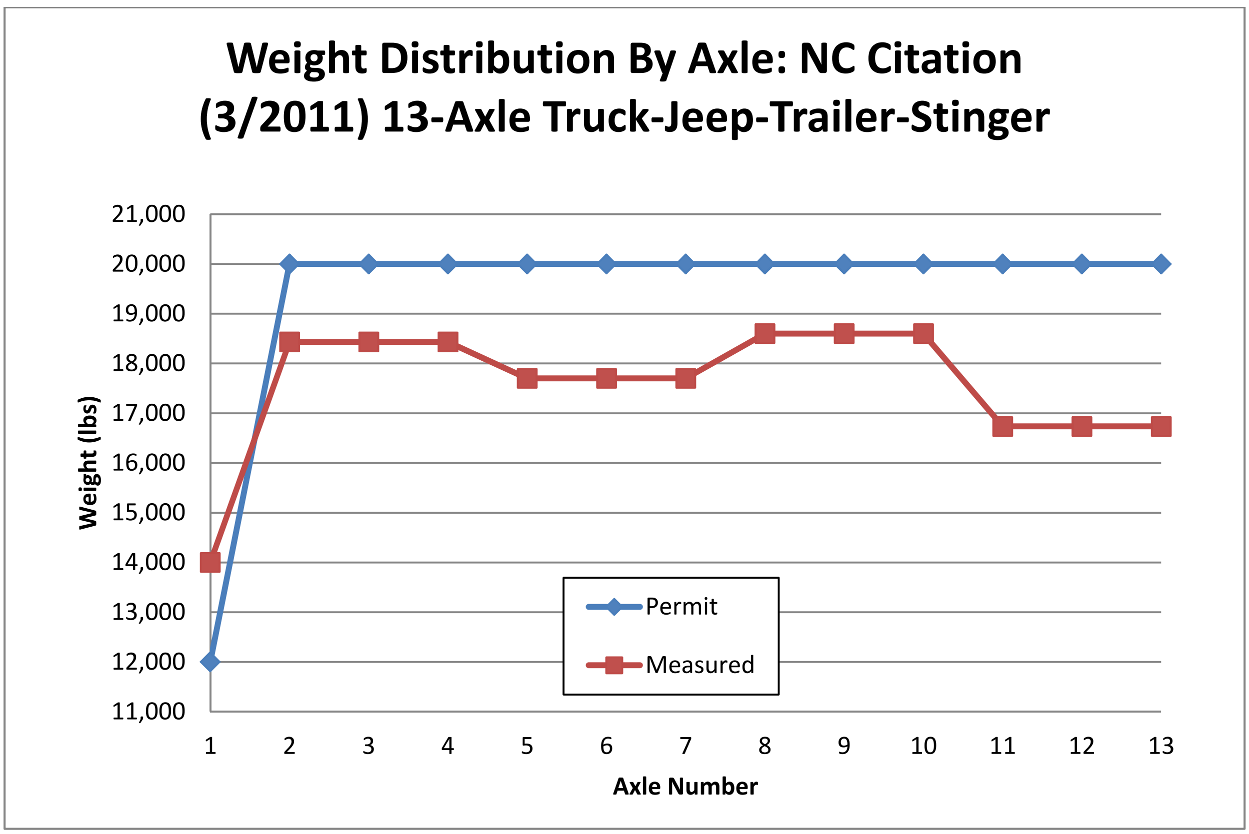

Figure 37 Weight Distribution 13-Axle Truck-Jeep-Trailer-Stinger 3/2011.

This truck had only one overweight axle - the steering axle at 2,000 pounds (16.7%) over the superload permit weight. The other axles ranged from 1,400 to 3,267 pounds (7.0% to 16.3%) under the allowed permit weight. The entire truck was 23,600 pounds (9.4%) below the allowed gross permit weight. Axles 2 through 10 have a relatively uniform weight distribution, with the axle weights varying by 900 pounds. The axles of the stinger, axles 11, 12, and 13 carried only 16,733 pounds per axle, which is 1,867 pounds lower than the preceding axle group. This may be because the stinger was not designed to carry as much weight as a standard axle group, or the mechanism used to transfer weight to the stinger may not have been set to transfer enough weight. It appears that the carrier overestimated axle weights when applying for the superload permit to allow for weight variance between axles.

Of the five trucks with NC SHP citations it appears that three of the carriers over estimated axle weights when applying for their superload permits to allow for variations in axle weights. However, for each of these trucks the steering axle was found to be overweight. The other axles varied from 4.7% to 26.5% below the superload permit weight. Another similarity between these trucks is that they all had gross weights significantly lower than the estimated gross weight from the superload permit, being between 8.1% and 16.4% below the gross weight listed on their respective superload permits. These trucks had sections of approximately uniform weight distribution with variations below 900 pounds. The axle weights between these sections of approximately uniform distribution varied significantly, having differences well over 1,000 pounds. Without information how each truck's load was oriented and distributed, it is difficult to draw any conclusion on the effect of how these trucks were loaded on the weight distribution.

The remaining two NC citation trucks for configuration 1 had a number of axles over or close to axle weights listed on their respective superload permits. Overweight axles ranged from negligibly over to 4.3% over the permit weight, excluding steer axles and the assumed lift axle on the 8-axle truck-trailer-stinger. This assumed lift axle was 15.0% overweight, although, its weight was estimated to be lower than the weights of the other two axles in that axle group on the permit. The NC SHP's method of weighing entire axle groups means that this axle may have weighed less than the assumed equal weight distribution for that axle group, therefore the 15.0% overweight shown may not be accurate. Both of these trucks were over gross weight, being 0.1% and 2.3% over their respective permitted gross weights. This may indicate that the carriers were operating the trucks at the upper limit of their ability without having to add additional axles. This may have left them no room to overestimate axle weights when applying for a superload permit, because listing higher weights would have probably caused the permit application to be denied. Alternately, it is possible that the carriers were misinformed of the weight of the cargo by their customers, causing them to choose equipment and estimate axle weights incorrectly. As with the other three trucks, these trucks had sections of approximately uniform weight distribution with variations below 700 pounds. The axle weights between these sections of approximately uniform distribution varied significantly, having differences of over 1,000 pounds. Without information on the loads for each truck and how they were loaded it is impossible to draw any conclusion on the effect of how these trucks were loaded on the weight distribution.

2.5.1.3 Georgia DOT Data

GDOT supplied weight data taken from seven superload permitted trucks stopped for axle spacing violations and weighed by the GA SHP. The data includes permit and measured axle weights and axle spacings. A sample truck schematic, shown in Figure 38 below, shows the general truck configuration, but diagrams for each truck were not available. Therefore, truck configurations were verified by comparing the axle spacings to those of known configurations. It was determined that all the citations were for trucks resembling configuration 1, truck-jeep-trailer-stinger. Since the other configurations generally have more than one axle per axle-line, the permit axle weights of the citations were also noted and found to be approximately 20,000 pounds. This weight would seem to indicate only one axle per axle-line, further indicating that all the citations were for configuration 1 trucks. However, without truck schematics the exact configurations are open to question.

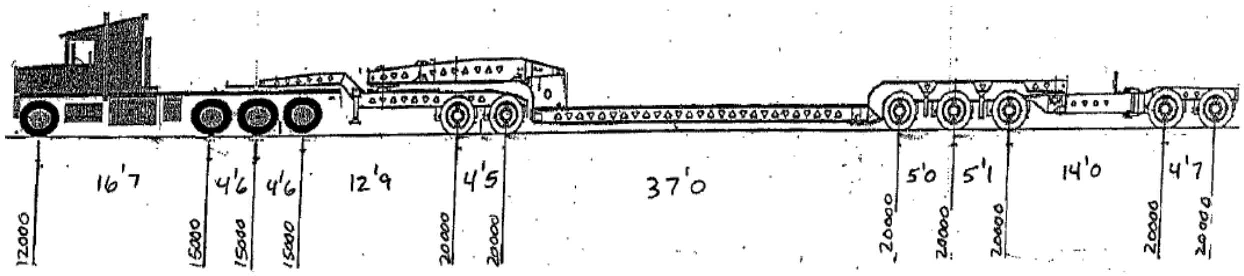

Figure 38 Sample Truck Schematic for GDOT Data.[23]

According to the GDOT data it appears that the GA SHP does not round weights down to the nearest 100 pounds as the NC SHP does. In addition, axle weights seem to be recorded individually which is also different from NC SHP methods. This allows better consideration of the weight distribution characteristics for these trucks.

Citation 1 from the GA data is an 11-axle truck that matches typical characteristics for a truck-jeep-trailer-stinger configuration. From axle spacings given in the spreadsheet, it appears to be a truck-tractor with three axles pulling a three-axle jeep and a three-axle trailer with a two-axle stinger.

As can be observed in Table 14 and Figure 39 below, this truck does not exhibit an equal weight distribution to the axles. The first stinger axle, axle 10, is the only overweight axle, at 1,220 pounds (6.1%) over the permit weight. This may indicate that the mechanism that transfers load to the stinger was not set properly, malfunctioning, or incapable of transferring weight equally to the stinger axles. The steering axle is 2,420 pounds (13.4%) under the permit weight. The rest of the axles are under the allowable permit weight, ranging from 300 to 2,540 pounds (1.5% to 12.7%) below permit weight. The gross weight of the truck is 11,340 pounds (5.2%) under the gross weight allowed by the superload permit. There is a 660-pound difference between the truck drive axles (axles 2 and 3). The jeep axles (axles 4, 5, and 6) have a weight range of 500 pounds, while the trailer axles (axles 7, 8, and 9) have a weight range of 400 pounds. The stinger axles (axles 10 and 11) have the largest range between axles in an axle group at 1,900 pounds. Except for the stinger, the axle groups have a relatively equal load distribution to the axles within those respective groups.

[23] Source: GDOT

Table 14 GA Data Truck 1: 11-Axle Truck-Jeep-Trailer-Stinger

Axle	Axle Spacing from #11 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	113.82	18,000	15,580	-2,420	-13.4
2	96.82	20,000	19,700	-300	-1.5
3	92.32	20,000	19,040	-960	-4.8
4	75.99	20,000	17,460	-2,540	-12.7
5	71.41	20,000	17,960	-2,040	-10.2
6	66.83	20,000	17,860	-2,140	-10.7
7	27.83	20,000	19,720	-280	-1.4
8	23.25	20,000	19,320	-680	-3.4
9	18.67	20,000	19,480	-520	-2.6
10	4.50	20,000	21,220	1,220	6.1
11	0.00	20,000	19,320	-680	-3.4
Gross		218,000	206,660	-11,340	-5.2

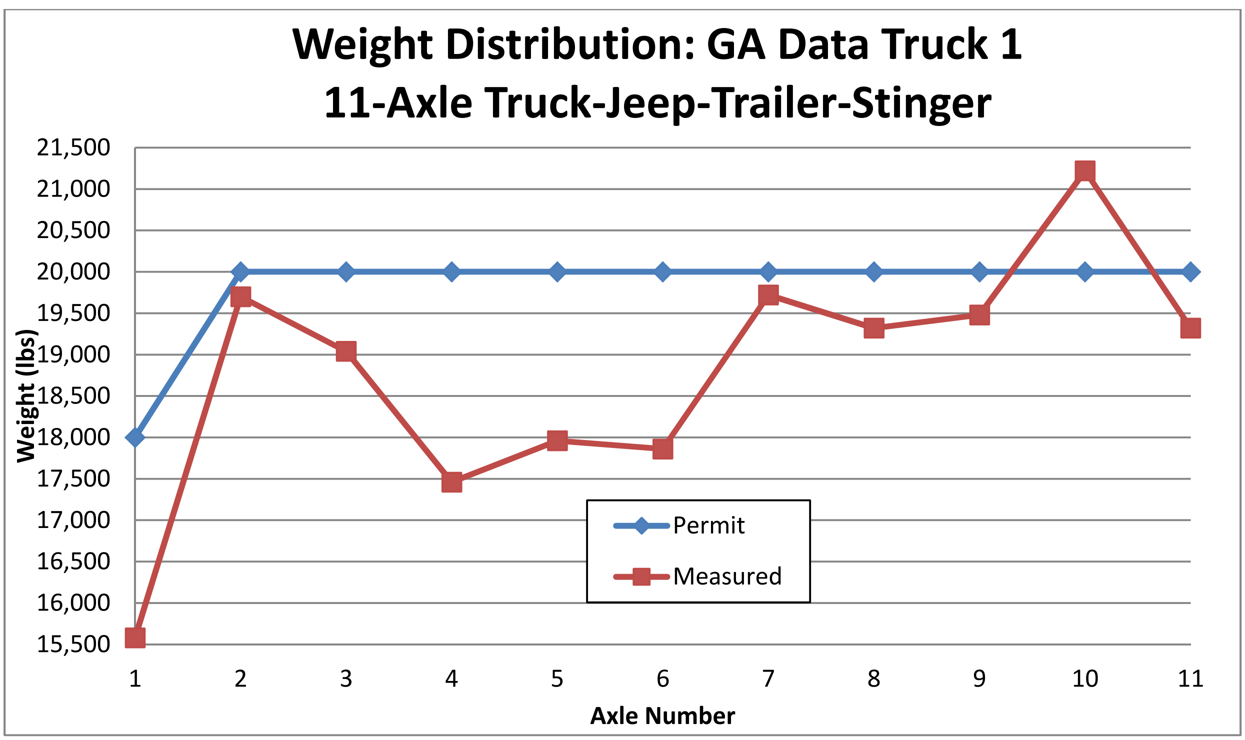

Figure 39 Weight Distribution - GA Data Truck 1: 11-Axle Truck-Jeep-Trailer-Stinger.

Between axle groups, the weight distribution is very uneven with weight discrepancies greater than 1,500 pounds. Without information regarding the size and orientation of the load, it is difficult to determine any relationship between the load type and the weight distribution characteristics of the truck. It does seem that this carrier overestimated axle weights when applying for the superload permit to compensate of variations in axle weight due to the difference in gross vehicle weights. Indeed, the maximum axle weight was estimated.

Citation 2 from the GA data is an 11-axle truck that matches typical characteristics for a truck-jeep-trailer-stinger configuration. Examining the axle spacings, it appears to be a truck-tractor with three axles pulling a three-axle jeep and a three-axle trailer with a two-axle stinger.

Table 15 GA Data Truck 2: 11-Axle Truck-Jeep-Trailer-Stinger

Axle	Axle Spacing from #11 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	86.00	17,000	16,260	-740	-4.4
2	69.00	20,000	19,580	-420	-2.1
3	64.50	20,000	19,360	-640	-3.2
4	48.17	19,000	18,300	-700	-3.7
5	43.58	19,000	18,380	-620	-3.3
6	39.00	19,000	18,460	-540	-2.8
7	27.83	20,000	19,480	-520	-2.6
8	23.25	20,000	18,900	-1,100	-5.5
9	18.67	20,000	19,780	-220	-1.1
10	4.50	20,500	20,840	340	1.7
11	0.00	20,500	19,600	-900	-4.4
Gross		215,000	208,940	-6,060	-2.8

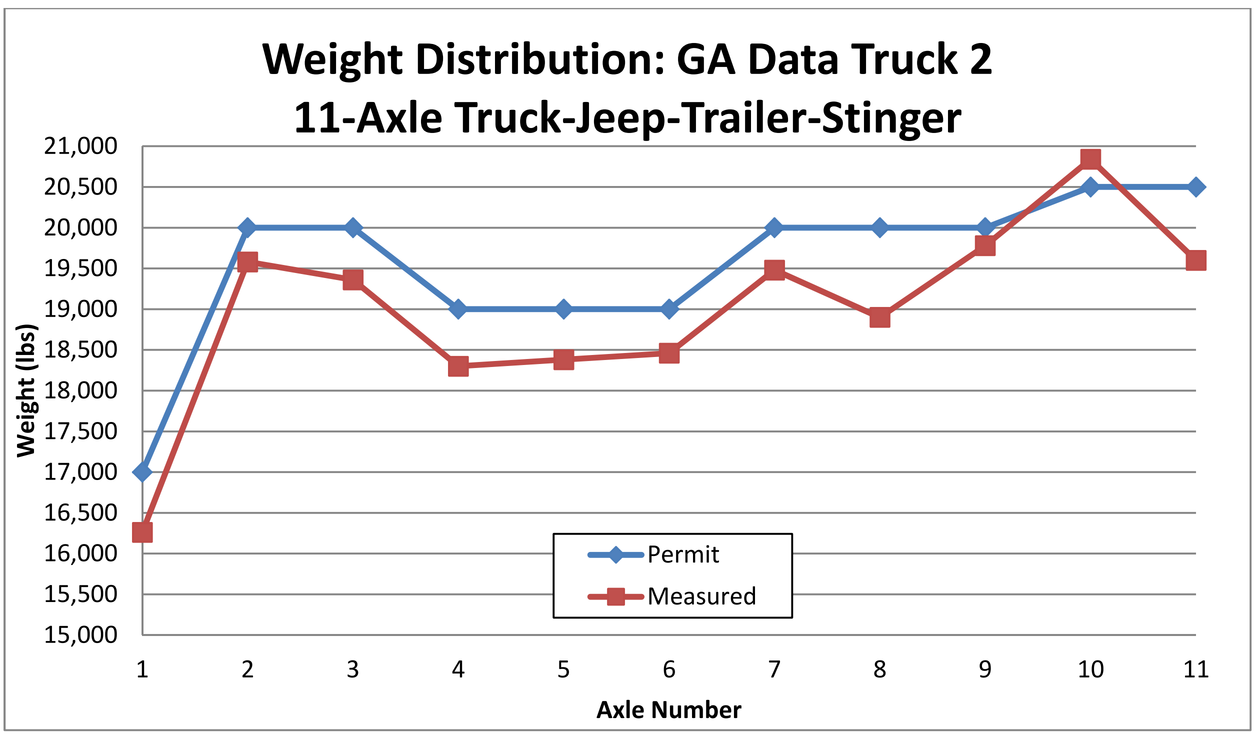

Figure 40 Weight Distribution - GA Data Truck 2: 11-Axle Truck-Jeep-Trailer-Stinger.

Figure 40 above shows a non-uniform axle weight distribution for this truck; though as indicated by the estimated permit weights this truck was not predicted to exhibit uniform weight distribution characteristics. As with the previous example, the first stinger axle, axle 10, was the only overweight axle for this truck, at 340 pounds (1.7%) over the estimated permit weight. This again may indicate that the mechanism that transfers load to the stinger was not set properly, malfunctioning, or incapable of transferring weight equally to the stinger axles. The steering axle was 740 pounds (4.4%) lower than the estimated permit weight. The remaining axles ranged from 220 to 1,100 pounds (1.1% to 5.5%) under the estimated permit weight. The gross weight was 6,060 pounds (2.8%) under the estimated permit weight.

The estimated permit weights indicate that axles within an axle group are expected to have a uniform weight distribution, while axle weights between axle groups are expected to vary. The tractor drive axle grouping (axles 2 and 3) exhibit a fairly uniform weight distribution, varying by only 220 pounds. The jeep axle group (axles 4, 5, and 6) also exhibit a uniform weight distribution, varying by only 160 pounds. The trailer axle group (axles 7, 8, and 9, shows less weight distribution consistency, varying by 880 pounds. The stinger axle group, axles 10 and 11) also did not show a uniform weight distribution, varying by 1,240 pounds. Between axle groups, the weights varied approximately as predicted on the permit. Without information on the load, its size, and location on the trailer, it is difficult to determine any relationship between the load type and the weight distribution characteristics of the truck. The difference in gross weights and most of the axle weights being lower than estimated, it appears that this carrier overestimated axle weights when applying for the superload permit to compensate for possible variations in axle weight.

Citation 3 from the GA data is an 11-axle truck that matches typical characteristics for a truck-jeep-trailer-stinger configuration. From axle spacings given in the spreadsheet, it appears to be a truck-tractor with four axles pulling a two-axle jeep and a three-axle trailer with a two-axle stinger.

Table 16 GA Data Truck 3: 11-Axle Truck-Jeep-Trailer-Stinger

Axle	Axle Spacing from #11 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	109.92	18,000	15,780	-2,220	-12.3
2	95.92	20,000	15,760	-4,240	-21.2
3	91.42	20,000	13,100	-6,900	-34.5
4	86.92	20,000	12,880	-7,120	-35.6
5	70.58	20,000	21,400	1,400	7.0
6	66.08	20,000	21,500	1,500	7.5
7	27.50	20,000	16,260	-3,740	-18.7
8	23.00	20,000	18,260	-1,740	-8.7
9	18.50	20,000	16,180	-3,820	-19.1
10	4.50	20,000	17,000	-3,000	-15.0
11	0.00	20,000	17,980	-2,020	-10.1
Gross		218,000	186,100	-31,900	-14.6

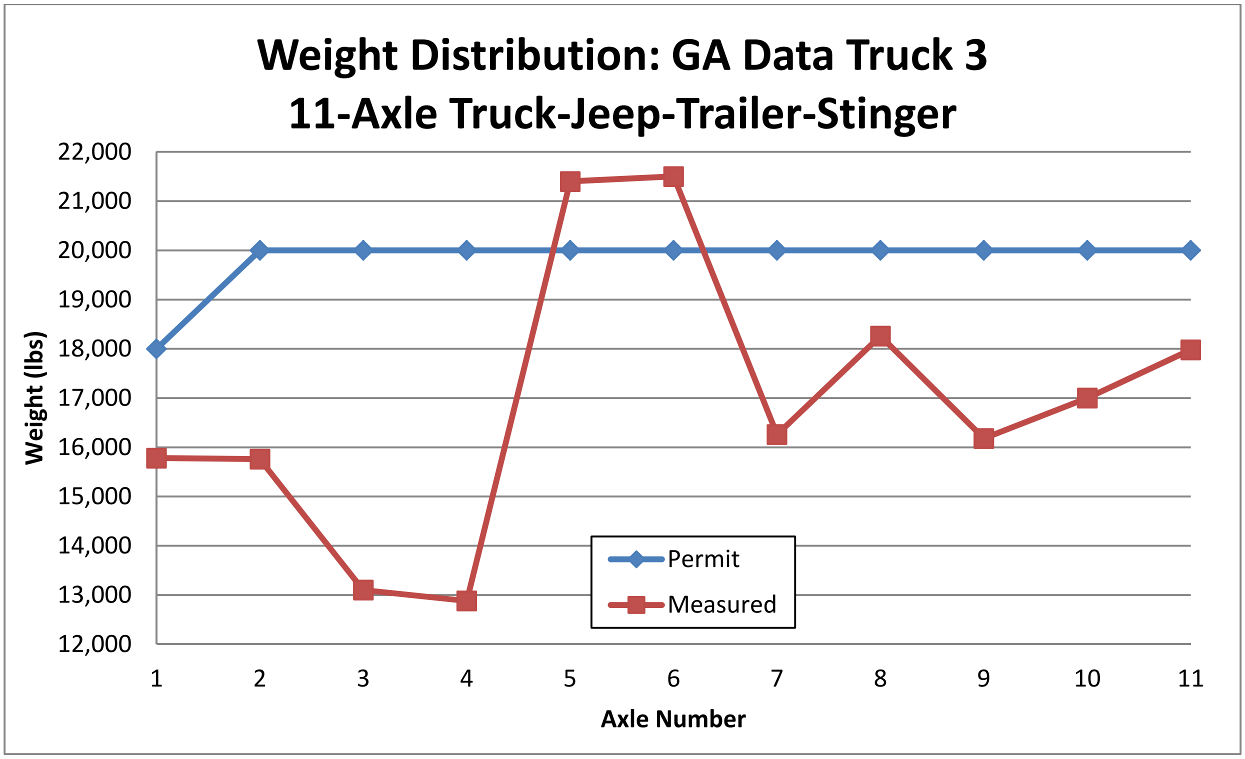

Figure 41 Weight Distribution - GA Data Truck 3: 11-Axle Truck-Jeep-Trailer-Stinger.

The third GA example estimates a uniform weight distribution for the permit weights, but as seen in Figure 41 above, the measured weight data shows a non-uniform weight distribution. The two jeep axles (axles 5 and 6) are the only overweight axles for this truck, at 1,400 pounds (7.0%) and 1,500 pounds (7.5%), respectively, over the estimated permit weights. The steer axle was 2,200 pound (12.3%) under the permit weight. The remaining axles ranged from 1,740 to 7,120 pounds (8.7% to 35.6%) under weight. The gross weight of the truck was 31,900 pounds (14.6%) below the permit gross weight.

With the exception of the jeep axle group (axles 5 and 6) most of the axle groups did not exhibit a uniform weight distribution within their respective groups, having axle weight variances of greater than 900 pounds. In contrast, the two jeep axles varied in weight by only 100 lbs. The axle group consisting of axles 2, 3, and 4 had a weight variance of approximately 2,800 pounds, due to the weight of axle 2 being much higher than that of axles 3 and 4. It is likely that axle 2 was a lift axle that was improperly set too low, causing it to carry a much greater load than the other two drive axles. For the trailer axle group (axles 7, 8, and 9) there is a 2,080-pound variance between axles mainly caused by axle 8, since axles 7 and 9 vary by only 80 pounds. The reason for the weight discrepancy between axle 8 and the other two axles cannot be ascertained without more information. The two stinger axles, axles 10 and 11 have a weight variance of 980 pounds. This may indicate that the mechanism that transfers load to the stinger was not set properly, malfunctioning, or incapable of transferring weight equally to both stinger axles. Without information on the load, its size, and location on the trailer, it is difficult to determine any relationship between the load type and the weight distribution characteristics of the truck. It does seem, from the gross weight and most of the axle weights being lower than estimated, that this carrier overestimated axle weights when applying for the superload permit to compensate of variations in axle weight.

Citation 4 from the GA data is for a 13-axle truck that has characteristics typical of a truck-jeep-trailer-stinger configuration. From axle spacings given in the spreadsheet, it appears to be a truck-tractor with four axles pulling a three-axle jeep and a three-axle trailer with a three-axle stinger.

Table 17 GA Data Truck 4: 13-Axle Truck-Jeep-Trailer-Stinger

Axle	Axle Spacing from #13 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	122.83	18,000	14,720	-3,280	-18.2
2	108.67	19,000	12,160	-6,840	-36.0
3	104.08	19,000	17,340	-1,660	-8.7
4	99.50	19,000	17,200	-1,800	-9.5
5	84.17	19,000	14,520	-4,480	-23.6
6	79.17	19,000	14,520	-4,480	-23.6
7	74.17	19,000	14,980	-4,020	-21.2
8	34.50	19,000	16,560	-2,440	-12.8
9	29.50	19,000	16,260	-2,740	-14.4
10	24.50	19,000	16,180	-2,820	-14.8
11	10.00	19,000	16,300	-2,700	-14.2
12	5.00	19,000	16,620	-2,380	-12.5
13	0.00	19,000	15,660	-3,340	-17.6
Gross		246,000	203,020	-42,980	-17.5

As can be seen in Figure 42 below, the fourth GA truck has a uniform weight distribution estimated on the permit but the measured weights do not support this distribution. There are no overweight axles for this truck, with all axles significantly below the weight estimated on the permit. The steer axle (axle 1) was 3,280 pounds (18.2%) under the permitted weight. Axle 2 was 6,840 pounds (36.0%) below the permit weight; in addition, it was approximately 5,100 pounds less than axles 3 and 4 in the same axle group. This seems to indicate that axle 2 is a lift axle that was improperly set too high causing it to carry less load than the other two axles in the group. The remaining axles range from 1,660 to 4,480 pounds (8.7% to 23.6%) below the estimated permit weights. The measured gross weight of the truck is 42,980 pounds (17.5%) less than the gross weight estimated for the superload permit.

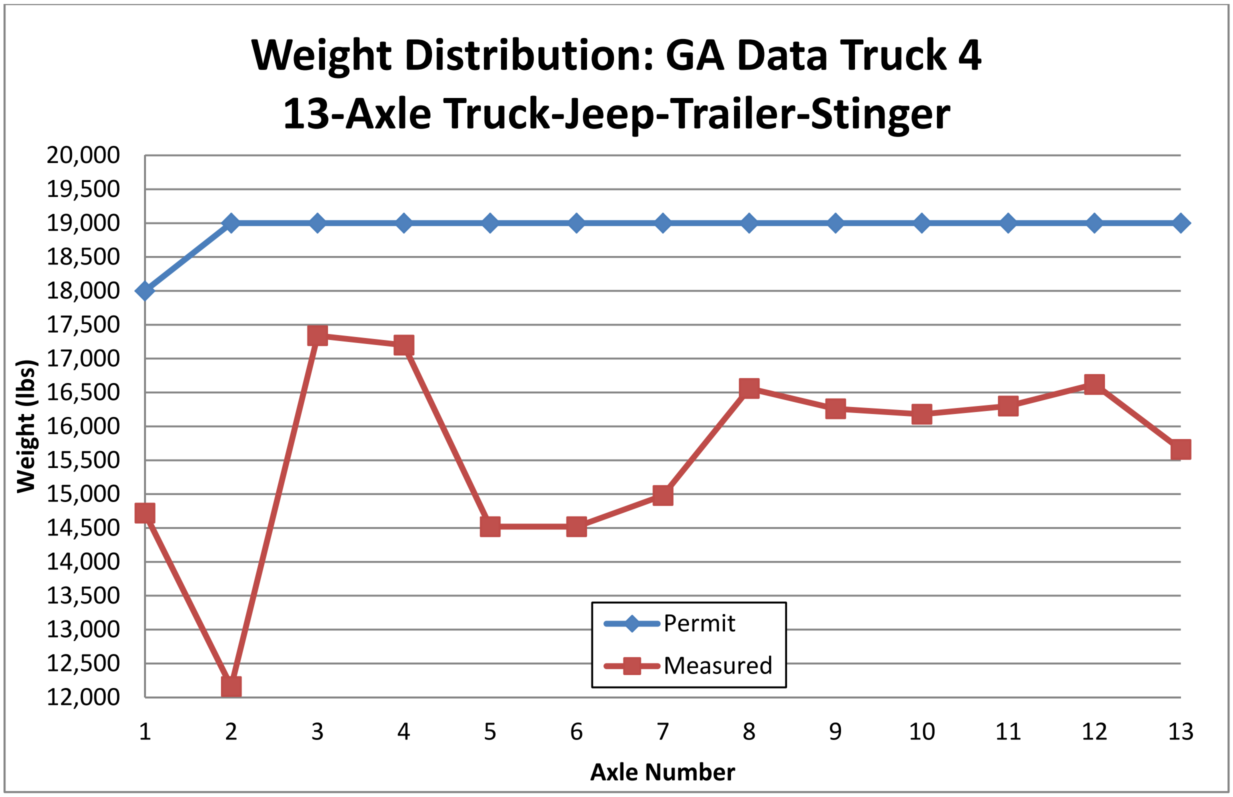

Figure 42 Weight Distribution - GA Data Truck 4: 13-Axle Truck-Jeep-Trailer-Stinger.

With exceptions, the axle groups show a relatively uniform weight distribution within the respective groupings but weight distribution between axle groups is non-uniform. The tractor drive axle grouping, axles 2, 3, and 4, do not exhibit a uniform weight distribution because of the weight discrepancy for axle 2 as described above. Axles 3 and 4 though show a relatively uniform weight distribution, having a variance of only 140 pounds. Between axles 3 and 4 and axles 5, 6, and 7 there is approximately a sudden 2700-pound decrease in axle weight. The jeep axles (axles 5, 6, and 7) are relatively uniform and vary by 460 pounds. Between the jeep axle group and the trailer axle group (axles 8, 9, and 10), there is an increase of approximately 1,200 pounds. The trailer axles have a relatively uniform weight distribution with a variance of 380 pounds. There is very little change in axle weight from the trailer axle group to the stinger axle group (axles 11, 12, and 13). The first two axles of the stinger axle group are relatively uniform, varying by only 320 pounds, although the last stinger axle is approximately 1,000 pounds lower than the other two axles. The reason for this is unknown but may indicate that the mechanism that transfers load to the stinger was not set properly, malfunctioning, or incapable of transferring weight equally to all the stinger axles. Without information on the load, its size, and location on the trailer, it is difficult to determine any relationship between the load type and the weight distribution characteristics of the truck. It does seem, from the gross weight and most of the axle weights being lower than estimated, that this carrier overestimated axle weights when applying for the superload permit to compensate for variations in axle weight.

Citation 5 from the GA data is a 12-axle truck that has characteristics typical of a truck-jeep-trailer-stinger configuration. From axle spacings given in the spreadsheet, it appears to be a truck-tractor with four axles pulling a three-axle jeep and a three-axle trailer with a two-axle stinger.

Table 18 GA Data Truck 5: 12-Axle Truck-Jeep-Trailer-Stinger

Axle	Axle Spacing from #12 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	114.92	17,000	15,600	-1,400	-8.2
2	100.42	19,333	12,160	-7,173	-37.1
3	95.83	19,333	15,460	-3,873	-20.0
4	91.33	19,334	14,780	-4,554	-23.6
5	75.83	19,333	19,760	427	2.2
6	71.33	19,333	19,080	-253	-1.3
7	66.83	19,334	18,100	-1,234	-6.4
8	27.83	19,333	19,060	-273	-1.4
9	23.33	19,333	19,260	-73	-0.4
10	18.83	19,334	18,800	-534	-2.8
11	4.50	19,500	19,340	-160	-0.8
12	0.00	19,500	19,440	-60	-0.3
Gross		230,000	210,840	-19,160	-8.3

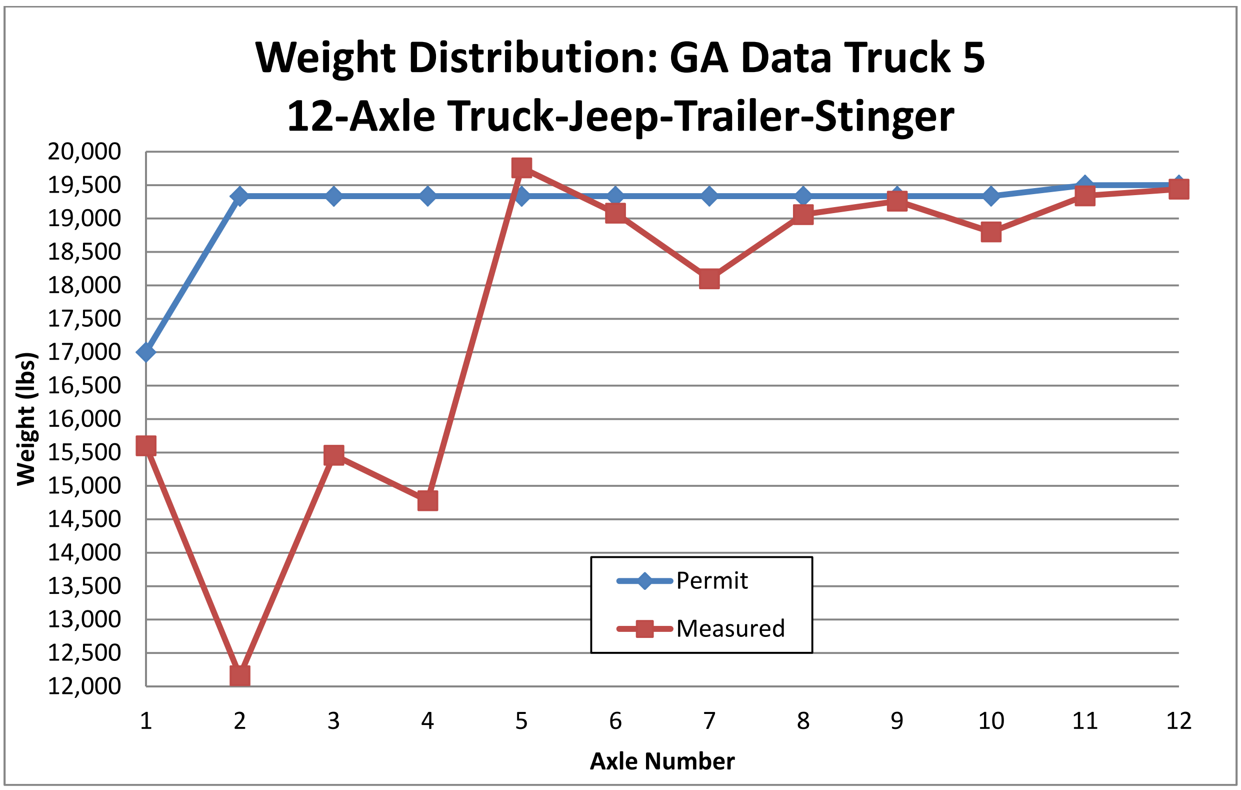

Figure 43 Weight Distribution - GA Data Truck 5: 12-Axle Truck-Jeep-Trailer-Stinger.

As shown above in Figure 43 above, the fifth GA truck estimates a uniform weight distribution on the permit but the measured weights do not show a uniform weight distribution. There is one slightly overweight axle, axle 5, at 427 pounds (2.2%) over the permit weight. The steer axle, axle 1, is 1,400 pounds (8.2%) under the permitted weight. Axle 2 is 7,173 pounds

(37.1%) below the permit weight; in addition, it was approximately 3,000 pounds less than axles 3 and 4 in the same axle group. This seems to indicate that axle 2 is a lift axle that was improperly set too high causing it to carry less weight than the other two axles in the group. Axle 3 was 3,873 pounds (20.0%) under the permit weight. Axle 4 was 4,554 pounds (23.6%) under the permitted weight. The remaining axles were much closer to the estimated weight on the permit, ranging from 60 to 1,234 pounds (0.3% to 6.4%) lower than the estimated permit weight. The measured gross weight of the truck was 19,160 pounds (8.3%) below the estimated gross weight on the permit.

Only the trailer and stinger axle groups exhibited a uniform weight distribution within their respective axle groups, having variances of 460 pounds and 100 pounds respectively. The tractor drive axles and the jeep axle group had non-uniform weight distributions within their respective axle groups, having variances of 3,300 pounds and 1,660 pounds respectively. Between axle groups, there is a drastic increase in weight between the tractor drive axles and the jeep axles, while the axle weights between the jeep, trailer, and stinger are generally within ± 3% of the estimated permit weight, with the exception of axle 7. Without information on the load, its size, and location on the trailer, it is difficult to determine any relationship between the load type and the weight distribution characteristics of the truck. It does seem, from the gross being much lower than estimated, that this carrier overestimated weight when applying for the superload permit to compensate of variations in axle weight. Though it appears that because the tractor drive axle group, axles 2, 3, and 4, carried much less weight than the other axle groups that this cause the jeep, trailer and stinger axle groups to be much closer to the estimated permit weights.

Citation 6 from the GA data is a 13-axle truck that has characteristics typical of a truck-jeep-trailer-stinger configuration. From axle spacings given in the spreadsheet, it appears to be a truck-tractor with four axles pulling a three-axle jeep and a three-axle trailer with a three-axle stinger.

Table 19 GA Data Truck 6: 13-Axle Truck-Jeep-Trailer-Stinger

Axle	Axle Spacing from #13 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	122.62	18,000	14,540	-3,460	-19.2
2	108.20	20,000	14,820	-5,180	-25.9
3	103.62	20,000	18,580	-1,420	-7.1
4	98.76	20,000	18,680	-1,320	-6.6
5	83.42	20,000	16,520	-3,480	-17.4
6	78.42	20,000	16,540	-3,460	-17.3
7	73.42	20,000	16,400	-3,600	-18.0
8	34.08	20,000	19,840	-160	-0.8
9	29.08	20,000	19,720	-280	-1.4
10	24.08	20,000	19,880	-120	-0.6
11	10.00	20,000	20,500	500	2.5
12	5.00	20,000	20,920	920	4.6
13	0.00	20,000	17,920	-2,080	-10.4
Gross		258,000	234,860	-23,140	-9.0

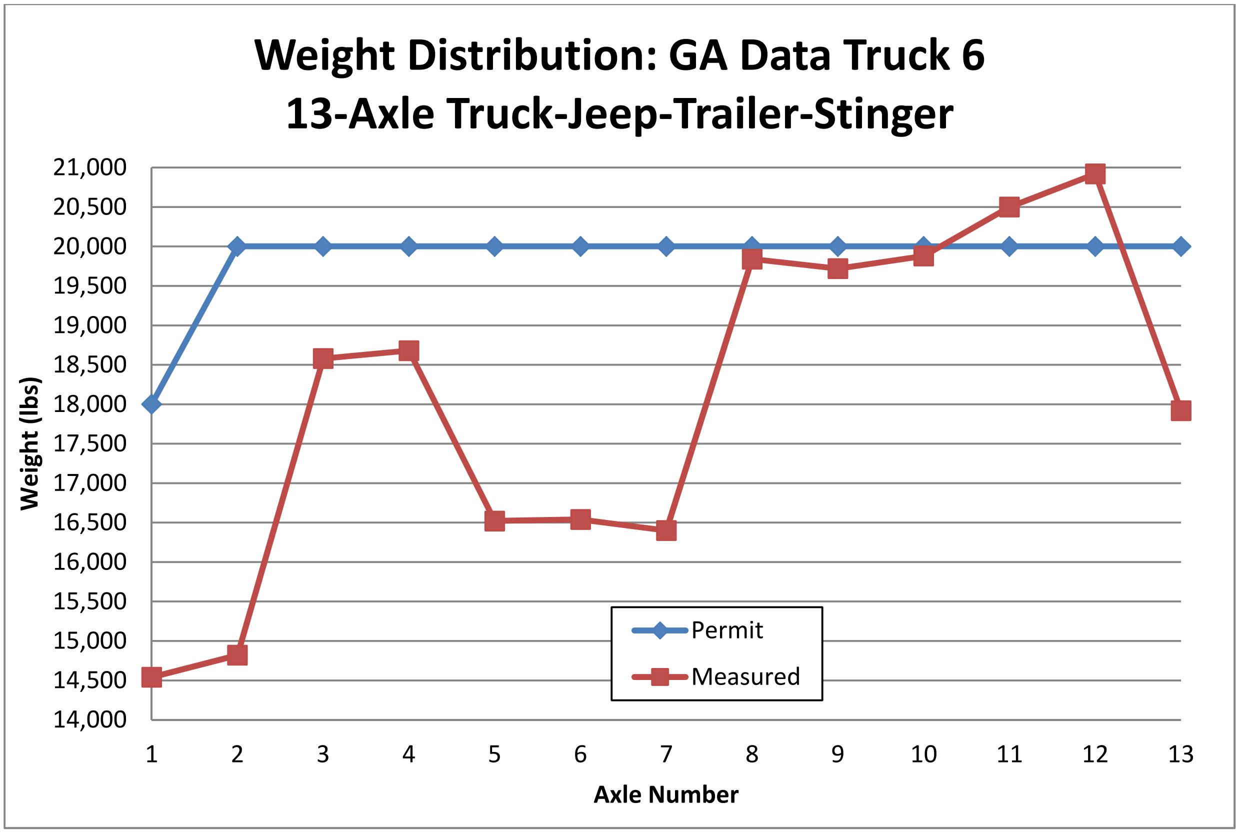

Figure 44 Weight Distribution - GA Data Truck 6: 13-Axle Truck-Jeep-Trailer-Stinger.

Figure 44, above, shows that the sixth GA truck has estimates a uniform weight distribution on the permit but the measured weights do not show a uniform weight distribution. The first two stinger axles, axles 11 and 12, are overweight. Axle 11 is 500 pounds (2.5%) overweight and axle 12 is 920 pounds (4.6%) over the estimated permit weight. The steer axle is 3,460 pounds (19.2% under the estimated permit weight. Axle 2 is 5,180 pounds (25.9%) below the permit weight; in addition, it was approximately 3,800 pounds less than axles 3 and 4, which are in the same axle group. This seems to indicate that axle 2 is a lift axle that was improperly set too high causing it to carry less weight than the other two axles in the group. The remaining axles ranged from 120 to 3,600 pounds (0.6% to 18.0%) below the permitted weight. The measured gross weight was 23,140 pounds (9.0%) below the estimated gross weight listed on the permit. Within individual axle groups, weight distribution was relatively uniform, but between axle groups, the axle weights were not distributed uniformly. Axles 3 and 4 varied by only 100 pounds, although as discussed above axle 2 carried much less weight. Between the tractor drive axle group and the jeep axle group, axles 5, 6, and 7, there was an approximate 2,200-pound axle weight decrease. The jeep axle group had an axle weight variance of only 140 pounds. While there was an approximate 3,400-pound increase in axle weights from the jeep axle group to the trailer axle group (axles 8, 9, and 10). The trailer axle group had an axle weight variance of 160 pounds. For the stinger axle group (axles 11, 12, and 13) there was a much larger axle weight variance observed. The first two axles were overweight and had an axle weight variance of 420 pounds. The last stinger axle carried much less weight than the other two in the group being approximately 2,900 pounds lower. The reason for this is unknown but may indicate that the mechanism that transfers load to the stinger was not set properly, malfunctioning, or incapable of transferring weight equally to all the stinger axles. Without information on the load, its size, and location on the trailer, it is difficult to determine any relationship between the load type and the weight distribution characteristics of the truck. It does seem, from the gross weight and being lower than estimated, that this carrier overestimated weights when applying for the superload permit to compensate for variations in axle weight. Although, it seems that because the jeep axle group carried much less weight than the other axle groups that this forced the trailer and stinger axle groups closer to the estimated permit weights.

Citation 7 from the GDOT data is an 11-axle truck that has characteristics typical of a truck-jeep-trailer-stinger configuration. From axle spacings given in the spreadsheet, it appears to be a truck-tractor with four axles pulling a two-axle jeep and a three-axle trailer with a two-axle stinger.

Table 20 GA Data Truck 7: 11-Axle Truck-Jeep-Trailer-Stinger

Axle	Axle Spacing from #11 (ft)	Weight (lbs)			% Difference From Permit
		Permit	Measured	Difference From Permit	
1	109.17	12,000	12,220	220	1.8
2	92.50	17,000	13,380	-3,620	-21.3
3	88.00	17,000	14,360	-2,640	-15.5
4	83.50	17,000	14,200	-2,800	-16.5
5	70.33	21,000	19,780	-1,220	-5.8
6	65.83	21,000	19,880	-1,120	-5.3
7	28.67	18,000	17,380	-620	-3.4
8	23.67	18,000	17,400	-600	-3.3
9	18.67	18,000	18,580	580	3.2
10	4.50	20,000	17,500	-2,500	-12.5
11	0.00	20,000	16,740	-3,260	-16.3
Gross		199,000	181,420	-17,580	-8.8

The final GA example for this superload configuration does not exhibit a uniform weight distribution, though the carrier did not estimate it as such on the permit. There were two overweight axles, axle 9 at 580 pounds (3.2%) over the permit weight, and axle 1 at 220 pounds (1.8%) above the permit weight. The remaining axles ranged from 600 to 3,620 pounds (3.3 to 21.3%) below the estimated permit axle weights. The measured gross weight of the truck was 17,580 pounds (8.8%) below the estimated permit gross weight.

There were definite axle weight jumps observed between the axle groups and axle weight variations within axle groups. The tractor drive axle group had an axle weight variance of 980 pounds. Axles 3 and 4 are relatively close in weight having a difference of only 160 pounds, with most of the weight variance cause by axle 2. Axle 2 is possibly a lift axle that was set slightly too high and therefore carried lees weight than the other two ales in the group. There was an increase of approximately 5,500 pounds between the drive axles and the jeep axles. The jeep axle group, axles 5 and 6, were relatively uniform with a difference of only 100 pounds. There was a decrease of approximately 2,400 pounds between the jeep axles and the trailer axles. The first two trailer axles were very close in weight with a difference of only 20 pounds. The last trailer axle, axle 9, was approximately 1,100 pounds heavier than the other two axles in the group. In addition, the axle weights from this axle through the two stinger axles appear to decrease nearly linearly. This variation may be caused by the mechanism that transfers weight from the trailer to the stinger not being set properly or malfunctioning.

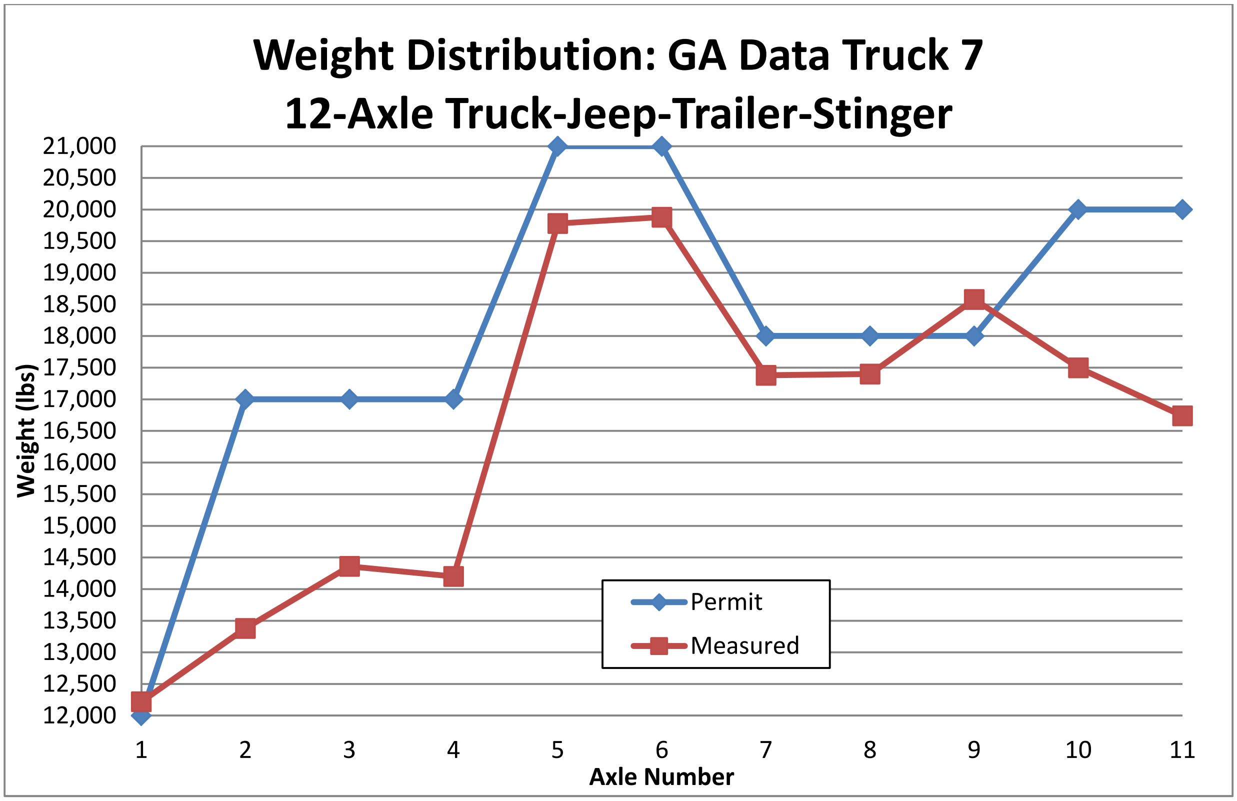

Figure 45 Weight Distribution - GA Data Truck 7: 11-Axle Truck-Jeep-Trailer-Stinger.

This variation may also account for the axle weight difference of 760 pounds observed in the stinger axles. Without information on the load, its size, and location on the trailer, it is difficult to determine any relationship between the load type and the weight distribution characteristics of the truck. It does seem that this carrier attempted to more accurately estimate axle weights and not just assume a uniform weight distribution, while still appearing to slightly overestimating axle weights to provide a cushion.

All seven GA examples for configuration 1 had measured weight distributions that were non-uniform. Since the GA data had a finer resolution than the NC citation data (axle weights instead of axle group weights), it can be seen that while most of the time axles within an axle group have a relatively uniform weight distribution this is not always the case for individual axles. When a lift axle is employed, it tends to carry a higher or lower weight than the other axles in the group. This possibly occurs for one of several reasons. First, the lift axle may not be designed to carry as much weight as the other axle, as some lift axles only have two tires as opposed to the four on a standard axle, lowering its weight capacity. Additionally, if the height of the lift axle is manually controlled by the driver, operator error may cause the axle to carry more weight or less weight by being set too low or high. In addition, malfunctioning equipment on the lift axle may cause it to carry a different amount of weight than the other axles in the group. Also observed in the GA data, was that the weight distribution within the stinger axle group generally was not uniform. As noted previously, hydraulics or mechanical air pressure is generally used to transfer weight to the stinger assembly. As for a lift axle if the weight transfer mechanism is manually operated by the driver, operator error may cause discrepancies in the weight distribution. Furthermore, design of the stinger assembly may play a large role in the effectiveness of transferring weight equally to every stinger axle. Equipment malfunction may also play a role in uneven weight distributions within the stinger axle group. Other axle groups also occasionally showed a non-uniform weight distribution, though without more information on the specific trucks it is difficult to explain why this occurs.

In addition, none of the examples from the GA data showed a uniform distribution between axle groups. Of the seven trucks, five estimated a uniform weight distribution on their superload permits, while two estimated non-uniform weight distributions. However, without more information from the carrier companies who applied from the permits it is difficult to tell why the two trucks estimated non-uniform distributions. All of the trucks in the GA data had gross weights lower than the estimated gross weight on the superload permit. The gross weights ranged from 2.8% to 17.5% below permit estimates. Generally, it seems from the overestimation of gross truck weight and axle weight estimates around 20,000 pounds, the typical upper limit allowed, that carriers generally attempted to overestimate weights in order to provide themselves a buffer or cushion. Even the two trucks that estimated non-uniform axle weight distributions seemed to attempt to give themselves a buffer of at least 500 pounds per axle. Although seen in the data, this did not preclude the trucks from having overweight axles. One truck had no overweight axles, three trucks had one overweight axle, and three trucks had two overweight axles. The percent difference from the estimated permit weight for the overweight axles ranged from 1.7% to 7.5%.

2.5.1.4 Configuration 1 Summary

None of the fourteen examples of configuration 1 showed a uniform axle weight distribution. The 10-axle Progress Energy truck did not have a permit available for comparisons of estimated weight distributions to measured distributions. Of the remaining 13 examples for this configuration, nine estimated uniform axle weight distributions while four estimated non-uniform distributions. A summary table of the configuration 1 trucks is given in Table 21 below.

The 13-axle mobile transformer had a load that comprised the entire body of, was permanently attached to the trailer, and non-uniform in weight. This would explain why a non-uniform axle weight distribution was estimated for this truck. A Progress Energy official stated that the axle weight distribution was estimated by the trailer manufacturer and that they used these estimates when applying for a superload permit. It appears that there was no effort to overestimate the weights for the truck to provide a buffer for weight deviations from the permit. Also noted, was that the lift axle on the tractor was malfunctioning and it was difficult to get this axle to carry weight, causing other nearby axles to carry more weight. These two reasons would explain why this truck had eight overweight axles and the steering axle was 21.8% overweight. No information is known on the load type, size, or positioning for any of the other configuration 1 examples. However, in the GA data it appeared that there were similar lift axle problems as with the Progress Energy mobile transformer. This was not observable in the NC citation data because the NC SHP records axle group weights and not individual axle weights.

Of the thirteen examples, number of overweight axles ranged from 0 to 9, and percent overweight ranged from negligible to 21.8%. Only two of the trucks were observed to be over gross weight with the highest being 2.3% over estimated gross weight, with the rest of the trucks being below estimated gross weight. The average number of overweight axles for the data was 2.8, although this may be skewed slightly high because of the three trucks that had a large number of overweight axles. The median number of overweight axles for the sample group was 1. The average percent over permit estimate for axle weight was 6.4%. The sample trucks averaged 7.5% below estimated gross weight listed on the superload permit.

Table 21 Configuration 1 Summary

Truck	# of Axles	Uniform Estimate	# Overweight Axles	% Over Permit Axle Estimate		% Diff Gross Weight
				Maximum	Minimum	
PE Mobile Transformer	13	No	8	21.8	0.5	-0.4
NC 7/2007	9	Yes	1	15.7	--	-16.4
NC 6/2008	8	No	7	15	0	2.3
NC 7/2008	13	Yes	1	4.4	--	-8.1
NC 12/2008	13	Yes	9	4.3	0.3	0.1
NC 3/2011	13	Yes	1	16.7	--	-9.4
GA Truck 1	11	Yes	1	6.1	--	-5.2
GA Truck 2	11	No	1	1.7	--	-2.8
GA Truck 3	11	Yes	2	7.5	7	-14.6
GA Truck 4	13	Yes	0	--	--	-17.5
GA Truck 5	12	Yes	1	2.2	--	-8.3
GA Truck 6	13	Yes	2	4.6	2.5	-9
GA Truck 7	11	No	2	3.2	1.8	-8.8
Average	**12**	**--**	**2.8**	**6.4**		**-7.5**

2.5.2 Configuration 2: Drop-Deck Gooseneck

The superload configuration 2, drop-deck gooseneck style trucks, employs a load deck suspended between axle groups with goosenecks and transfer load to the axles through the use of connecting bridges. They come in two main types, a single-lane, having only one axle per axle-line and a dual-lane, having two axles per axle-line. The dual-lane trucks have the ability to adjust their axle-line widths to alter their footprint on the ground and spread out load on the pavement. Data was gathered for four configuration 2 trucks from the NC SHP and GDOT. Weight data for one truck was supplied by the NC SHP through a citation and cross-referenced with the superload permit from the NCDOT. Weight data for the final three trucks of this configuration was provided by GDOT through permits of trucks originating at the Port of Savannah. The data and subsequent analysis for each of these trucks will be discussed in further detail below.

2.5.2.1 North Carolina State Highway Patrol Citation

In January of 2012, the NC SHP weighed a 19-axle-line dual-lane transporter operating in Polk County, NC. The truck was traveling from the SC state line to the TN state line. The truck is shown in Figure 46 below. This truck had a VIN number for the tractor unit that did not match the VIN listed on the superload permit, thus invalidating the permit and prompting the NC SHP to weigh the truck. The resulting citation was supplied to the NCSU team by the SHP, and the original superload permit with corresponding truck schematic, shown in Figure 47 below, were obtained from the Oversize-Overweight Permit department at NCDOT for comparison to the NC SHP's measured weights.

Figure 46 19-Axle-Line Dual-lane Transporter Weighed by NC SHP in Polk Co, NC.[24]

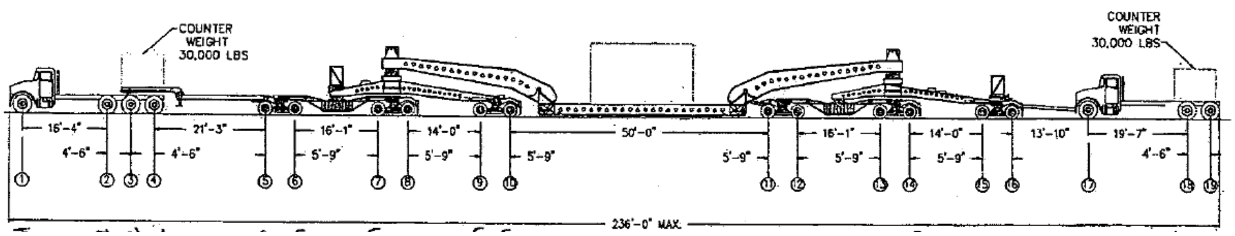

Figure 47 19-Axle-Line Dual-Lane Transporter Schematic.[25]

This citation data, though valuable, has several limitations that should be noted. The NC SHP, in fairness to the carrier, always rounds portable scale readings down to the nearest 100 pounds. The NC SHP uses a different definition of axle from this study; it considers any set of laterally arranged tires an axle, while for the purpose of this study an axle has been defined as a set of four interconnected tires and an axle-line as a set of laterally arranged axles. Because of the definition used by the NC SHP, weights are only given by axle-line. Finally, the NC SHP, in adhering to NC weight laws, weighs and records weights of axle groups together and therefore weights are given by axle group and not individual axles. An example of The NC SHP preparing to weight a tandem axle-line group for this truck is shown in Figure 48 below.

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[24] Picture Source: NC SHP
[25] Source: NCDOT

Figure 48 NC SHP Preparing to Weigh a Tandem Axle-Line with Portable Scales.[24]

To analyze the data from the citation, weight for each axle-line group was assumed to be equally distributed to the axle-lines in those respective groups. These weights were then compared to the carrier estimated weights from the superload permit and a table and graph of the measured weight distribution verses the estimated weight distribution are supplied below.

Table 22 NC Citation 19-Axle-Line Dual-Lane Drop-Deck Gooseneck

Axle-Line	Axle-Line Spacing From #19 (ft)	Weight (lbs)			% Difference from Permit
		Permit	Measured	Difference from Permit	
1	229.17	15,000	12,100	-2,900	-19.3
2	212.83	20,000	15,667	-4,333	-21.7
3	208.33	20,000	15,667	-4,333	-21.7
4	203.83	20,000	15,667	-4,333	-21.7
5	182.58	40,000	41,100	1,100	2.8
6	176.83	40,000	41,100	1,100	2.8
7	160.75	40,000	37,800	-2,200	-5.5
8	155.00	40,000	37,800	-2,200	-5.5
9	141.00	40,000	37,150	-2,850	-7.1
10	135.25	40,000	37,150	-2,850	-7.1
11	85.25	40,000	37,900	-2,100	-5.3
12	79.50	40,000	37,900	-2,100	-5.3
13	63.42	40,000	37,700	-2,300	-5.8
14	57.67	40,000	37,700	-2,300	-5.8
15	43.67	40,000	37,400	-2,600	-6.5
16	37.92	40,000	37,400	-2,600	-6.5
17	24.08	12,000	12,700	700	5.8
18	4.50	20,000	14,150	-5,850	-29.3
19	0.00	20,000	14,150	-5,850	-29.3
Gross		607,000	558,200	-48,800	-8.0

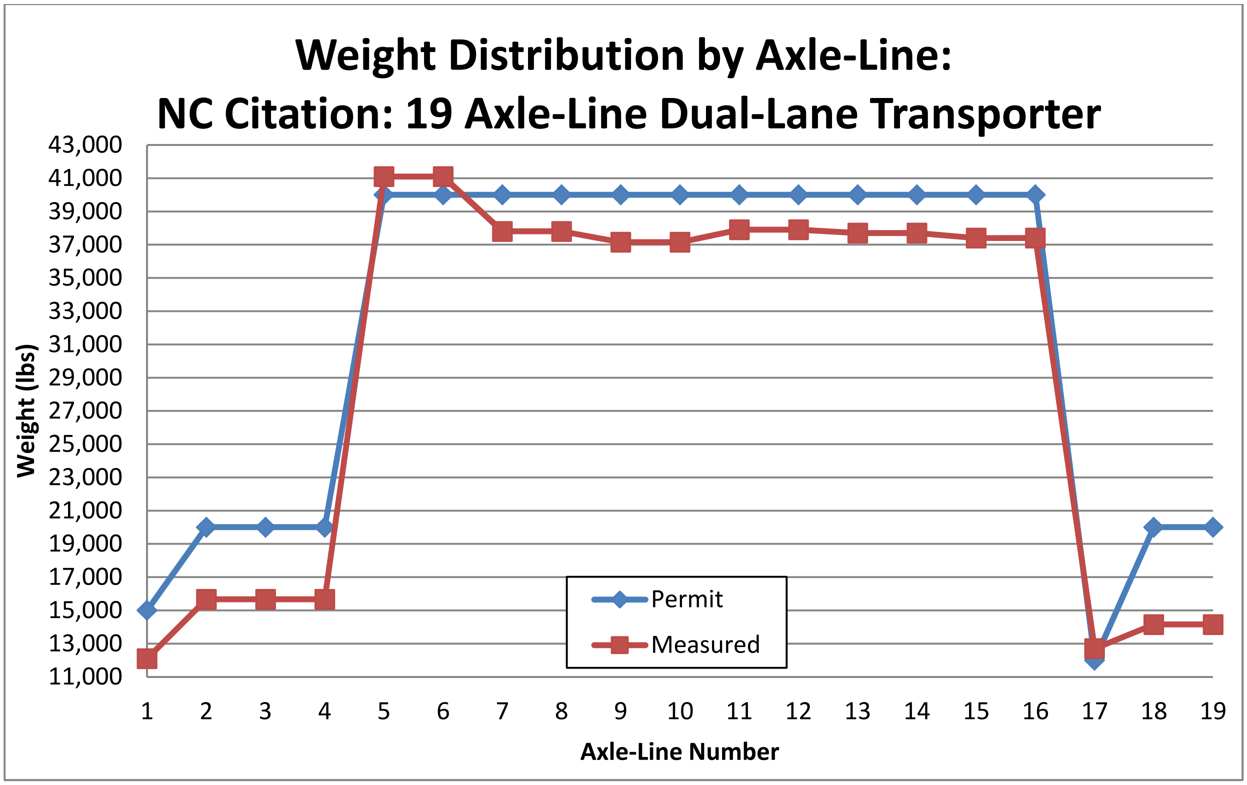


Figure 49 Weight Distribution - NC Citation 19 Axle-Line Dual-Lane.

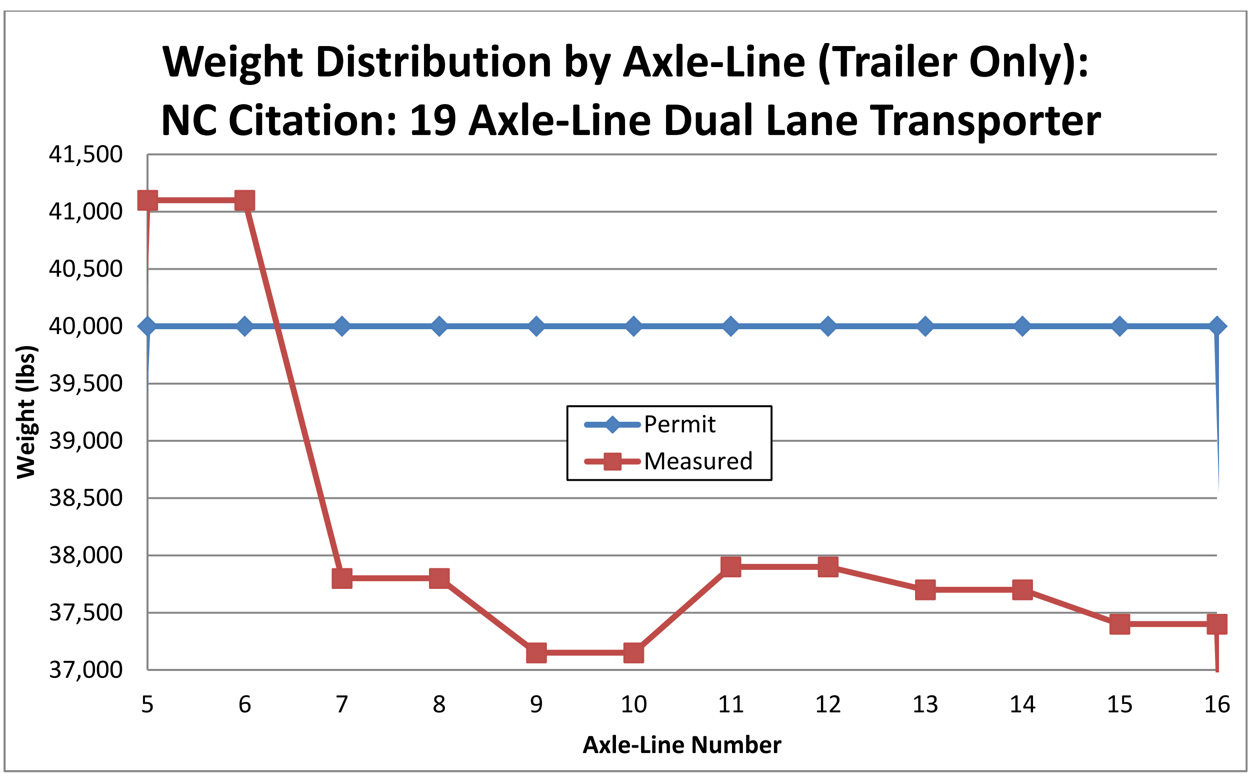


Figure 50 Weight Distribution - NC Citation 19 Axle-Line Dual-Lane (Trailer Only).

As can be seen in Figure 49 above, most of the axle-lines are below the estimated permit weight, with only three overweight axles-lines, the first two trailer axle-lines, and the steer axle of the push truck. The two overweight trailer axles-lines are 1100 pounds (2.8%) greater than the permitted weight and have a noticeably higher weight than the rest of the trailer axle-lines being approximately 3,000 pounds heavier. The steer axle for the push truck is 700 lbs (5.8%) over the estimated permit weight. The remaining axle-lines range from 5850 to 2200 pounds (29.3% to 5.3%) below permitted weight. The measured overall gross weight of the vehicle was 48,800 pounds (8%) lower than the gross weight estimated on the permit.

The weight distribution across the trailer appears fairly uniform across the axle-lines with the exception of the first two trailer axle-lines, axle-lines 5 and 6. As noted before, this axle-line group is approximately 3,000 pounds heavier per axle-line than the other trailer axle-line groups. This may be caused by the extra weight of the coupling mechanism, hooking the pull tractor to the trailer, being carried by this axle group. Trucks of this configuration often use counterweights to add weight to the tractor drive axles for increased traction. As seen in Figure 49 above, the tractor drive axles carried 4,333 pounds per axle less than estimated; therefore, some of the weight from the counterweight was possibly transferred through the coupling to the first trailer axle-line group. Although these are possible explanations, the actual reason for the weight distribution discrepancy is unknown. The remaining trailer axle-line groups had a much more uniform weight distribution having a weight variance of only 750 pounds per axle-line. Assuming weight within an axle-line group distributes equally to each axle, this equates to a weight variability of 375 pounds per axle. With the vehicle being significantly under its permitted gross weight and most axle-lines also being under the estimated permit weights, it seems that the carrier over-estimated the weight for the superload permit to compensate for variations in axle-line weight.

2.5.2.2 Georgia DOT Port of Savannah Permits

GDOT regularly requires superloadS originating in the Port of Savannah to be weighed by the GA SHP before a permit is issued. When the permit is then issued, the weights listed on the permit are the actual measured weights and not the carrier-estimated weights. Also, the GDOT differentiates between axle-lines and axles for superload permits, listing separate weights for the left and right axle in an axle-line. This is in contrast with NC policy, which treats an axle-line as a single axle. The GA SHP records weights for individual axles, as opposed to NC SHP’s policy recording weights for axle-line groups. This will allow a finer analysis of the weight distribution characteristics of these configuration 2 trucks.

GDOT supplied three applicable permits for analysis in this study. Only one of the permits supplied had a corresponding truck schematic available and because of GA policy of issuing the superload permits with measured weights this is the only vehicle from GA with carrier-estimated weights. The other two trucks were determined to be configuration 2 trucks by comparing axle-line weights and spacings listed on the superload permit to axle-line weights and spacings of known configuration 2 trucks. One of these trucks was a single-lane vehicle and the other was a dual-lane vehicle. Since these two vehicles do not have carrier-estimated weights, the analysis for these trucks is limited.

Vehicle 1 (GA permit #K0455281) was issued in May of 2011 for a trip from Savannah, GA to the Alabama state line on I-85. There was no truck schematic available for this truck and the carrier-estimated weights are unknown. The axle spacings listed on the permit match those typical for a single-lane configuration 2 truck. It had a single pull tractor with four axles and a trailer with 15 axles and the load deck located between axles 10 and 11. A photograph of a similar is shown below for reference.

Figure 51 Guy M. Turner Single-Lane 19 Axle Drop-Deck Gooseneck.[26]

Table 23 GA Permit #K0455281

Axle	Axle Spacing from #19 (ft)	Measured Weight (lbs)
1	181.75	11,600
2	165.33	15,600
3	160.92	22,400
4	156.42	22,100
5	141.33	20,400
6	136.33	20,300
7	131.33	19,900
8	117.17	20,000
9	112.17	20,300
10	107.08	19,800
11	58.42	18,300
12	53.42	19,800
13	48.42	19,800
14	34.25	19,300
15	29.33	19,300
16	24.17	18,700
17	10.17	20,000
18	5.17	19,400
19	0.00	19,200
Gross Weight		366,200

[26] Picture Source: http://www.guymturner.com/19_Axle_gallery/19.axle.gallery.index.htm

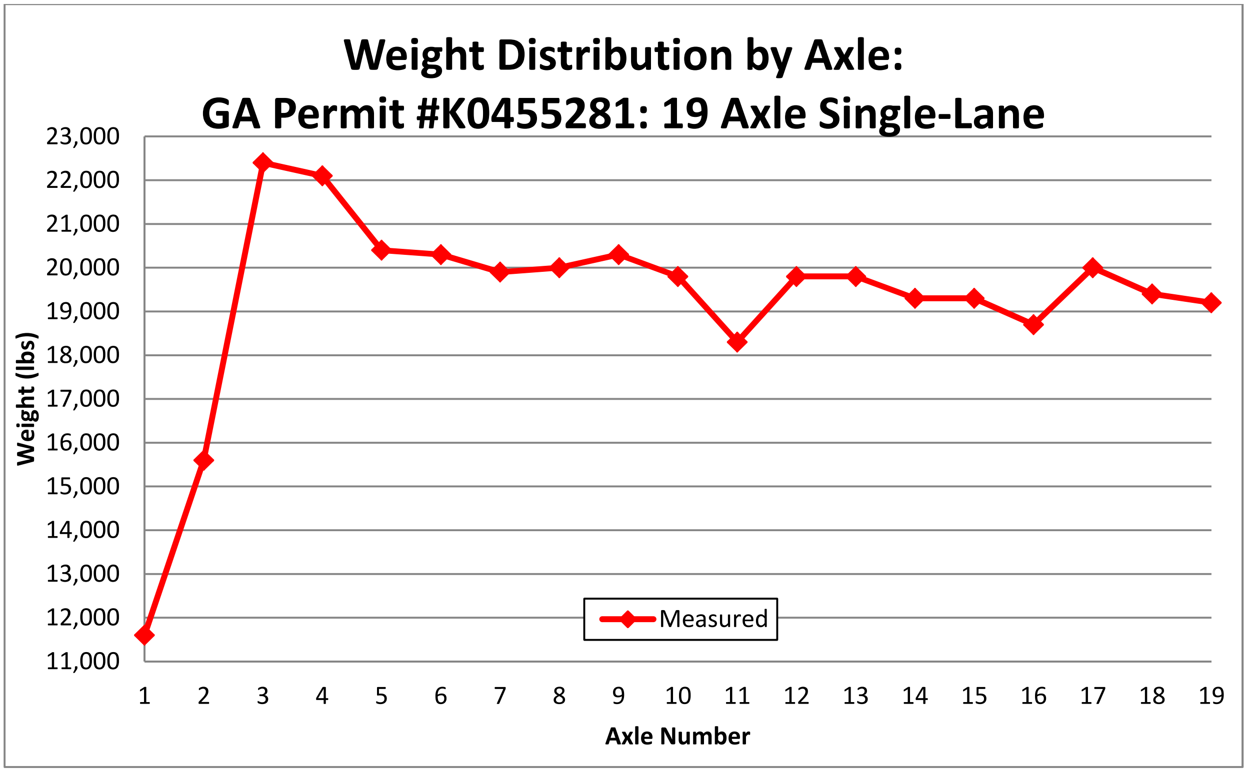


Figure 52 Weight Distribution by Axle - GA Permit #K0455281.

This truck had a gross weight of 366,200 pounds and trailer axle weights ranging from 18,300 to 20,400 pounds. As seen in Figure 52 above, axle 2 had a much lower weight than the other two axles in the same group, axles 3 and 4, weighing approximately 6,800 pounds less. Axle 2 is most likely a lift axle that may not have been designed to carry as much weight as a standard axle or was set too high causing it to carry less weight than the other axles in that axle group. Axles 3 and 4 have only a difference of 300 pounds but are approximately 2,000 pounds heavier than the trailer axles. This may be caused by the counterweight frequently used by these trucks to increase traction on the drive tires of the tractor.

Overall, the trailer axles have a weight variance of 2,100 pounds and seem to decrease from front to back. The decrease in weight from front to back on the trailer may be caused by the load being positioned slightly forward of the center of gravity of the trailer or could also be cause by the truck being weighed on a slight incline. The trailer axles in front of the load deck, axles 5 through 10, had a relatively uniform weight distribution varying by only 600 pounds. The trailer axles following the load deck, axles 11 through 19, had a much less uniform weight distribution varying by 1,500 pounds. One third of this variance occurs because of the low weight recorded for axle 11, 18,300 pounds. Without more information, it is difficult to determine a reason for this anomalous reading. The last axle group (axles 17, 18, and 19) has a range of 800 pounds and there is a 1,300-pound increase from axle 16 of the previous axle group to axle 17. More information is needed to draw reasonable conclusions as to why the axles following the load deck had a much less uniform weight distribution than the axles preceding the load deck.

Vehicle 2 from GA (permit #K0382781) was issued in April of 2011 for a trip from Savannah, GA to West Point, GA. There was no truck schematic available for this truck and the carrier-estimated weights are unknown. From the axle spacings listed on the permit, it was determined to be a dual-lane configuration 2 truck. It has a pull tractor with four axles, a trailer with 12 axles-lines with the load deck located between axles-lines 10 and 11, and a push tractor with three axles. A photograph of a similar truck without a push tractor is shown below for reference.

Figure 53 Guy M. Turner Dual-Lane Drop-Deck Gooseneck.

The weight distribution for this truck was analyzed by axle-line to make it comparable to the NC citation data. Weights for the left and right axles were summed across each axle-line and the results are given in Table 24 below.

Table 24 Weight by Axle-Line GA Permit #K0382781.

Axle-Line	Axle-Line Spacing from #19(ft)	Measured Axle-Line Weight (lbs)
1	246.33	11,600
2	230.00	12,900
3	225.50	17,300
4	221.08	17,200
5	199.83	45,000
6	194.08	45,400
7	178.08	41,700
8	172.33	42,300
9	158.33	42,200
10	152.58	42,300
11	86.33	43,100
12	80.50	42,800
13	64.50	43,400
14	58.67	43,000
15	44.75	44,200
16	39.00	44,300
17	25.50	13,000
18	4.50	17,300
19	0.00	16,700
Gross Weight		625,700

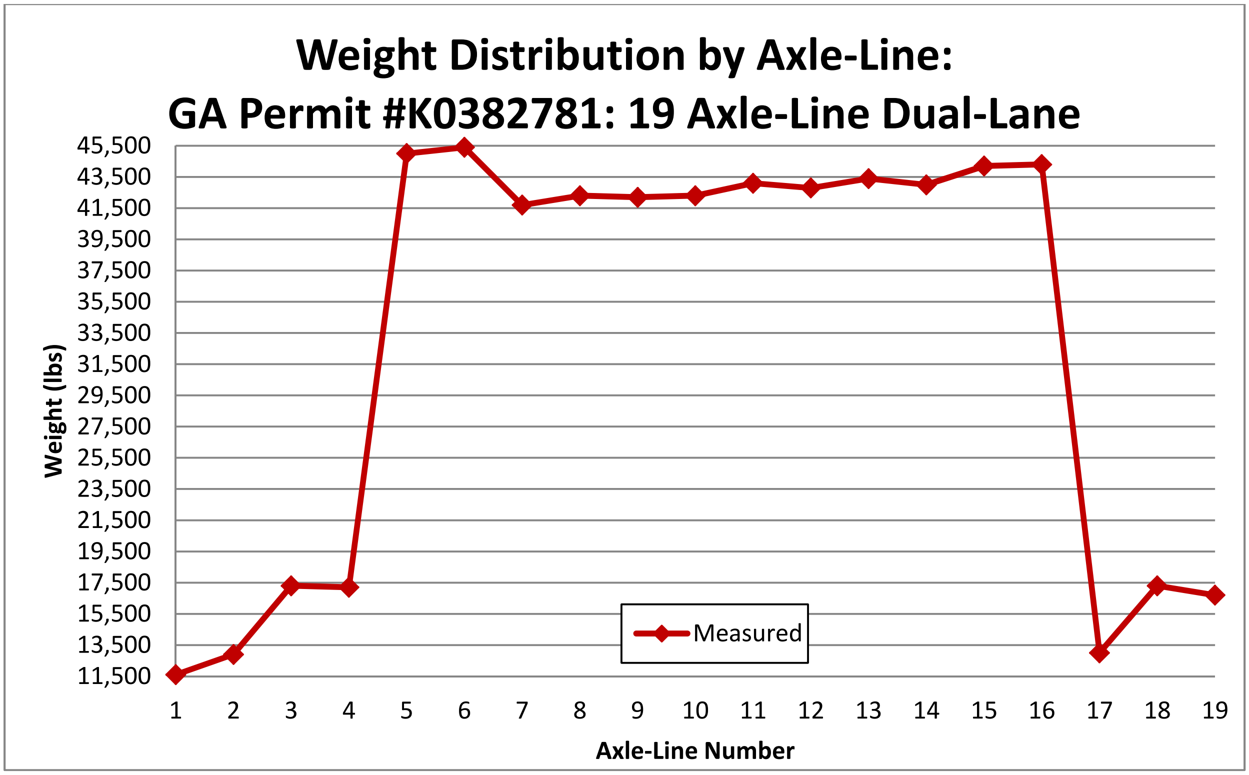


Figure 54 Weight Distribution by Axle-Line - GA Permit #K0382781.

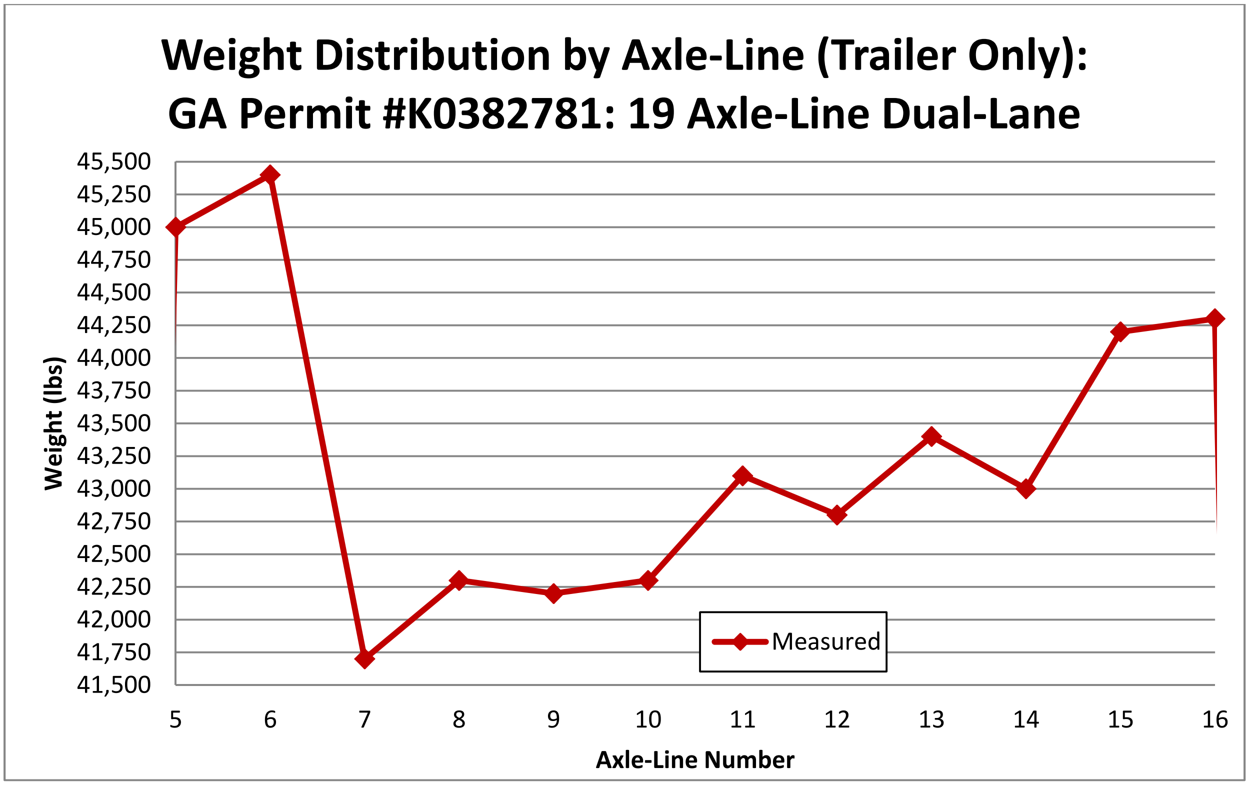


Figure 55 Weight Distribution by Axle-Line (Trailer Only) – GA Permit #K0382781.

This truck has a gross weight of 627,700 pounds and trailer axle-line weights ranging from 41,700 to 45,400 pounds. As seen in Figure 54 above, axle 2, on the pull tractor, has a much lower weight than the other two axles in the same group, axles 3 and 4, weighing approximately 4,300 pounds less. Axle 2 is most likely a lift axle that may not have been designed to carry as much weight as a standard axle or was set too high causing it to carry less weight than the other axles in that axle group. Conversely, axles 3 and 4 are relatively uniform in weight having only a difference of 100 pounds. The drive axles on the push tractor are also relatively uniform having a weight difference of 600 pounds.

Overall, the trailer axles-lines have a weight variance of 3,700 pounds with much of the variance caused by the first two trailer axle-lines, axle-lines 5 and 6. These two axle-lines carry significantly more weight than the other trailer axle-lines as was observed in the NC citation example. This may be caused by the extra weight of the coupling mechanism, hooking the pull tractor to the trailer, being carried by this axle group. Trucks of this configuration often use counterweights to add weight to the tractor drive axles for increased traction and some of the weight from the counterweight was possibly transferred through the coupling to the first trailer axle-line group. Although these are possible explanations, the actual reason for the weight distribution discrepancy is unknown. There is a significant decrease in axle-line weight, 3,700 pounds, from axle-line 6 to 7. Axle-line weights then seem to increase from front to rear starting at axle-line 7. The weight variance for axle-lines 7 through 16 is 2,600 pounds. The increase in weight from front to back on the trailer may be caused by the load being positioned slightly behind of the center of gravity of the trailer or could also be cause by the truck being weighed on a slight incline. There is also a significant weight increase of approximately 1,200 pounds, from axle-line 14 to the last two trailer axle-lines, axle-lines 15 and 16. Since this truck has a push tractor, this may be caused by the last two trailer axle-lines carrying extra weight from the coupling mechanism. Next, the data for this truck was analyzed by axle and Data is given in Table 25 on page 57.

As seen in Figure 56 on page 57, the left and right side axles are relatively uniform within an axle-line, with four exceptions. Overall, the right side axles are generally heavier than the left side axles, which may be due to the load being slightly shifted to the right of the center of gravity of the trailer. It could also be cause by the truck being weighed on a slight incline tilting the truck slightly to the right. The weight variance between axles in an axle-line ranges from 100 to 1,200 pounds. The largest weight variance between axles in an axle-line occurs in axle-line 13. Four of the axle-lines have weight variances of 800 pounds or greater, with the remaining eight axle-lines having weight variances between axles of 600 pounds or less. The axle-lines with the larger weight variances occur within two axle-line groups. Axle-lines 7 and 8 both have a 900-pound weight variance between left and right axles. Axle-lines 13 and 14 have weight variances of 1,200 pounds and 800 pounds respectively between left and right axles. Since both of these weight distribution irregularities occur within axle-line groups, it is possible that unlevel ground or an equipment malfunction caused the right side axles to carry much more weight than the left side axles.

Table 25 Weight by Axle GA Permit #K0382781.

Axle-Line	Axle-Line Spacing from #22 (ft)	Axle Weight (lbs)		
		Measured		
		Left Side Trailer	Tractor	Right Side Trailer
1	246.33		11,600	
2	230.00		12,900	
3	225.50		17,300	
4	221.08		17,200	
5	199.83	22,200		22,800
6	194.08	22,600		22,800
7	178.08	20,400		21,300
8	172.33	20,700		21,600
9	158.33	21,200		21,000
10	152.58	21,000		21,300
11	86.33	21,300		21,800
12	80.50	21,300		21,500
13	64.50	21,100		22,300
14	58.67	21,100		21,900
15	44.75	21,800		22,400
16	39.00	22,200		22,100
17	25.50		13,000	
18	4.50		17,300	
19	0.00		16,700	
Gross Weight		625,700		

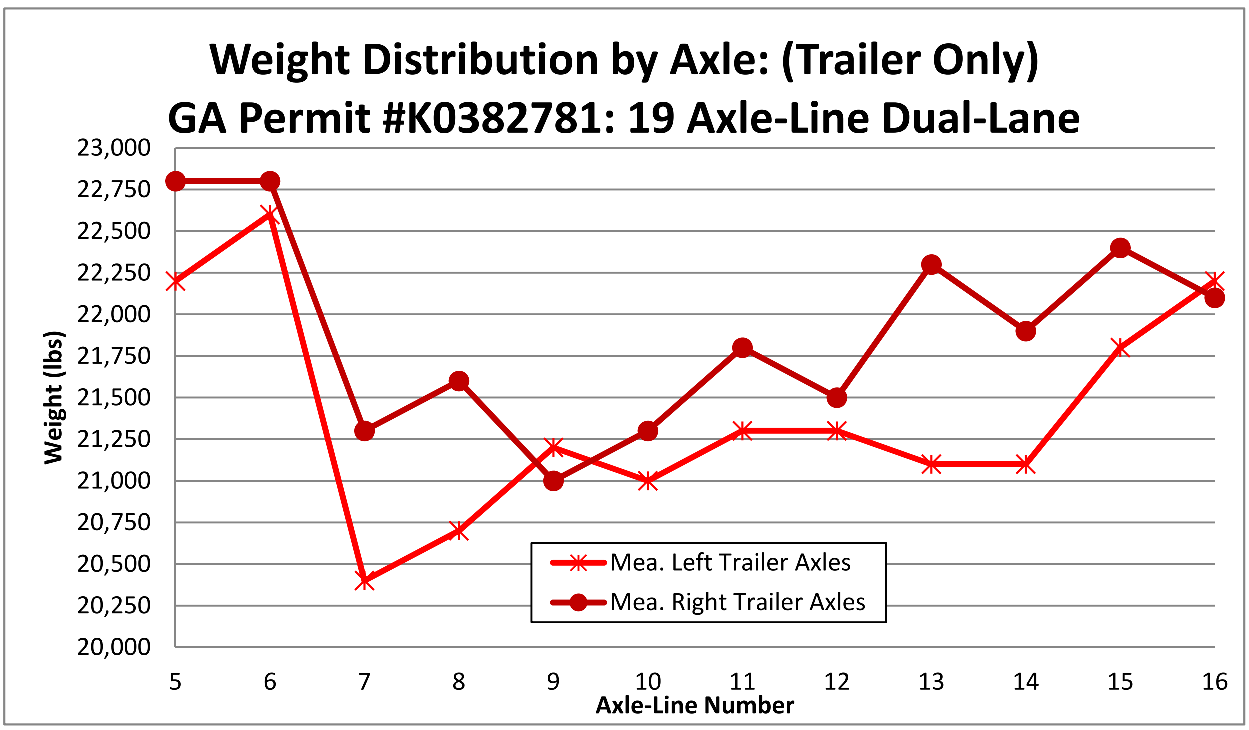


Figure 56 Weight Distribution by Axle (Trailer Only) – GA Permit #K0382781.

The final example from the GA data is GA permit #K0383872. The permit was issued in April of 2011 for a trip from Savannah, GA to West Point, GA. The truck schematic, shown in Figure 57 below, was also supplied and it had the carrier-estimated weights listed for comparison to the measured weights.

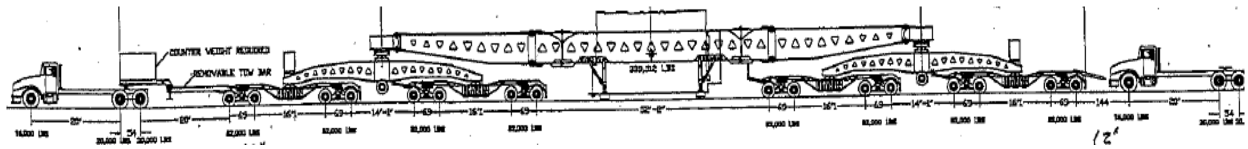


Figure 57 Truck Schematic GA Permit #K0383872 McTyre Trucking Co.[27]

Weight distribution for this truck was analyzed by axle-line to make it comparable to the NC citation data. Weights for the left and right axles were summed for every axle-line and the results are given in Table 26 below.

Table 26 Weight by Axle-Line GA Permit #K0383872

Axle-Line	Axle-Line Spacing from #22 (ft)	Axle-Line Weight (lbs)			% Difference From Est.
		Estimated	Measured	Difference from Est.	
1	273.42	16,200	15,800	-400	-2.5
2	253.42	20,000	19,800	-200	-1.0
3	248.92	20,000	19,600	-400	-2.0
4	288.00	41,000	41,500	500	1.2
5	222.17	41,000	40,000	-1,000	-2.4
6	206.08	41,000	38,300	-2,700	-6.6
7	200.33	41,000	39,700	-1,300	-3.2
8	186.33	41,000	39,500	-1,500	-3.7
9	180.58	41,000	39,200	-1,800	-4.4
10	164.42	41,000	38,900	-2,100	-5.1
11	158.58	41,000	38,800	-2,200	-5.4
12	106.83	41,000	39,200	-1,800	-4.4
13	101.17	41,000	39,300	-1,700	-4.1
14	84.92	41,000	39,100	-1,900	-4.6
15	79.17	41,000	39,400	-1,600	-3.9
16	64.83	41,000	39,800	-1,200	-2.9
17	59.17	41,000	39,400	-1,600	-3.9
18	43.00	41,000	39,300	-1,700	-4.1
19	37.17	41,000	38,900	-2,100	-5.1
20	24.58	16,200	15,900	-300	-1.9
21	4.58	20,000	17,300	-2,700	-13.5
22	0.00	20,000	17,600	-2,400	-12.0
Gross Weight		768,400	736,300	-32,100	-4.2

[27] Source: GDOT

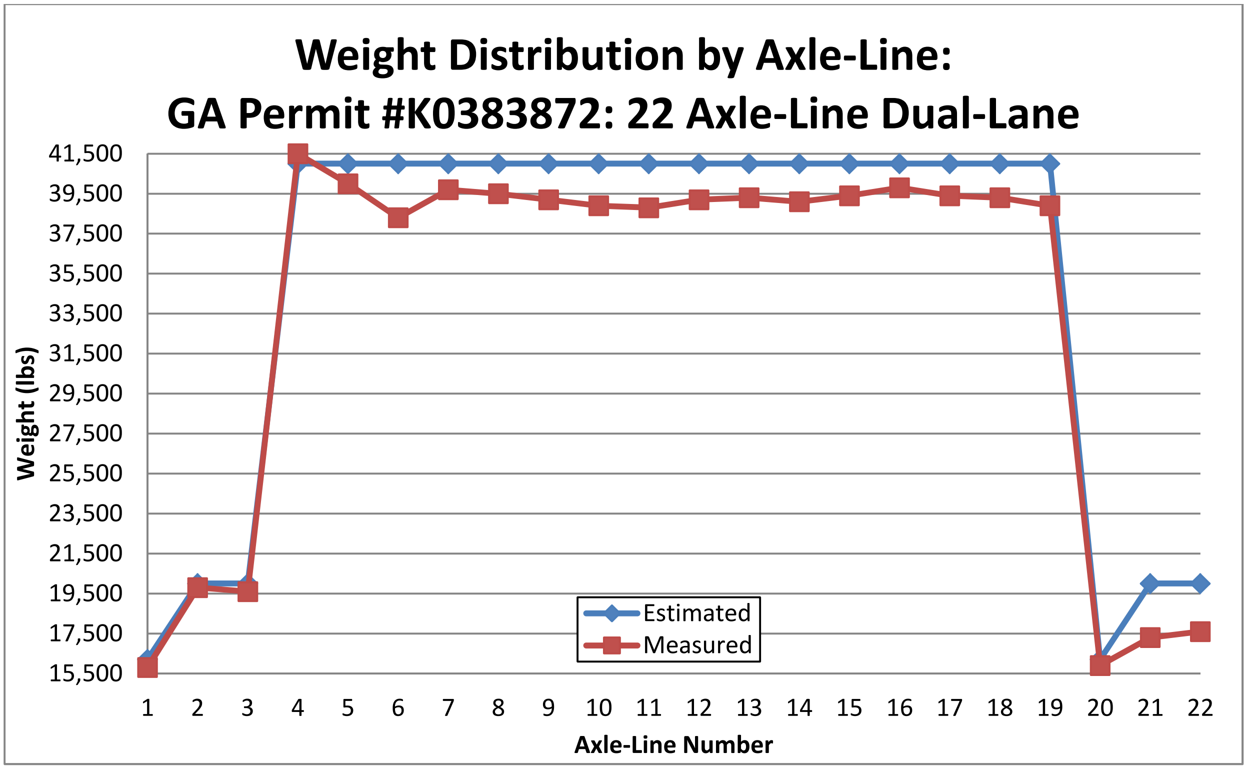


Figure 58 Weight Distribution by Axle-Line - GA Permit #K0383872.

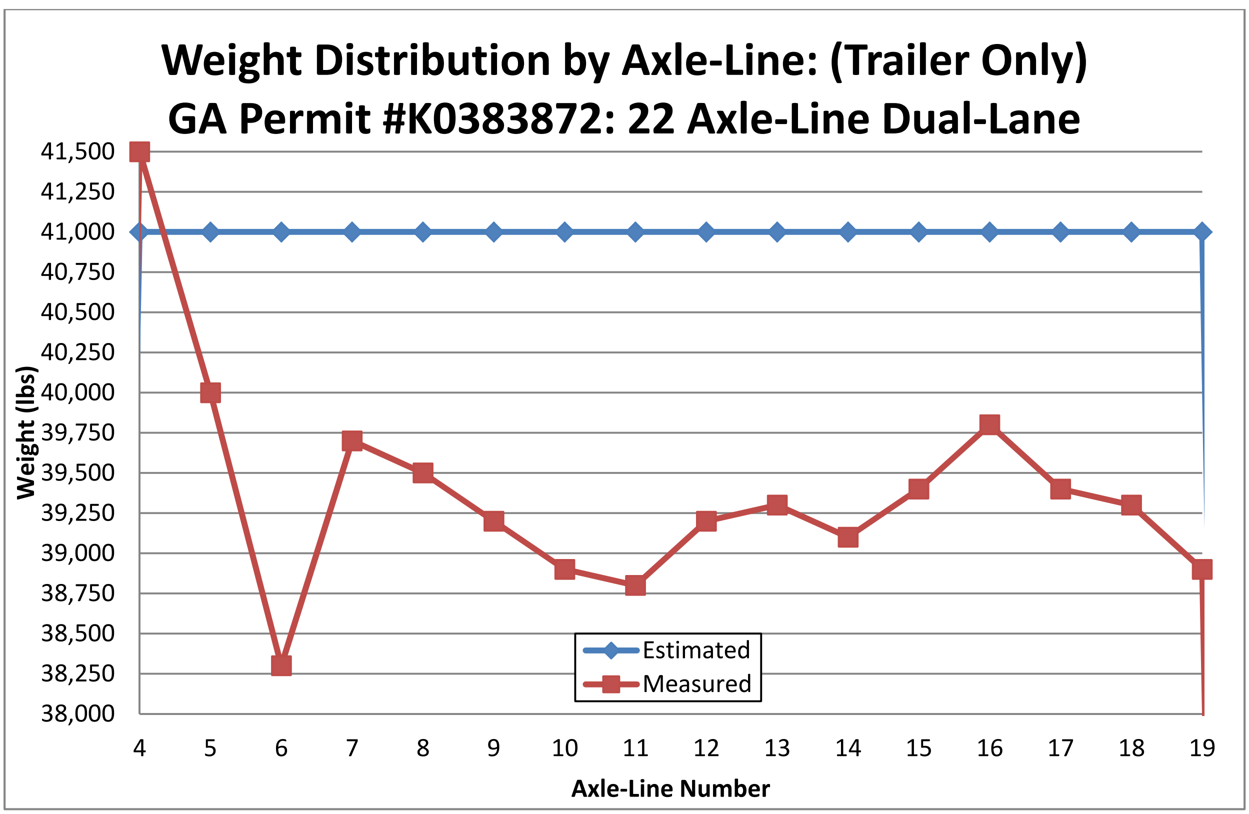


Figure 59 Weight Distribution by Axle-Line (Trailer Only) - GA Permit #K0383872.

The truck had only one axle-line that was over the estimated weight, axle-line 4, which was only 500 pounds (1.2%) over the permitted value. This is the first trailer axle-line and was approximately 1,500 pounds heavier than the rest of the trailer axle-lines. This may be caused by the extra weight of the coupling mechanism, hooking the pull tractor to the trailer, being carried by this axle-line. Trucks of this configuration often use counterweights to add weight to the tractor drive axles for increased traction and some of the weight from the counterweight was possibly transferred through the coupling to the first trailer axle-line. The rest of the trailer axle-lines ranged from 1,000 to 2,700 pounds (2.4% to 6.6%) below the estimated axle-line weights. The tractor axle for both tractors ranged from 200 to 2,700 pounds (1.0% to 13.5%) under the carrier-estimated axle weights. The gross weight of the truck was 32,100 pounds (4.2%) less than the estimated gross weight of the truck. The drive axles of the pull tractor and the push tractor were relatively uniform having a weight variance of 200 pounds and 300 pounds respectively. The trailer axle-lines had a weight variance of 3,200 pounds, and as noted previously much of this variance was due to the first axle-line, axle-line 4, weighing significantly more than the others do. As seen in Figure 59 above, axle-line 6 weighed considerably less than the other trailer axle-lines, and without more information it is impossible to determine the reason for this discrepancy. Neglecting those two axle-lines, the rest of the axle-lines have a relatively uniform weight distribution and removing those two axle-lines reduces the axle-line weight variance to 1,200 pounds. This would equate to a variance of 600 pounds per axle, since there are two axles per axle-line. The weights for the trailer only were analyzed by axle and are shown in Table 27 below.

Table 27 Weight by Axle GA Permit #K0383872 (Trailer Only)

Axle-Line	Axle-Line Spacing from #22 (ft)	Axle Weight (lbs)						% Difference From Estimated	
		Estimated		Measured		Difference from Estimated			
		Left	Right	Left	Right	Left	Right	Left	Right
4	288.00	20,500	20,500	21,200	20,300	700	-200	3.4	-1.0
5	222.17	20,500	20,500	20,000	20,000	-500	-500	-2.4	-2.4
6	206.08	20,500	20,500	20,000	18,300	-500	-2,200	-2.4	-10.7
7	200.33	20,500	20,500	21,000	18,700	500	-1,800	2.4	-8.8
8	186.33	20,500	20,500	21,000	18,500	500	-2,000	2.4	-9.8
9	180.58	20,500	20,500	20,700	18,500	200	-2,000	1.0	-9.8
10	164.42	20,500	20,500	19,900	19,000	-600	-1,500	-2.9	-7.3
11	158.58	20,500	20,500	20,100	18,700	-400	-1,800	-2.0	-8.8
12	106.83	20,500	20,500	20,000	19,200	-500	-1,300	-2.4	-6.3
13	101.17	20,500	20,500	19,900	19,400	-600	-1,100	-2.9	-5.4
14	84.92	20,500	20,500	19,300	19,800	-1,200	-700	-5.9	-3.4
15	79.17	20,500	20,500	19,600	19,800	-900	-700	-4.4	-3.4
16	64.83	20,500	20,500	20,700	19,100	200	-1,400	1.0	-6.8
17	59.17	20,500	20,500	20,400	19,000	-100	-1,500	-0.5	-7.3
18	43.00	20,500	20,500	19,600	19,700	-900	-800	-4.4	-3.9
19	37.17	20,500	20,500	19,500	19,400	-1,000	-1,100	-4.9	-5.4

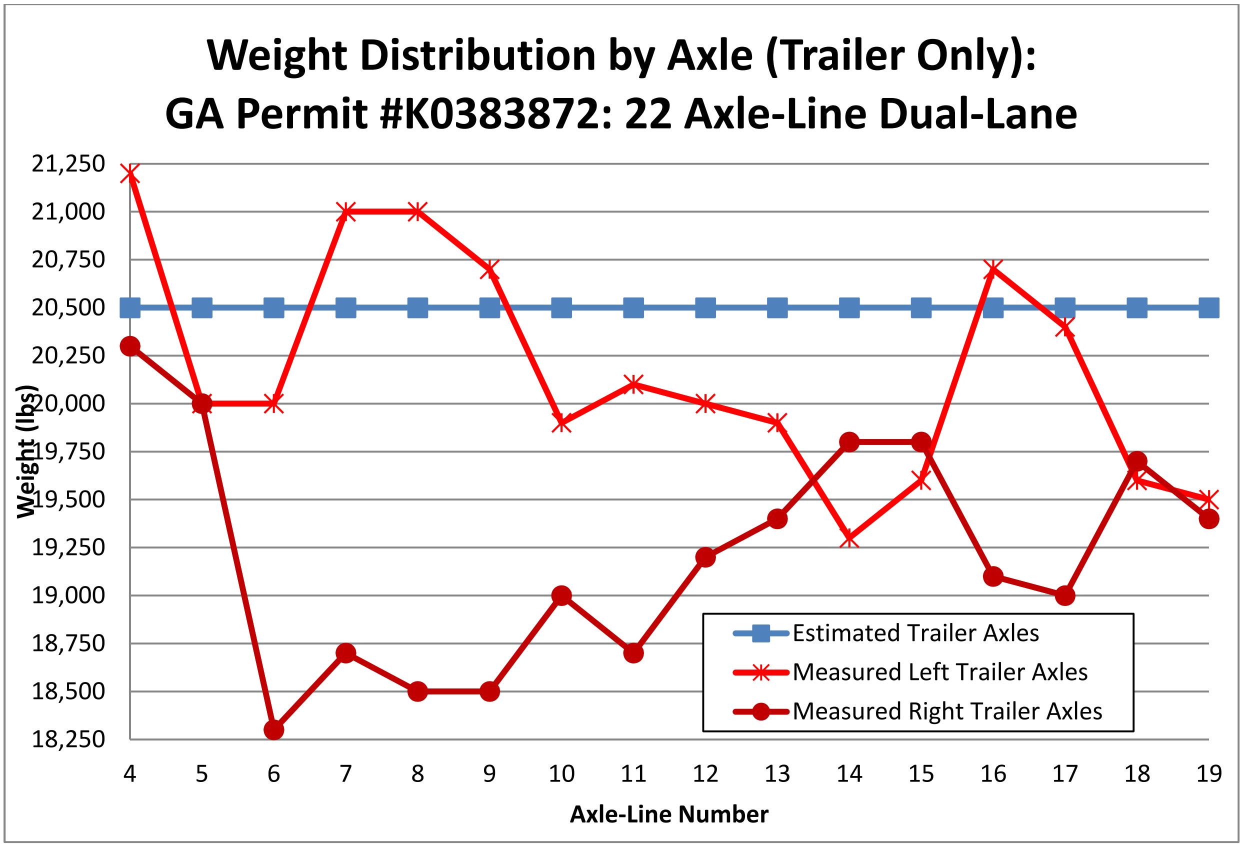


Figure 60 Weight Distribution by Axle (Trailer Only) - GA Permit #K0383872.

Figure 60 above displays the left and right side axles, which do not exhibit an even weight distribution. The left side axles are generally heavier than the right side axles with 51.2% of the trailer weight carried on the left side axles and 48.8% of the trailer weight carried on the right side axles. This may be caused by the load being slightly left of the center of gravity of the trailer or the truck being weighed on a slight incline, either of which would shift the weight distribution of the trailer. There are five axles along the left side exceeding the estimated axle weight, ranging from 200 to 700 pounds (1.0% to 3.4%) above the estimated axle weight. The remaining axles range from 100 to 2,000 pounds (0.5% to 9.8%) below estimated axle weights. Overall, the axles on both sides have a weight variance of 2,900 pounds, with the left side and right side axles having a weight variance of 1,900 pounds and 2,000 pounds respectively. The weight variance between axles within an axle-line ranges from 0 to 2,500 pounds. Nine out of eleven trailer axle-lines had a weight variance between axles of 900 pounds or greater. This seems to indicate that for this example the weight distribution between trailer axles was non-uniform. Without more information on the load and the ground conditions at the time of the weighing, it is difficult to draw conclusions on the cause for the non-uniform weight distribution observed. It does appear that the carrier attempted to overestimate weights to account for variations in axle weight, since the gross weight and most axle weights were below estimates. The axles that exceeded estimates only did so by relatively small amounts.

2.5.2.3 Configuration 2 Summary

For superload configuration 2, data was collected for four trucks: One dual-lane truck from an NC citation, and one single lane truck and two dual-lane trucks from GA permits. When the weight data was aggregated by axle-line, it was found that weights tend to distribute relatively uniformly across the trailer axle-lines. Although, it was observed in all the dual-lane examples that the first one or two trailer axle-lines generally carried more weight than the other trailer axle-lines. This was possibly due to the added weight of the coupling mechanism or weight from the counterweight on the tractor being transfer through the coupling and being carried by these axle-lines. Also noted was that the two GA examples with tractors with lift axles was that as with configuration 1, the lift axle generally carried a different amount of weight than the other axles in the same axle group. This could occur because the lift axle may not be designed to carry as much weight as a standard axle, or the operator may improperly set the height of the lift axle. When the weight data for the GA examples was aggregated by axle, the first two GA trucks showed a relatively uniform weight distribution while the last truck did not. In addition, the two GA dual-lane vehicles showed a tendency for the axles on one side to carry more weight than the axles on the other side. This may have been due to the loads on these trucks being located slightly off center or the trucks may have been weighed on a slight incline, shifting the center of gravity of the truck.

Only one of the GA examples and the NC citation example had carrier-estimated weight available for comparison to the measured weights. A summary table of the results of the comparison for these two trucks is provided in Table 28 below. The NC example had three axle-lines over the estimated weight, two trailer axle-lines, and a tractor steer axle. The GA example had one trailer axle-line over the estimated weight. The percent over the estimated axle-line weights ranged from 1.2% to 5.8%. The weight data for the NC example was only by axle-line while the GA example had weights given by axle. The GA example had five axles slightly above the estimated axle weights ranging from 1.0% to 3.4% over. Both of the examples had gross truck weights lower than estimated, which seems to indicate that the carriers overestimated weight to account for variations in weight distribution.

Table 28 Configuration 2 Summary

Truck		NC Citation	GA Permit #K0383872
Axle-lines	Number	19	22
	Number Over Estimates	3	1
	Max % Over Estimate	5.8	1.2
	Min % Over Estimate	2.8	--
Axles	Number	31	38
	Number Over Estimates	--	5
	Max % Over Estimate	--	3.4
	Min % Over Estimate	--	1.0
% Difference from Est. Gross Wt.		-8.0	-4.2

2.5.3 Configuration 3: Singlewide Modular

Superload configuration 3, singlewide modular style trucks, employ module units that are hooked together laterally to construct trailers of needed length. Individual modules generally have two axles per axle-line and each axle is hydraulically suspended. Weight distribution across modules is achieved with the use of rigid center beams, bolt plate coupling, and linked hydraulic suspensions. The hydraulic suspensions for the axles are linked in three or four groups. Data was collected for two configuration 3 units with the help of project partners Guy M. Turner and Progress Energy. Field weighs were conducted at Progress Energy's Shearon Harris power plant facility on two singlewide modular units operated by Guy M. Turner. The data and subsequent analysis for each of these trucks will be discussed in further detail below.

2.5.3.1 Shearon Harris Field Weighs

In late February 2012, the NCSU team was invited to Shearon Harris power plant to weigh two singlewide Goldhofer units, an 11-axle-line truck towed unit and a 10 axle-line self-propelled unit, operated on the plant property by Guy M. Turner. The towed unit was weighed a total of three times over two days and the self-propelled unit was weighed once on the second day. These units were only operated internally to the Shearon Harris power plant and never traveled on public roadways, thus no superload permits exists for these moves. Therefore, the weight for each unit was estimated using dead weight estimates supplied by Guy M. Turner and the shipping weight listed on the side of the transformers being transported.

Note, photography is not allowed on Shearon Harris property by unauthorized personnel for security reasons. The plant management supplied the following image, Figure 61, of the 11 axle-line Goldhofer, weighed and operated by Guy M. Turner Inc. at the plant. The self-propelled Goldhofer was not photographed, instead, Figure 62 is an example of a typical self-propelled singlewide Goldhofer, and Figure 63 is an example schematic. It is not the actual unit weighed at the Shearon Harris plant.

Figure 61 Towed 11 Axle-Line Goldhofer, Shearon Harris Plant.[28]

[28] Photo courtesy of Progress Energy

Figure 62 Example of a Self-Propelled Singlewide Modular Unit.[29]

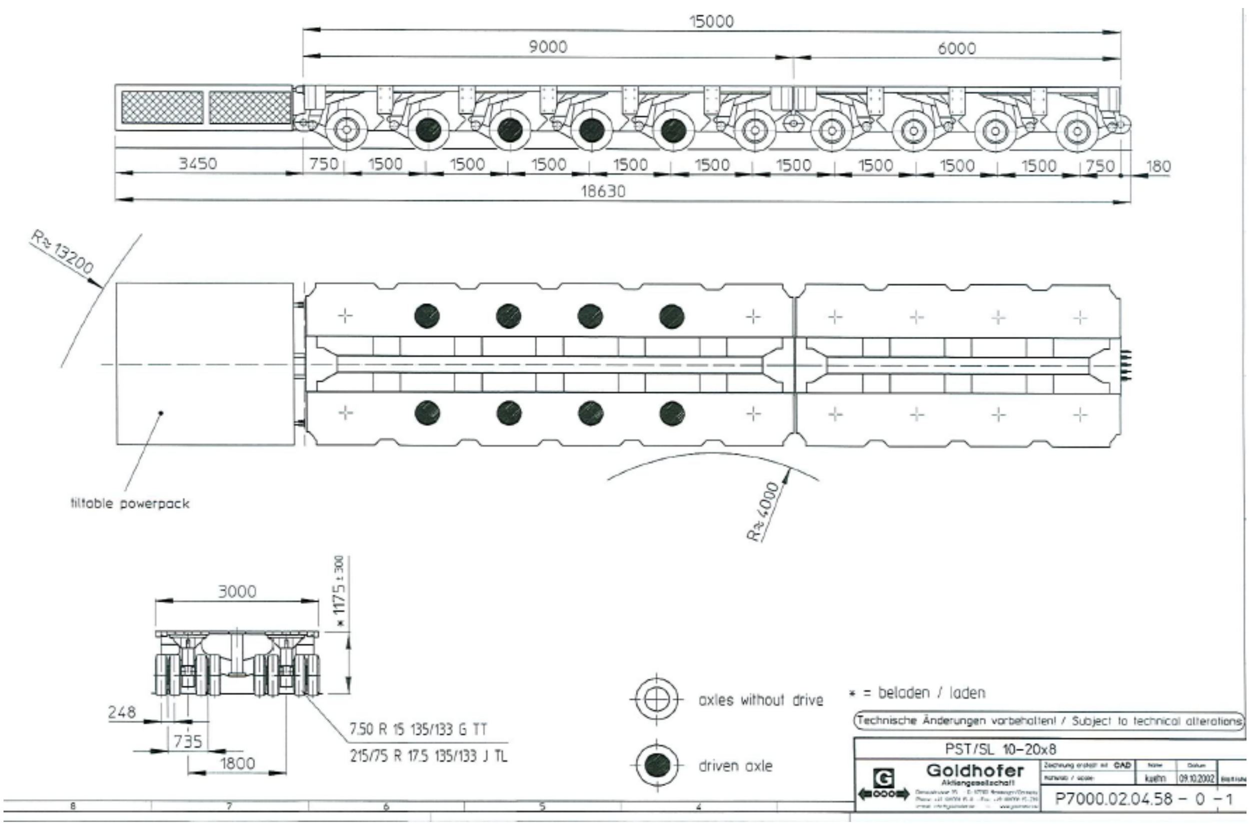


Figure 63 Example Self-Propelled Singlewide Modular Unit Schematic.[30]

Goldhofer units are modular and have hydraulic suspension for each axle. Axles are grouped together in suspension groups by linking the hydraulic suspension for the respective axles. The singlewide units have two axles per axle-line and can be arranged with 3-point or 4-point suspension. These suspension groupings can be arranged as the operator sees fit. Both the

[29] Photo courtesy of Guy M. Turner
[30] Source: Goldhofer AG

units weighed were arranged with a 4-point suspension, meaning that driver side axles were separate from passenger side axles and then these groups were subdivided into a front group and rear group. Shown below is an example of a 4-point suspension with a four and seven axle front to back split, with each block representing a suspension grouping.

Front	4 Axles	7 Axles
	4 Axles	7 Axles

Figure 64 Example of a Four-Point Suspension.

This data has several limitations that should be noted. The scales used were supplied by Guy M. Turner and had not been calibrated since they were purchased; therefore, the accuracy of these scales is unknown. The SHP recommends that when weighing trucks using portable scales that the ground should be a level, paved surface for accuracy. The units were weighed on a gravel surface that had a slight driver side to passenger side incline. Due to the safety concern of placing and reading scales under the Goldhofer units, only the outside sets of tires were weighed. It was also noticed that a few outside tires were flat on the units which could possibly cause the inside tires that were not weighed to carry more weight. A Guy M. Turner official also noted that because these loads were not running on public roads that they were allowing more weight per axle-line than they would if seeking a permit. It was also noted that they were not as careful about getting the center of gravity of the load exactly at the center of the trailer as they would have if operated on public roads. Due to the limitations of the data, the analysis will be more general than in previous sections and focus on overall weight distribution trends.

The 11 axle-line singlewide truck-towed Goldhofer was weighed three times with different suspension groupings. Trial 1 had a 4-point suspension with a 4 and 7 axle split, with no weight carried on the gooseneck connecting the trailer to the truck. Trial 2 had a four-point suspension with a 6 and 5 axle split, with no weight carried on the gooseneck. Trial 3 had a four-point suspension with a 4 and 7 axle split, with weight carried on the gooseneck. The total gross weight for this unit was estimated as described above and an equal distribution of weight was assumed for comparison to the measured weights. Note, the estimated weights were estimated by the research team and not Guy M. Turner, and are not representative of weight estimates that would be used for application for a superload permit. A Guy M. Turner official stated that they would regularly overestimate axle weights when applying for a superload permit to provide a buffer for possible axle-line weight variances. Data for each trial of the truck-towed 11 axle-line singlewide modular for each trial and estimated weight distribution are given below.

Table 29 Measured Weight: 11 Axle-Line Singlewide Truck-Towed

	Trial 1		Trial 2		Trial 3	
	Outside Tires only		**Outside Tires only**		**Outside Tires only**	
	Weight (lbs)		Weight (lbs)		Weight (lbs)	
Axle-Line	Driver Side	Passenger Side	Driver Side	Passenger Side	Driver Side	Passenger Side
1	9500	9400	9900	9200	10400	9500
2	8200	8600	9000	9200	10000	9400
3	8000	8000	8600	8300	10000	8800
4	8000	9000	8500	9400	10000	9000
5	11600	11000	8400	9100	12800	10300
6	12800	10800	8600	9100	13000	10400
7	12600	11800	13000	12100	13100	11300
8	12500	12000	13200	11800	13100	11200
9	12100	13000	13000	12400	13000	12000
10	12000	12500	13400	12400	13000	11600
11	11500	13100	13050	12500	12800	12100

Table 30 Estimated Weight: 11 Axle-line Singlewide Towed

Axle-Line	Estimated Weight (lbs)	
	Driver Side	Passenger Side
1	21988	21988
2	21988	21988
3	21988	21988
4	21988	21988
5	21988	21988
6	21988	21988
7	21988	21988
8	21988	21988
9	21988	21988
10	21988	21988
11	21988	21988
Gross Weight	483743	

It was assumed that the weight for the inside tires was equal to the measured weight of the corresponding outside tire, thus each axle weighed twice the measurement for the outside tires. These weights were graphed to compare to the estimated weight distribution, and are displayed in Figure 65 to Figure 68 below.

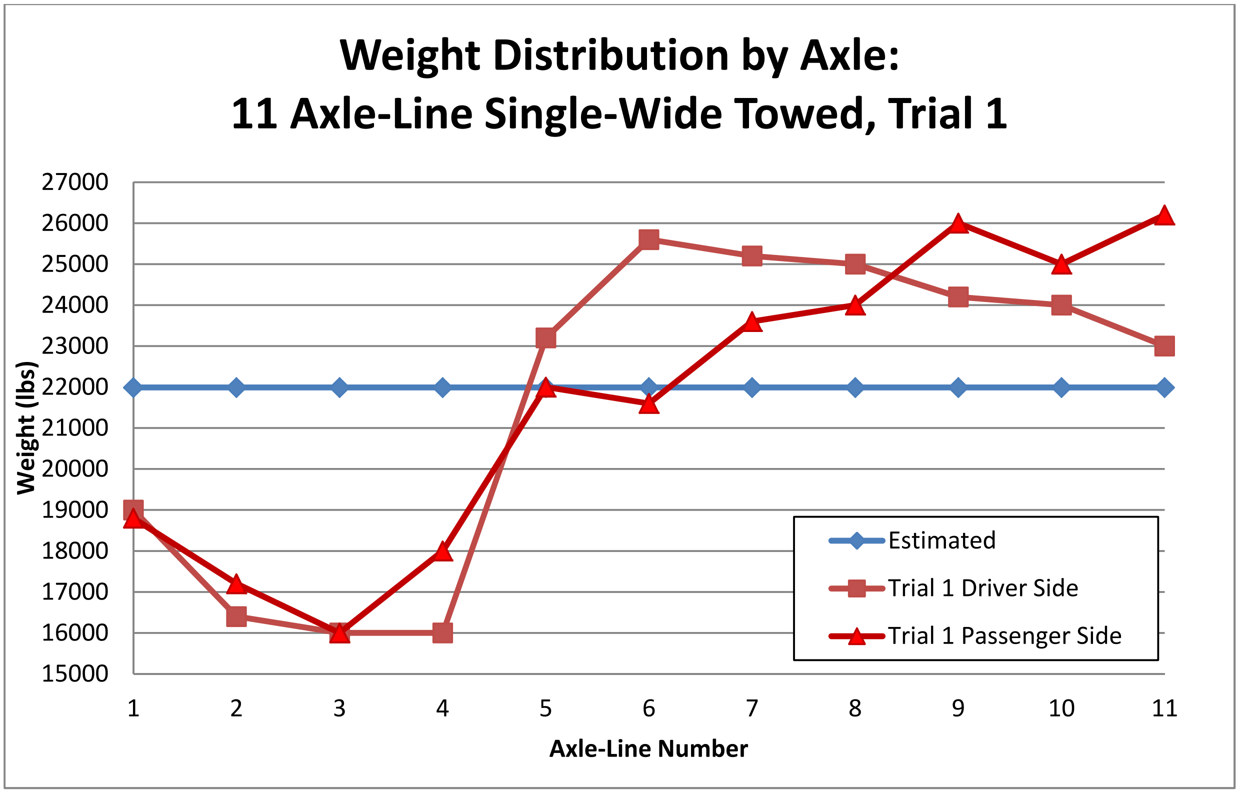


Figure 65 Weight Distribution by Axle - 11 Axle-Line Singlewide Towed Trial 1.

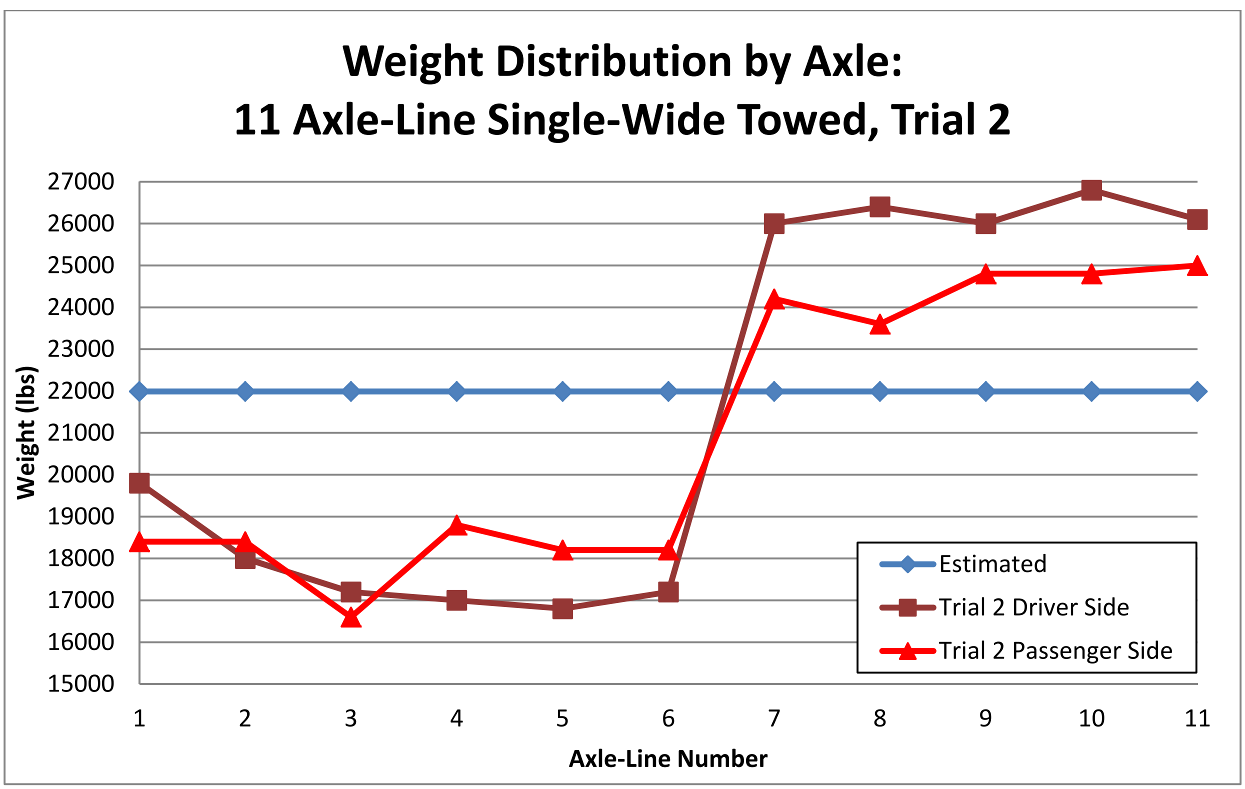


Figure 66 Weight Distribution by Axle - 11 Axle-Line Singlewide Towed Trial 2.

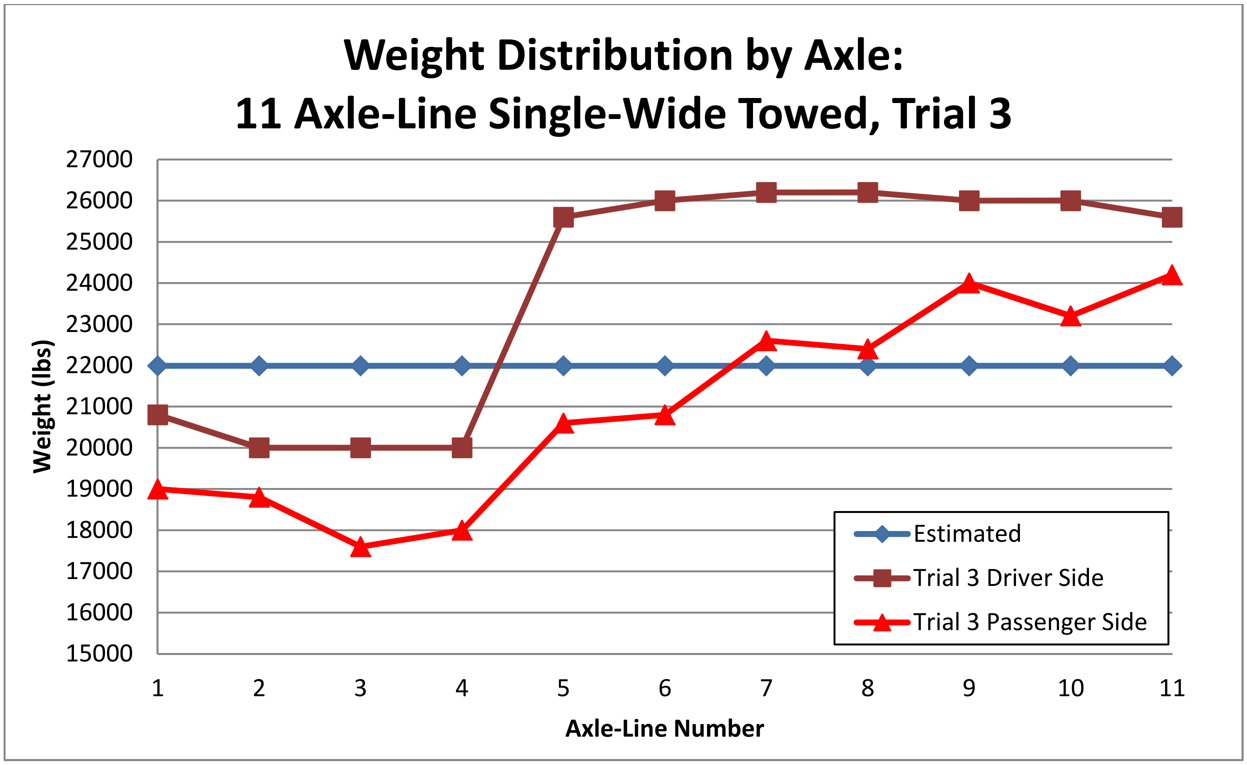


Figure 67 Weight Distribution by Axle - 11 Axle-Line Singlewide Towed Trial 3.

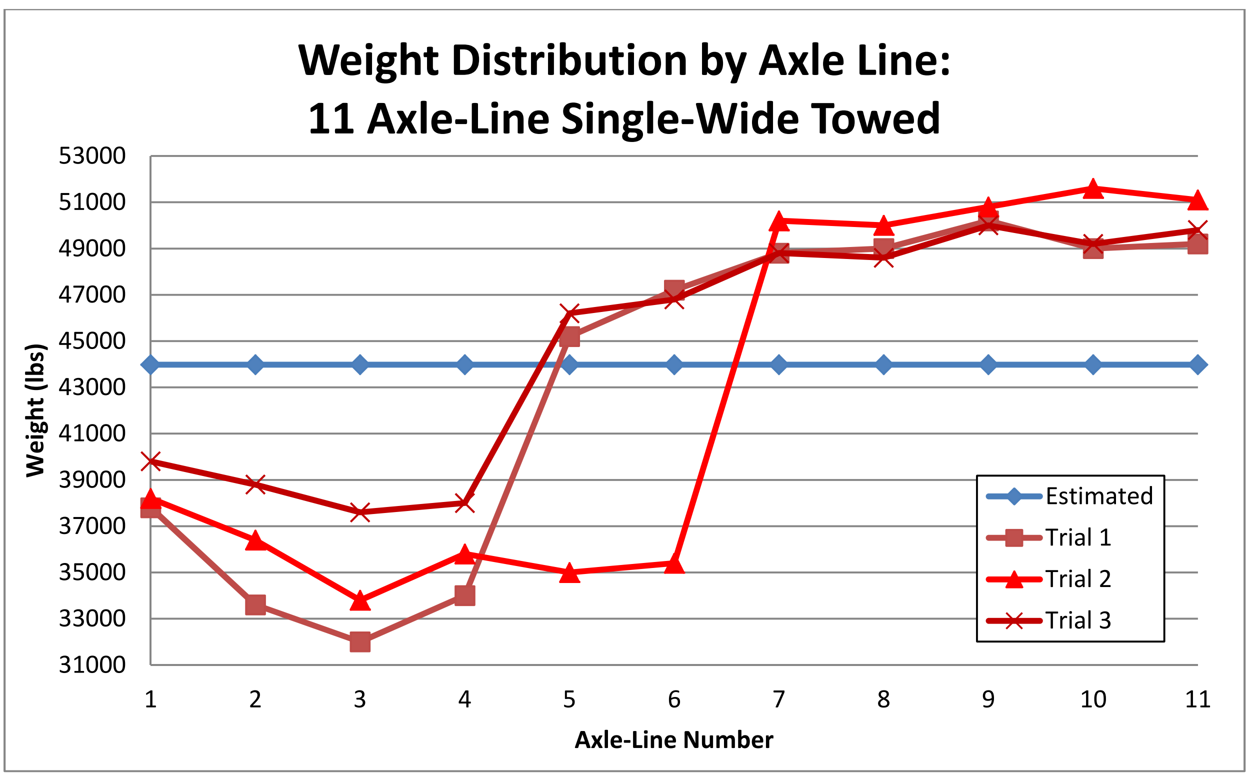


Figure 68 Weight Distribution by Axle-Line - 11 Axle-Line Singlewide Towed.

As can be seen in the graphs above, axle weights within a hydraulically linked suspension grouping have a fairly uniform weight distribution; however, axle weights between suspension groups are not uniform. In each case, a distinct change in average axle weights can be seen between axle groups. The unit carried significantly more weight on the rear suspension groups than on the front ones for every trial. This indicates that the center of gravity of the load was most likely located behind the center of the trailer, shifting more weight rearward on the trailer. The weight distribution between suspension groups laterally is much closer than the weight distribution longitudinally between suspension groups longitudinally. This seems to indicate that the center of gravity of the load was closer to the center of the trailer laterally than it was longitudinally. In each trial, there is a marked increase in weight for the rear suspension groups as compared to the front suspension groups and the point of this increase changes as the suspension grouping changes. This highlights the ability of the hydraulic suspension of these trailers to distribute weight fairly uniformly within a suspension grouping and to change weight distributions by only changing the suspension grouping of the axles. Additionally, the greater axle weight variability within a suspension grouping for the passenger side axles as compared to the driver side is likely a result of one or more of the error sources previously described. The weight distribution was also aggregated and plotted by axle-line for all three trials, shown in Figure 68. This graph follows the trends of the other plots and making more apparent the weight distribution discrepancies front to back on the truck.

The 10-axle-line singlewide self-propelled modular unit was weighed once with a 4-point suspension setup with a 5 and 5 axle split. As before, only the outside tire sets were weighed and the axle weight was assumed twice the outside tire set weights. For comparison, estimated weights were calculated using dead weight estimates for the unit and shipping weight of the load and assumed to distribute equally to all axles. As before, the estimated weights were estimated by the research team and not Guy M. Turner, and are not representative of weight estimates that would be used for application for a superload permit. Weight data for each trial of the self-propelled 10 axle-line singlewide modular for each trial and estimated weight distribution are given below.

Table 31 Measured Weight 10 Axle-Line Singlewide Self-Propelled

	Outside Tires only Weight (lbs)	
Axle Line	Driver Side	Passenger Side
1	13900	14000
2	14500	14700
3	14700	14800
4	13700	15100
5	15000	15200
6	13200	11700
7	11000	13000
8	13100	13000
9	12800	13200
10	12700	12900

Table 32 10-Axle-Line Self-Propelled Goldhofer Estimated Weight

Axle-Line	Estimated Weight (lbs)	
	Driver Side	Passenger Side
1	24962	24962
2	24962	24962
3	24962	24962
4	24962	24962
5	24962	24962
6	24962	24962
7	24962	24962
8	24962	24962
9	24962	24962
10	24962	24962
Gross Weight	499243	

It was assumed that the weight for the inside tires was equal to the measured weight of the corresponding outside tire, thus each axle weighed twice the measurement for the outside tires. These weights were then plotted to compare to the estimated weight distribution, and are given in Figure 69 and Figure 70 below.

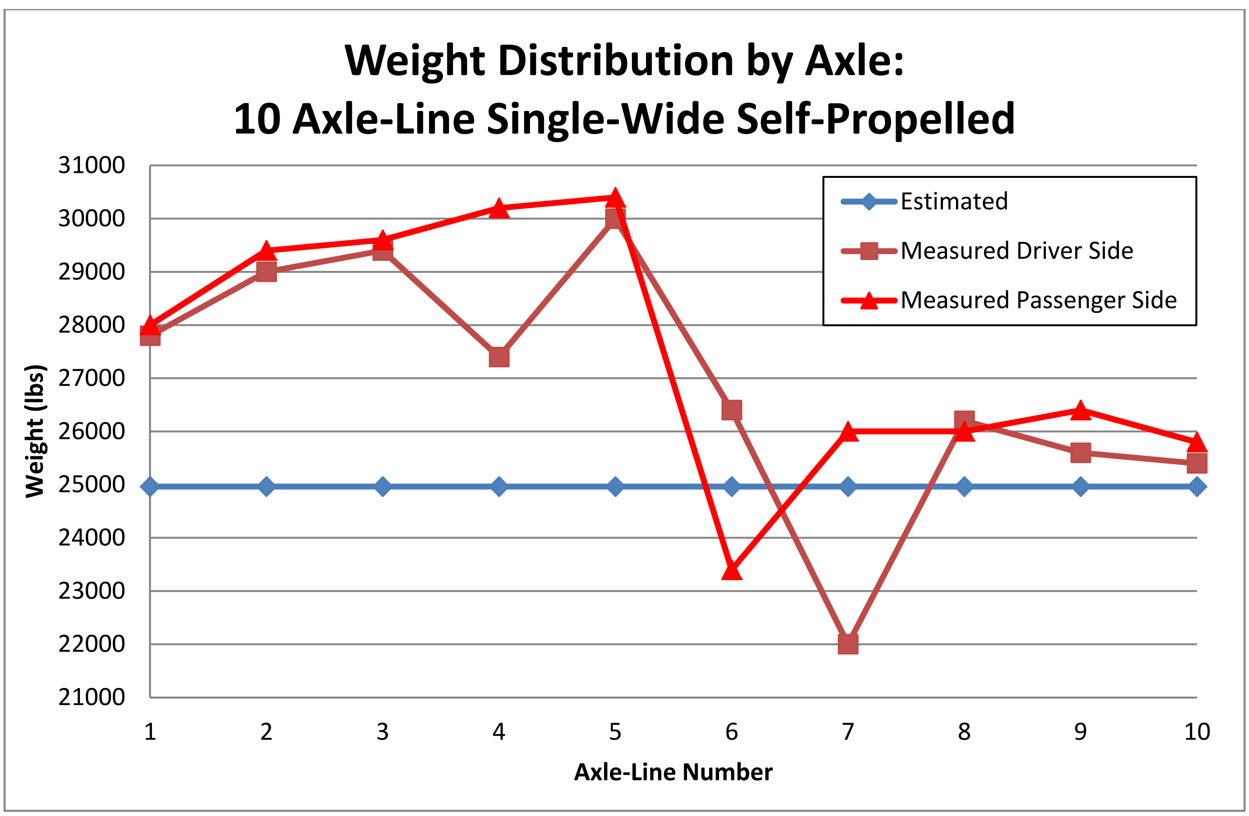


Figure 69 Weight Distribution by Axle - 10 Axle-Line Singlewide Self-Propelled.

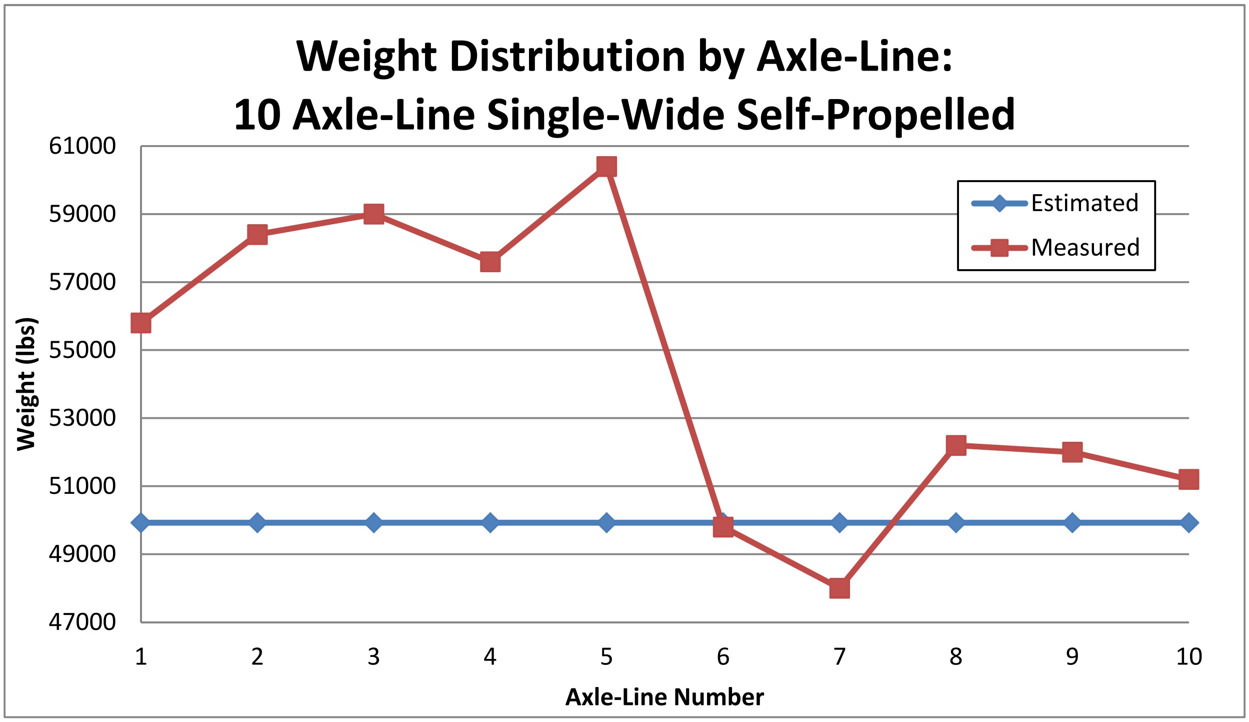


Figure 70 Weight Distribution by Axle-line - 10 Axle-Line Singlewide Self-Propelled.

As can be seen in Figure 69, there is once again a marked weight difference between front and back suspension groupings with the front axles carrying more weight than the rear axles. This seems to indicate that the center of gravity of the load was positioned slightly forward of the center of gravity of the truck. Since this is a self-propelled unit, axle-lines 2 through 5 weigh slightly more than other axle-lines because they are drive axles. As seen in Figure 62, self-propelled units have large power packs suspended from the front of the unit containing batteries and other equipment, which weighs approximately 19,000 pounds. The weight distribution between side to side suspension groupings carry nearly identical weights, indicating that the center of gravity of the load was positioned relatively close to the lateral center of the truck. It should be noted that the weight of axles 4 driver side, 6 passenger side, and 7 driver side deviate significantly from their respective suspension groupings. Flat tires were noted in these locations during weighing and it is surmised that this caused the un-weighed inside tires to carry most of the weight for the axle and thus reduced the measured weight of the outside tires. Other than these anomalous axles, the weight distribution between axles within each suspension group is fairly uniform. It is thought that the weight carried by each suspension grouping will be highly sensitive to placement of the load on the unit and where the front and back suspension groups are divided.

2.5.3.2 Configuration 3 Summary

Two examples of configuration 3 were weighed at the Progress Energy Shearon Harris power plant, an 11 axle-line truck-towed singlewide modular unit, and a 10 axle-line self-propelled singlewide modular unit. Guy M. Turner operated both units on the plant property and stated that since they were not operating on public roadways for these moves they were operating with more weight per axle than they would otherwise. They also stated that they were not as careful with the placement of the load on the units as they would have if they were operating on public roadways. Because of this, the recorded weights are not indicative of a superload that would operate on NC roads but are still useful for observing the weight distribution characteristics of configuration 3 units.

Each axle for a modular unit is hydraulically suspended and the hydraulics are linked into suspension groups to equalize hydraulic pressure and therefore axle load. Observed in both units was the ability of the hydraulic suspension to fairly evenly distribute weight to axles within linked suspension groups. Weights between suspension groups for both trucks showed longitudinal weight distribution discrepancies, with the front or rear suspension groups carrying significantly more weight than the other does. The 11 axle-line unit also showed weight distribution discrepancies laterally between suspension groups. Therefore, weight distribution between suspension groups seems highly dependent on the placement of the load on the trailer. To achieve uniform weight distribution the center of gravity of the load must be located over the center of the trailer.

2.5.4 Configurations 4 and 5: Doublewide Modular and Modular with Outriggers

No data was able to be taken on configuration 4, doublewide modular, or configuration 5, modular with outriggers, trucks and alternate sources of data were also unavailable. During the study, there were plans to weigh a configuration 4 truck, estimated at over a million pounds, being operated by project partner Guy M. Turner in Greensboro, NC. This truck carried a generator for a power plant and moved 17 miles from a rail siding to the power plant. The NCDOT canceled this opportunity when the customer receiving the load expressed reservations and concerns over delays the weighing might cause. A case study was instead performed on this load by interviewing NCDOT engineers from that district involved in the move. The case is included in the pavement analysis chapter.

Configuration 4 and 5 trucks are very similar to configuration 3 trucks, both being comprised of the same type of modular units arranged in different ways. Configuration 4 trucks have modular units arranged laterally and longitudinally and configuration 5 trucks employ extra axle groups attached to the modular units with I-beams. Since all three of these configurations use the same modular units, it is thought that the weight distribution characteristics will be similar to those observed for configuration 3 trucks.

2.6 Future Research Recommendations

Given the short timeframe of this study, measured weight data for this study was difficult to obtain. It is recommended that the NCDOT consider forming a partnership with the NC SHP to create a database of citations for superload permitted trucks. A database of citations would provide needed weight data for future research projects and could help provide NCDOT a resource for determining trends in violation types for superload permits. A database would alert NCDOT to companies that frequently violate superload permits, such that the DOT could work with those companies to bring them back into compliance and help protect NC’s transportation infrastructure.

Furthermore, a policy change should be considered that would allow NCDOT BMU, at their discretion, to request that a superload truck be weighed before a permit is issued, as in SC and TX. This would require a partnership with the NC SHP, to complete a requested weighing before a superload carrier receives a permit. A policy change such as this would require research to determine tolerances from estimated axle weights that could be allowed that would not require a new bridge study be completed, such that loads would not be unnecessarily delayed. The proposed change would allow BMU to have a better piece of mind when approving superloads that are approaching bridge safety limits and better protect NC's infrastructure.

2.7 Summary and Conclusions

Weight data was collected and analyzed for 20 superload trucks, with 14 for configuration 1, four for configuration 2, and two for configuration 3. The weight data for two configuration 1 trucks were collected in a field weigh, while the data for five trucks was supplied by the NC SHP through citation data, and data for the last seven configuration 1 trucks was supplied by GDOT. For configuration 2, the data for one truck was supplied by The NC SHP through a weight citation, the data for the other three trucks was supplied by GDOT through superload permits originating in the Port of Savannah. The data for the two configuration 3 trucks was collected in a field weigh.

None of the fourteen examples of configuration 1 showed a uniform axle weight distribution. One truck did not have a permit available for comparisons of estimated weight distributions to measured distributions. Of the remaining 13 examples for this configuration, nine estimated uniform axle weight distributions while four estimated non-uniform distributions. Axles within an axle group tended to have relatively uniform axle weights with two exceptions noted in several of the trucks. Many of the truck were thought to have lift axles, which carried a different amount of weight than the other axles in the same axle group. This could occur because the lift axle may not be designed to carry as much weight as a standard axle, or the operator may improperly set the height of the lift axle. In addition, stinger assemblies showed uneven weight distributions within their respective axle groups. Of the thirteen examples, number of overweight axles ranged from 0 to 9, and ranged from negligibly over to 21.8% overweight. Only two of the trucks were observed to be over gross weight with the highest being 2.3% over estimated gross weight, with the rest of the trucks being below estimated gross weight. The average number of overweight axles for the data was 2.8, although this may be skewed slightly high because of the three trucks that had a large number of overweight axles. The median number of overweight axles for the sample group was 1. The average percent over permit estimate for axle weight was 6.4%. The sample trucks averaged 7.5% below estimated gross weight listed on the superload permit. Weight distribution between axle groups is thought to be very sensitive to the placement of the load on the truck. Although, this truck configuration tends not to have a uniform weight distribution it seems many carrier, but not all, routinely overestimate axle weights when applying for superload permits to compensate for the non-uniform axle weight distribution.

For superload configuration 2, when the weight data was aggregated by axle-line, it was found that weights tend to distribute relatively uniformly across the trailer axle-lines. All dual-lane vehicles examined were observed to have the first one or two trailer axle-lines carry more weight than the following axle-lines. This was possibly due to the added weight of the coupling mechanism or weight from the counterweight on the tractor being transfer through the coupling and being carried by these axle-lines. The two GA trucks with tractor lift axles exhibited similar behavior to that of the configuration 1 trucks, in that the lift axle generally carried a different amount of weight than the other axles in the same axle group. This could occur because the lift axle may not be designed to carry as much weight as a standard axle, or the operator may improperly set the height of the lift axle. When the weight data for the GA vehicles was aggregated by axle, the first two GA trucks showed a relatively uniform weight distribution while the last truck did not. In addition, the two GA dual-lane vehicles showed a tendency for the axles on one side to carry more weight than the axles on the other side. This may have been due to the loads on these trucks being located slightly off center or the trucks may have been weighed on a slight incline shifting the center of gravity of the truck. Only one of the GA vehicles and the NC citation had carrier-estimated weight available for comparison to the measured weights. The NC vehicle had three axle-lines over the estimated weight, two trailer axle-lines, and a tractor steer axle. The GA vehicle had one trailer axle-line over the estimated weight. The percent over the estimated axle-line weights ranged from 1.2% to 5.8%. The weight data for the NC citation was only tabulated by axle-line while the GA vehicle had weights given by axle. The GA vehicle had five axle weights ranging from 1.0% to 3.4% over their permitted values. Both of the vehicles had gross truck weights lower than estimated, which seems to indicate that the carriers overestimated weight to account for variations in weight distribution.

The two configuration 3 units observed were not operated on public roadways and had axle weights higher than would be allowed if operated on public roadways. Because of this, the recorded weights are not indicative of a superload that would operate on NC roads but are still useful for observing the weight distribution characteristics of configuration 3 units. Observed in both units was the ability of the hydraulic suspension to fairly evenly distribute weight to axles within linked suspension groups. Weights between suspension groups for both trucks showed longitudinal weight distribution discrepancies, with the front or rear suspension groups carrying significantly more weight than the other does. The 11 axle-line unit also showed weight distribution discrepancies laterally between suspension groups. Therefore, weight distribution between suspension groups seems highly dependent on the placement of the load on the trailer. To achieve uniform weight distribution the center of gravity of the load must be located over the center of the trailer.

None of the trucks for any configuration observed displayed absolutely uniform weight distribution. The configuration 2 trucks seemed to distribute weight the best having fairly uniform weight distributions. Configuration 1 trucks seemed to distribute weight the worst having irregular weight distributions. The two configuration 3 trucks showed good weight distribution ability within suspension groups but non-uniform distributions between suspension groups. It appears that of all of the configurations weight distribution is highly dependent on the location of the load on the truck. Most of the carries for both of these configurations seemed to overestimate axle weights to compensate for variations in axle weight distribution.

CHAPTER 3. STRUCTURAL REPORT

This chapter will cover the structural analysis for the five superload configurations identified for use in this study. The organization of this chapter is as follows: a discussion of the background and problem, a discussion of the scope and objectives, a discussion of the research methodology used in this chapter, a literature review, a discussion of the model development, presentation of the structural analysis results, and lastly recommendations and conclusions.

3.1 Background and Problem Definition

In order for a superload to operate on public roads, an operator must obtain a permit from the NCDOT Oversize/Overweight (OSOW) Permit Unit. On average, NCDOT OSOW processes 150 to 200 of the permits per month (22). Some permits are valid for multiple trips between destinations, while others are only for a single use. Each superload is checked against a number of conservative limits to see if they automatically qualify for a permit. If the superload fails these checks, NCDOT OSOW sends the permit application to the NCDOT Bridge Unit for a more in-depth analysis using an in-house program called PERM6. PERM6 calculates superload demands relative to the HS 15-44 load pattern, a typical American Association of State Highway and Transportation Officials (AASHTO) design load. This value is compared with a current database rating of each bridge. If the superload still exceeds the bridge's demands, the vehicle's speed or lane of travel can be restricted to lower its demands. Finally, superloads can be re-routed to newer and stronger bridges.

Bridge data for North Carolina indicates that approximately 5.2% of National Highway System (NHS) bridges and 14.2% of non-NHS bridges are classified as structurally deficient. An additional 13.3% of NHS bridges and 14.5% of non-NHS bridges are functionally obsolete (23). This list of bridges that are deficient and frequency of superloads on the highways may lead to increased demands on bridges with decreased capacities. As such, the importance of keeping axle loads at or below the allowable limits is critical to the safety and maintenance of the state-owned road and bridge network in North Carolina.

Permit applicants typically assume that the total weight of a superload is distributed to each axle-line, even in instances where the load is confined to one part of the trailer and/or the load is not a uniform mass. The actual distribution of load strongly depends on the assumed stiffness, geometry, and lateral and longitudinal orientation of the truck as it travels. Despite these assumptions, the current NCDOT OSOW permitting policy does not require verification of the gross vehicle weight (GVW) or individual axle weights through the use of scales to weigh the superloads. Conventional overweight permitted vehicles have been found in violation of their permitted weight, suggesting that a more precise method of awarding overweight permits is needed for super heavy vehicles due to their greater potential for overloading bridges. Thus, a quantitative understanding of the empirical relationships between superload axle weights and spacings and their impacts on bridge superstructures are of critical importance to bridge infrastructure design and maintenance.

3.2 Objectives and Scope

The primary objectives of the structural portion of this research project are to apply standard AASHTO design practices to superloads and prestressed precast concrete (PPC) slab-on-girder bridge superstructures, to generalize superload demands, and to evaluate the accuracy of NCDOT BMU's current superload vetting process for bridge superstructures.

3.3 Research Methodology

One of the primary problems the NCSU research team discussed with the NCDOT OSOW was that little is known about the accuracy of their current permitting analysis method that estimates superload demands. The proposed research was to use the current AASHTO Load and Resistance Factor Design (LRFD) guidelines to analyze the effects of superloads for a variety of design limit states; however, an initial review found that the majority of North Carolina bridges are still rated using AASHTO Load Factor Design (LFD) standards. In order to evaluate the accuracy of the current permitting process and to have applicable results, bridges were modeled using AASHTO LFD standard design loads instead of LRFD.

In order to gather accurate superload weight distributions one option initially considered was fitting bridges with instrumentation to monitor superload passages. Apart from providing more accurate axle weights, differences in the response of the bridges before and after the superload's passage could be analyzed to detect damage to the superstructure. In most cases, superload moves occur with at most two or three days of advance notice. The lack of time prior to a superload move prevented bridge instrumentation from being a viable source of data for this study.

The primary source for weight and axle spacing data were weighings coordinated with the North Carolina State Highway Patrol (NCSHP). Four superload vehicles were weighed: two modular trailers and two combination vehicles (consisting of a truck, jeep, trailer, and stinger unit). The procedure for weighing these vehicles is discussed in detail in Chapter 2. Only PPC slab-on-girder bridges were modeled since they are typically more uniform in nature and their behavior is less dependent on secondary stiffening elements such as cross-bracing or girder diaphragms. This simplification allows for a wider number of bridge geometries to be tested in our analyses.

As a compromise between computational cost and accuracy, the plane-grillage method of analysis was selected to analyze the bridges. Plane-grillage analysis approximates a bridge as a mesh of frame elements each of which has representative stiffness and material properties. Longitudinal elements represent girders with attached portions of the bridge deck and transverse elements represent the properties of the slab for load distribution purposes. SAP2000 is a commercially available analysis program that can be used to analyze structural models ranging in complexity from 2D linearly-elastic static analyses up to 3D nonlinear dynamic analyses (24). In order to quickly and reliably create bridge models, a Matlab program was developed (termed BridgeMaker). The program takes common bridge characteristics as input parameters, and outputs a text file that can be imported into SAP2000 for analysis. Relevant data is then visually verified in SAP2000 and exported for further post-processing.

Maximum moment demands were calculated for representative superloads and the AASHTO LFD standard HS 20-44 loading. The HS loading is a hypothetical load case that represents typical highway loads for semi-trailers. The naming convention designates first the weight of the vehicle in tons and then the year the loading was proposed. In this report, year designations are omitted since only one AASHTO design load was used in analyses. HS-equivalent ratings were calculated for each superload. This rating represents the weight (in tons) that an HS vehicle would have to weigh to produce the same moment demand as the superload for the location of interest. The HS-equivalent ratings were calculated using the plane-grillage model and a modified version of NCDOT OSOW's current permitting process. The ratio of these two HS-equivalent ratings was calculated to estimate the conservatism of the modified NCDOT OSOW method. The modified NCDOT OSOW method and the calculation of values are discussed further in Section 3.7, "Analysis Results."

3.4 Literature Review

3.4.1 Superload Vehicle Studies

Turer and Aktan (25) monitored a superload weighing 817.7 kips that crossed three steel stringer bridges in Toledo, Ohio. Using finite element modeling, the bridges were modeled and calibrated with field measurements to determine if damage occurred during the crossing. No damage was found visually or analytically, though transverse deck stresses above cross braces were found to control over girder stresses. While a loss of composite action is typically expected, this was not found to be the case in any of the bridges monitored in the study.

Grimson *et al*. (26) monitored a pair of superloads weighing 2461 kips and 1025 kips crossing a prestressed concrete girder bridge in Louisiana. Acoustic emission sensors were placed on the bridge and calibrated using vehicles with a known weight prior to the superloads' passage. While the acoustic data indicated tensile stresses were slightly above standard stress limits, cracking was not observed and the bridge responded in a linear-elastic manner. The distribution of weights was found to be different than what was stated on the permits. Both superloads were front heavy, with the front trailer carrying 40% of the load as opposed to the stated 33% on the permit.

3.4.2 Prestressed Precast Concrete Girder Bridges

Zokaie *et al*. (27) calculated AASHTO LRFD and LFD live load distribution factors by performing a parametric study using plane-grillage models. Bridges were created while varying concrete strength, span length, girder sizes, and girder spacings for analysis. AASHTO LFD moment distribution factors were found to be highly conservative for longer bridges, while shear distribution factors were found to be unconservative when using the moment distribution formulas.

Kostem (28) examined slab-on-girder bridges with reinforced concrete and PPC girders. Parametric studies were performed using BOVAC, a program designed to simulate overloads on concrete bridges. Damage typically initiated through longitudinal cracking of the slab, either at the top of the slab's crossing a girder, or at the bottom of the slab midway between girders. It was also noted that cracking of the slab beyond acceptable limits typically preceded a loading level that could cause damage in prestressed girders.

3.4.3 Secondary Elements

Eamon and Nowak (29) examined nine bridges with three different span lengths, girder spacings, and deck thicknesses with various combinations of diaphragms, sidewalks, and barriers. Their experiments considered both simply supported steel and PPC slab-on-girder bridges. Overall, secondary elements were found to distribute loads more efficiently across the bridge superstructure, with a 10-40% decrease in girder distribution factors for most of the cases examined. Ultimate girder capacities were found to be a factor of 1.1 to 2.2 times larger than those of a bridge without secondary elements included. They conclude that neglecting the effects of secondary elements typically results in conservative demands, though the level of conservatism varies from bridge to bridge.

Akinci *et al*. (35) analyzed two steel bridges in Indiana using finite element analysis methods to determine the effects of parapets on the distribution of demands on bridges due to a sequence of superload vehicles. The models were calibrated using four tandem axle dump trucks loaded to approximately 43 kips each. The authors conclude that parapets can increase the capacity of most bridges when the bridge capacity is controlled by its external girders, but the type of parapets and connections were found to lead to inconsistent results.

3.4.4 Plane Grillage Model

Jaeger (31) summarizes the application of the plane-grillage method of modeling superstructures and discusses important aspects of applying the method to slab, slab-on-beam, cellular/box-beam, and voided slab bridges, as well as slabs that linearly vary in thickness over the bridge. The author concludes that the plane-grillage method is a viable method for both simple and more complex bridges and provides results similar in accuracy to finite element modeling.

3.4.5 Torsional Constant of Girders

El Darwish and Johnston (32) derived equations for calculating torsional constants for a variety of structural shapes. The equations were verified using a combination of finite difference modeling and Prandtl's membrane analogy. Eby et al. (33) modifies these equations, applying them to standard AASHTO PPC girders. Eby's modified equations show a marked improvement in accuracy over applying other approximate methods to obtain torsional constants for AASHTO PPC girders.

3.5 Model Development

3.5.1 Selection of Vehicles

Five superload vehicles were selected that represent commonly occurring superload types based on their arrangement of wheels and method of distributing loads:

Vehicle 1: Combination Vehicle (Truck-Jeep-Trailer-Stinger)
Vehicle 2: Drop-Deck Gooseneck with Extendable Axles
Vehicle 3: Singlewide Modular
Vehicle 4: Doublewide Modular
Vehicle 5: Modular with Outrigger Dollies

Figure 71 through Figure 75 depict drawings of the vehicles there were obtained from NCDOT OSOW. Two additional vehicle cases were created for Vehicles 2 and 5. Vehicle 2a has axle lines retracted to 12 ft while Vehicle 2b has axle lines fully extended to 18 ft. Similarly, Vehicle 5a has outrigger dollies attached while Vehicle 5b does not. The load originally carried by the outrigger dollies was redistributed among the modular axle-lines. These cases provide extra insight into how adjustable axle-lines and outrigger dollies influence the distribution of superload demands on bridges. Vehicles 2b, 4, and 5a are two lanes wide and were included only for analyses of the two-lane bridge models.

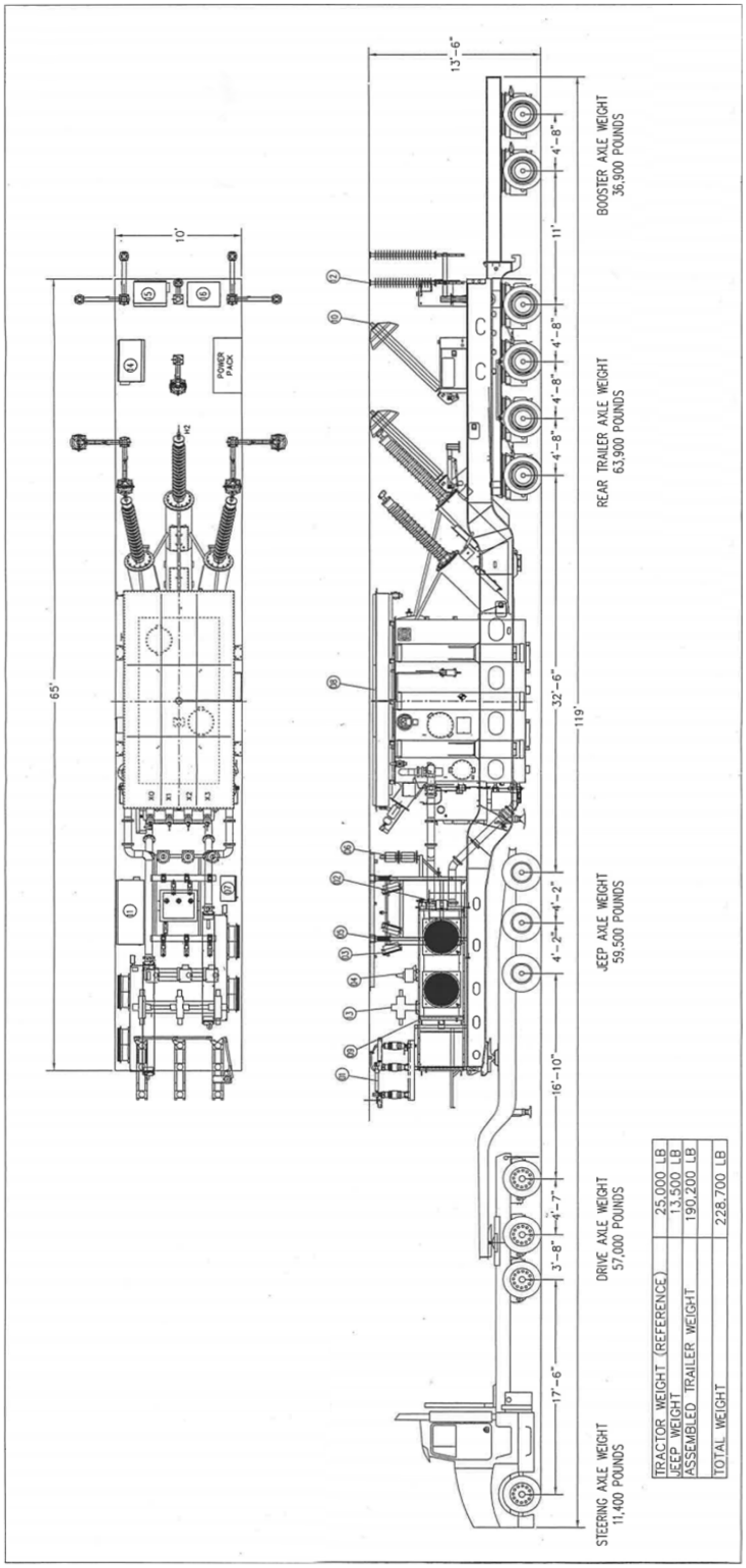


Figure 71 Vehicle 1: Combination Vehicle of Truck-Jeep-Trailer-Stinger.[31]

[31]Source: Progress Energy

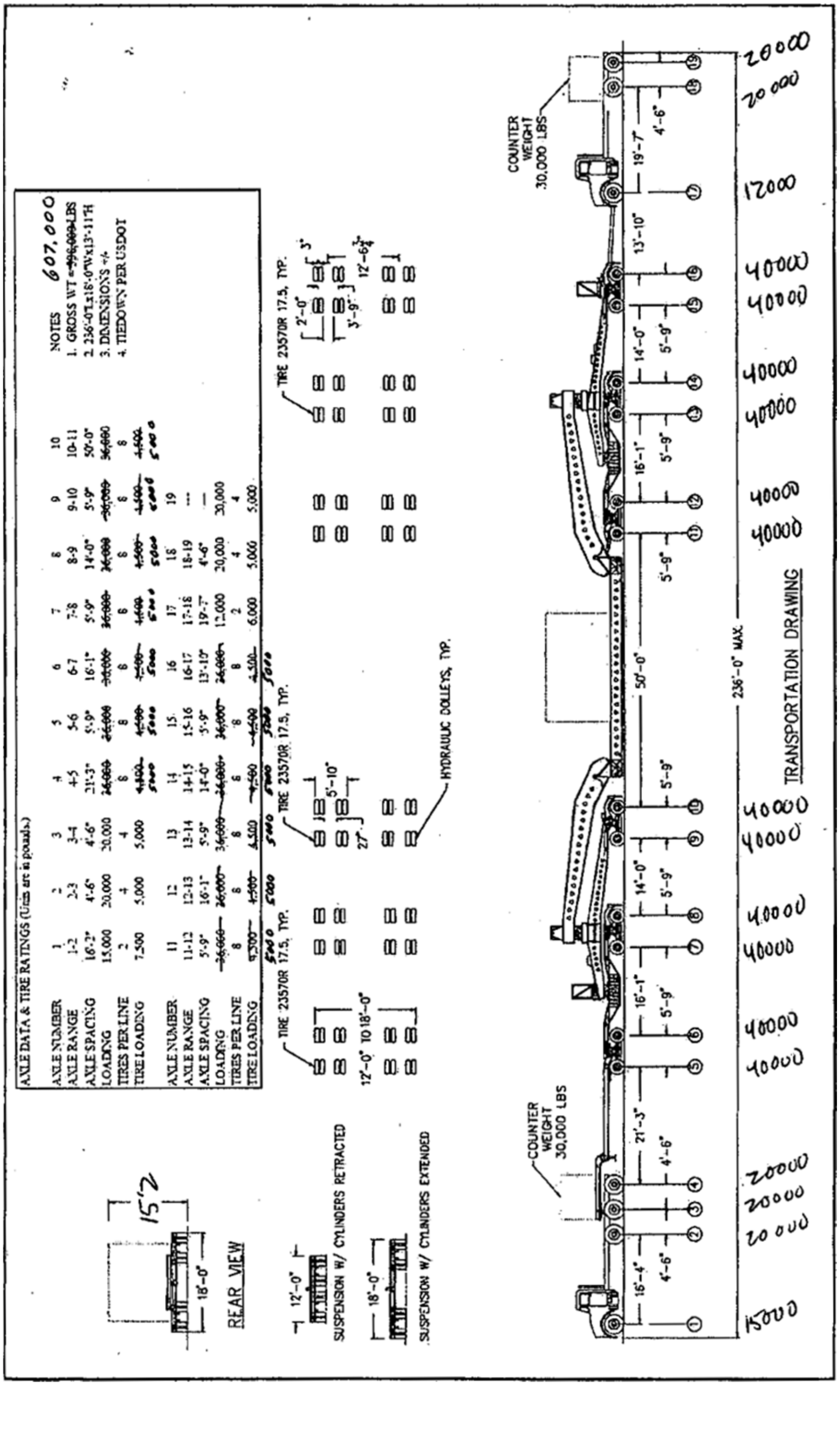


Figure 72 Vehicle 2a and Vehicle 2b: Drop-Deck Gooseneck with Expandable Axles-Lines.[32]

[32]Source: NCDOT

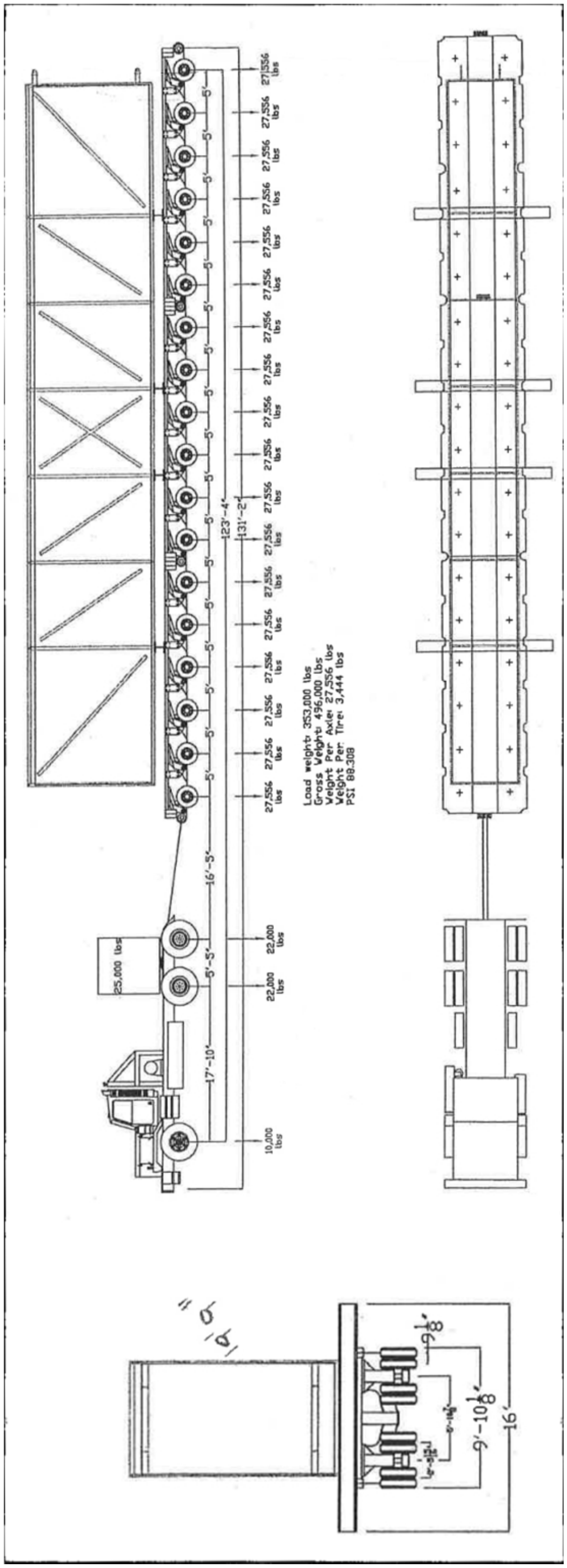


Figure 73 Vehicle 3: Singlewide Modular.[33]

[33]Source: NCDOT

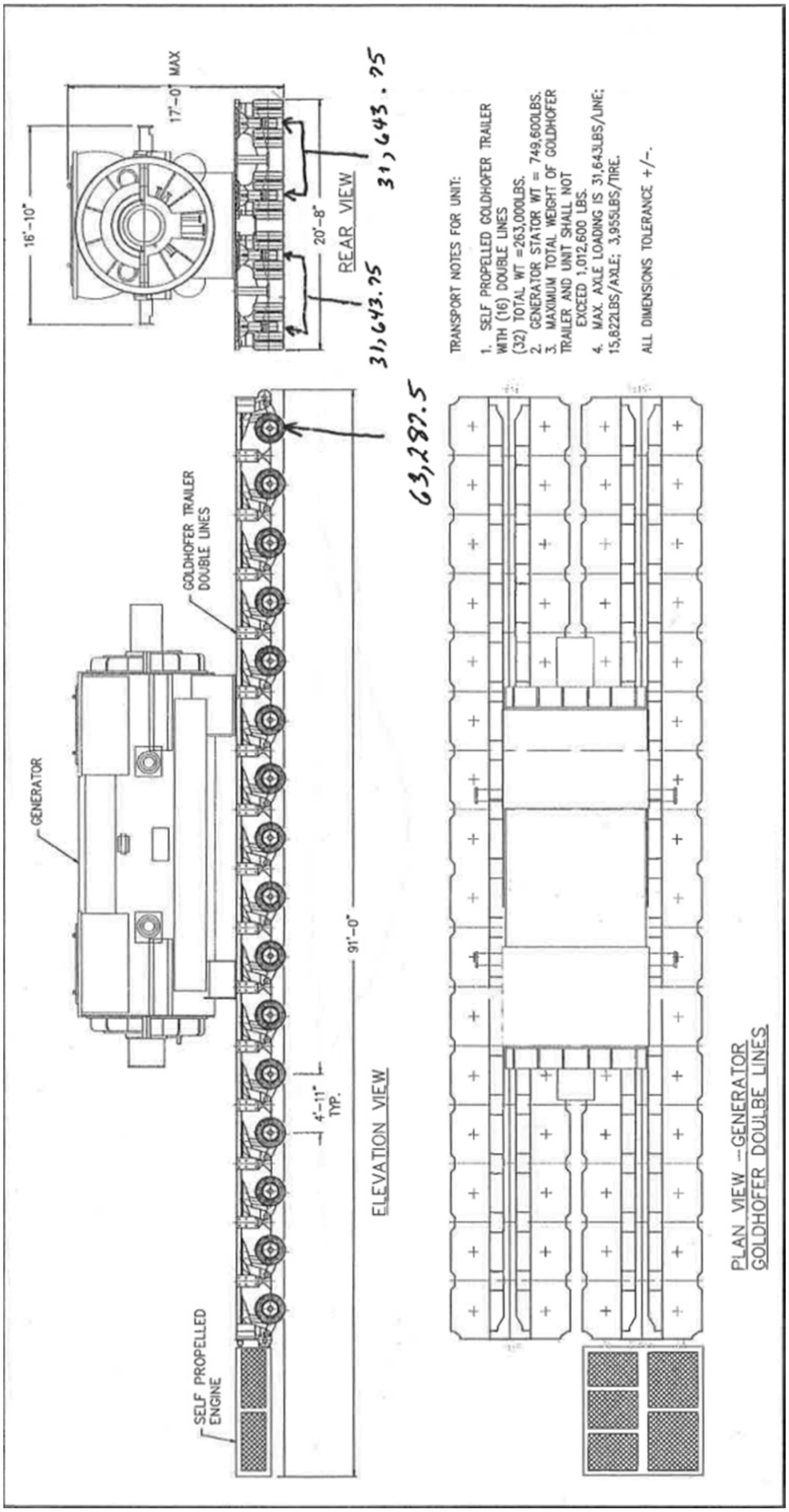
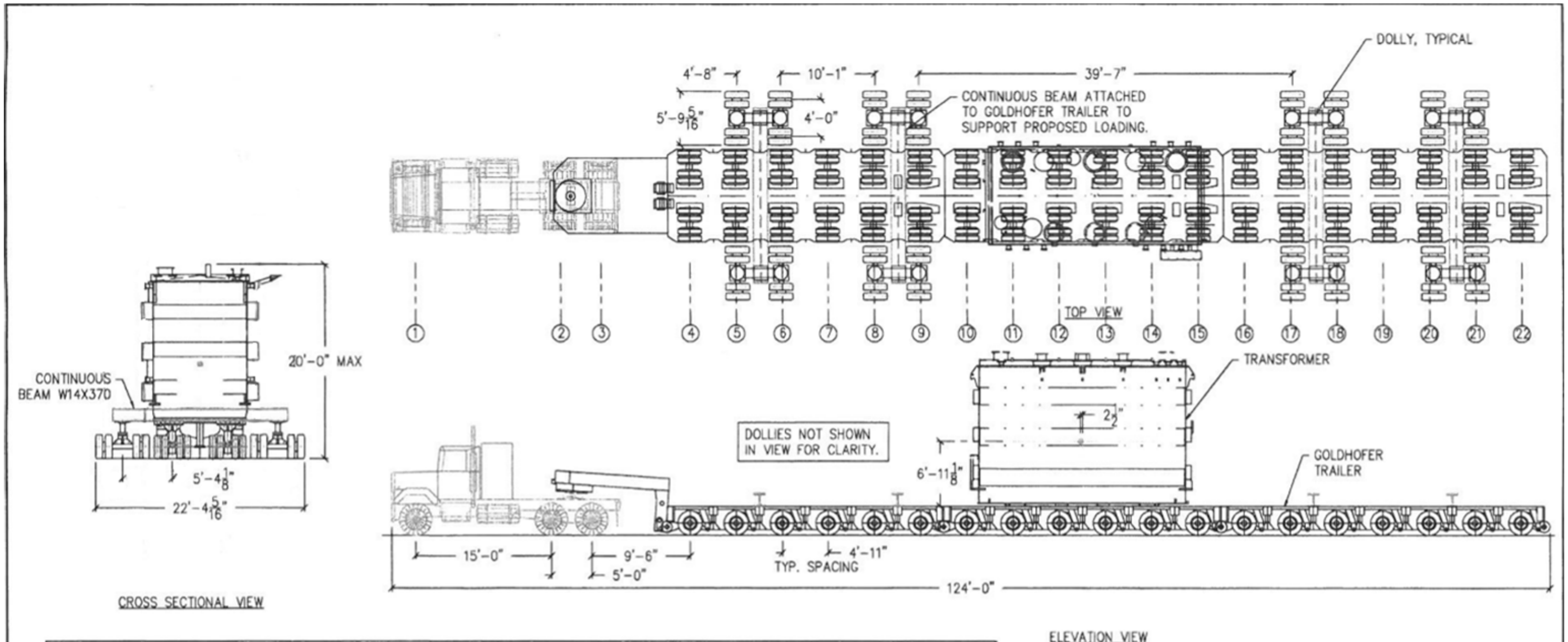


Figure 74 Vehicle 4: Doublewide Modular.[34]

[34] Source: NCDOT



AXLE DATA & TIRE RATINGS (Units are in pounds.)

AXLE NUMBER	1	2	3	4	5	DOLLY	6	DOLLY	7	8	DOLLY	9	DOLLY	10	11
AXLE RANGE	1-2	2-3	3-4	4-5	5-6	---	6-7	---	7-8	8-9	---	9-10	---	10-11	11-12
AXLE SPACING	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"
LOADING	16,500	22,000	22,000	25,000	25,000	44,000	25,000	44,000	25,000	25,000	44,000	25,000	44,000	25,000	25,000
TIRES PER LINE	2	4	4	8	8	8	8	8	8	8	8	8	8	8	8
TIRE LOADING	8,250	5,500	5,500	3,125	3,125	5,500	3,125	5,500	3,125	3,125	5,500	3,125	5,500	3,125	3,125

AXLE NUMBER	12	13	14	15	16	17	DOLLY	18	DOLLY	19	20	DOLLY	21	DOLLY	22
AXLE RANGE	12-13	13-14	14-15	15-16	16-17	17-18	---	18-19	---	19-20	20-21	---	21-22	---	----
AXLE SPACING	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"
LOADING	25,000	25,000	25,000	25,000	25,000	25,000	44,000	25,000	44,000	25,000	25,000	44,000	25,000	44,000	25,000
TIRES PER LINE	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
TIRE LOADING	3,125	3,125	3,125	3,125	3,125	3,125	5,500	3,125	5,500	3,125	3,125	5,500	3,125	5,500	3,125

GENERAL NOTES

1. GROSS WEIGHT = 887,500 LBS
2. UNIT WEIGHT = 644,000 LBS
3. HOLLANDER DOLLY WT = 3,200LBS
4. W14X132 WT = 2,640 LBS
5. TIEDOWN PER USDOT
6. DIMENSIONS +/-
7. DOLLYS CARRY 44K TOTAL

Figure 75 Vehicle 5a and Vehicle 5b: Modular with Optional Outrigger Dollies.[35]

[35] Source: NCDOT

Field-measured weights and axle spacings for Vehicle 1 were gathered from a weighing performed with assistance from the North Carolina State Highway Patrol (NCSHP), while Vehicles 2a and 2b utilize data provided by a previous superload weighing performed by NCSHP. Additional data from another NCSHP weighing was available for a superload similar to Vehicle 3, however, this data was neglected due to questionable site conditions and inconsistencies observed in the data. Details on the weighing of these vehicles can be found in Chapter 2. Vehicles 3, 4, 5a, and 5b were created from permits and drawings received from NCDOT OSOW. Since an elastic response is desired for superload passages on bridges, it was assumed that the members of the bridge remained elastic. This assumption allowed each superload to be scaled down to a GVW of 100 kips. As a result, moment demands and HS-equivalent vehicle weight results displayed below are per 100 kip. Conservatism ratios are unaffected by this scaling, and can be applied to scaled or non-scaled vehicles.

The standard HS-15 loading from AASHTO Standard Specifications for Highway Bridges was selected for analysis for ease of comparison with results from the NCDOT OSOW program, PERM6. The HS loading consists of a truck and a distributed lane load that are applied separately. Figure 76 and Figure 77 show the standard HS 15-44 truck and lane load, respectively.

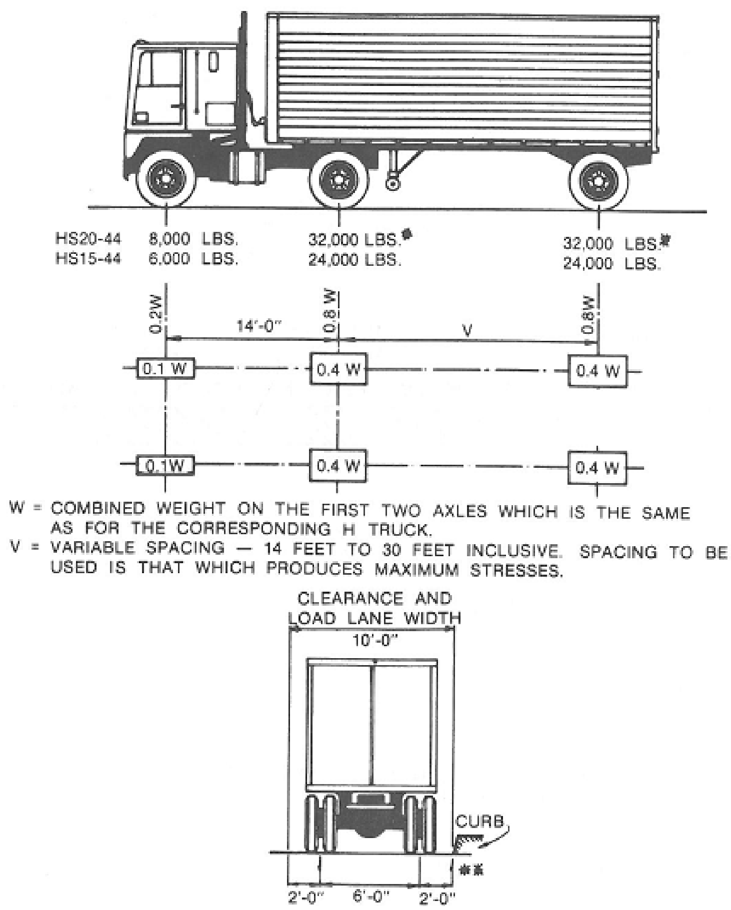


Figure 76 AASHTO HS Truck Loads.[36]

[36] Source: AASHTO Standard Specifications for Highway Bridges, 2002

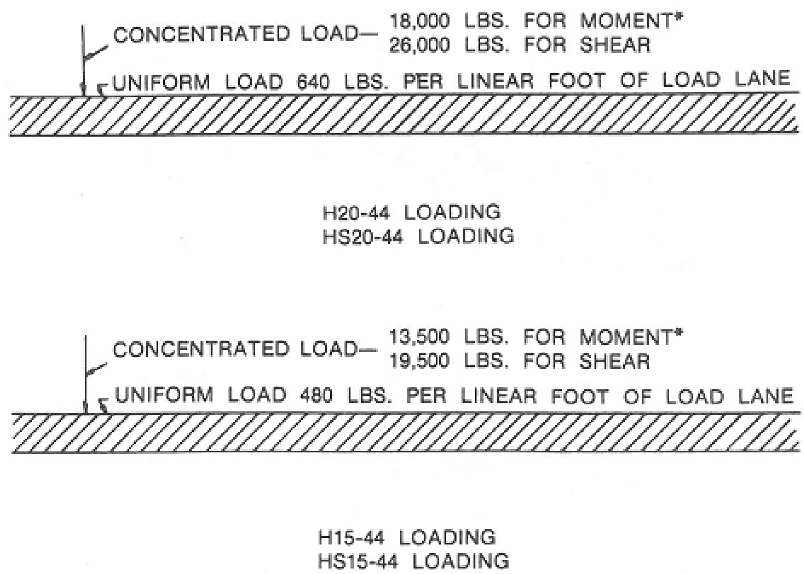


Figure 77 AASHTO HS Lane Loads.[37]

The HS lane load consists of a distributed load and an axle load placed at a location along the bridge to maximize moment demands. According to the AASHTO Standard Specifications (22), both the distributed load and axle load are distributed transversely across a distance of 10 ft across the 12 ft lane. In the case of multi-span bridges, a second axle load is added to separate span when calculating negative moment demands. This was implemented using a conservative approximation in SAP2000 by specifying that the distance between the two axle loads must be greater than half of the longest span length. For example, in the case of a bridge with span lengths of 33, 100, and 33 ft the minimum distance between axle loads would be 50 ft. For most bridge geometries, this ensures the maximum negative moment demands cannot be caused by the two axle loads being located in the same span.

3.5.2 Selection of Bridge Parameters

This study adopts a process similar to that used by Zokaie *et al*. (27) to examine live load distribution factors. Some parameters utilize the Zokaie's suggested values, while others were suggested by the NCDOT Structures Management Unit Manual. Models were created using a template simply supported bridge with values typical of an average bridge and then varying one of the following parameters at a time: span lengths, girder types, girder strength, girder spacing, slab strength, slab depth, and slab transverse slab cracked moment of inertia. While some correlation between variables is possible, this method allows for a smaller sample size while still providing insight into the interaction between superloads and bridges.

Due to expected differences in bridges designed for one or two lanes of loading, models with both one and two lanes were created for each selected set of parameters. Despite many of the bridges in North Carolina having three spans, simply supported bridges were analyzed when varying parameters other than span length and number of lanes to avoid complicating observable trends. Models of continuous bridges were created with varying span lengths and number of

[37] Source: AASHTO Standard Specifications for Highway Bridges, 2002

spans. The sections that follow discuss the range of values and typical value assumed for each parameter in this study.

3.5.2.1 Simply Supported Bridge Model Parameters

Span Lengths: Six span lengths were considered for simply supported bridges: 50, 100, 150, 200, 250, and 300 ft. A typical value of 100 ft was selected from a database of bridges within North Carolina, which was provided by NCDOT as a representative span length for simply supported PPC girder bridges. The 50 ft span represents a standard short simply supported bridge, while the longer spans represent bridges constructible through splicing girders together or using high strength concrete.

Girder Spacing: Spacings considered were: 2, 4, 6, 8, and 10 ft. A typical value of 6 ft was assumed. According to NCDOT OSOW, while wider spacings are possible, more narrowly spaced girders were typically less conservative due to AASHTO LFD design specifications.

Girder Types: In accordance with the NCDOT Structures Management Unit Manual, four standard PPC girder sizes were selected: AASHTO Type II, Type IV, and Type VI, as well as a 72” Modified Bulb Tee. The middle-sized of AASHTO Type IV girders was chosen as a typical girder. Figure 78 and Figure 79 display geometries of the girders selected.

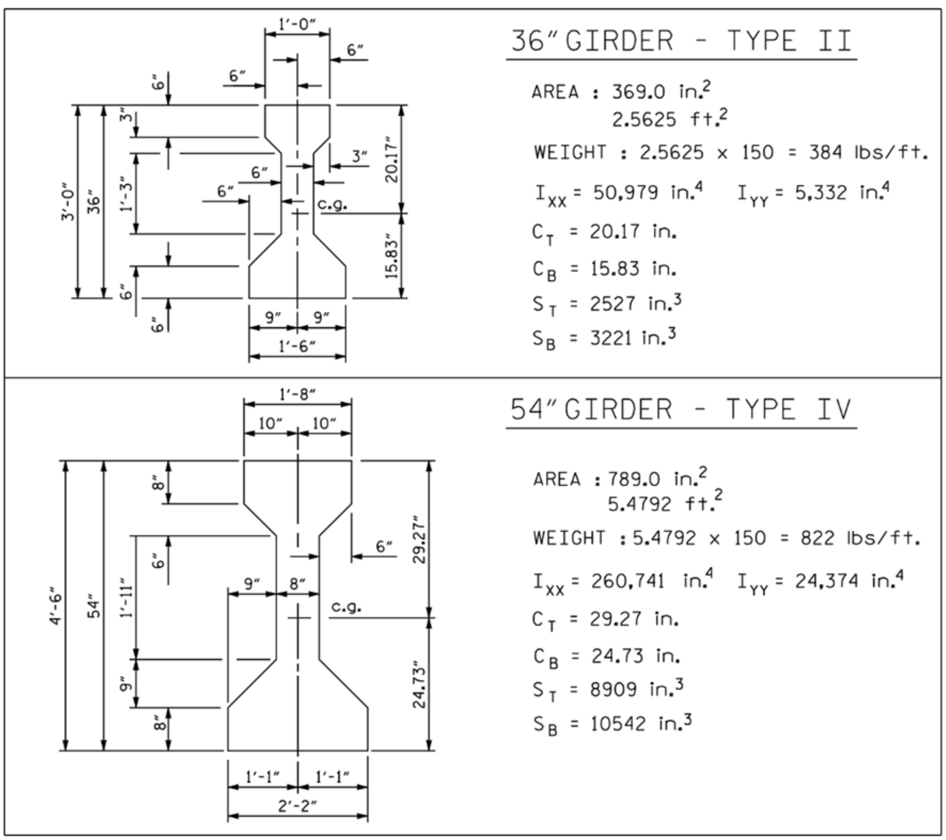


Figure 78 AASHTO Prestressed Precast Girder Types (1 of 2).

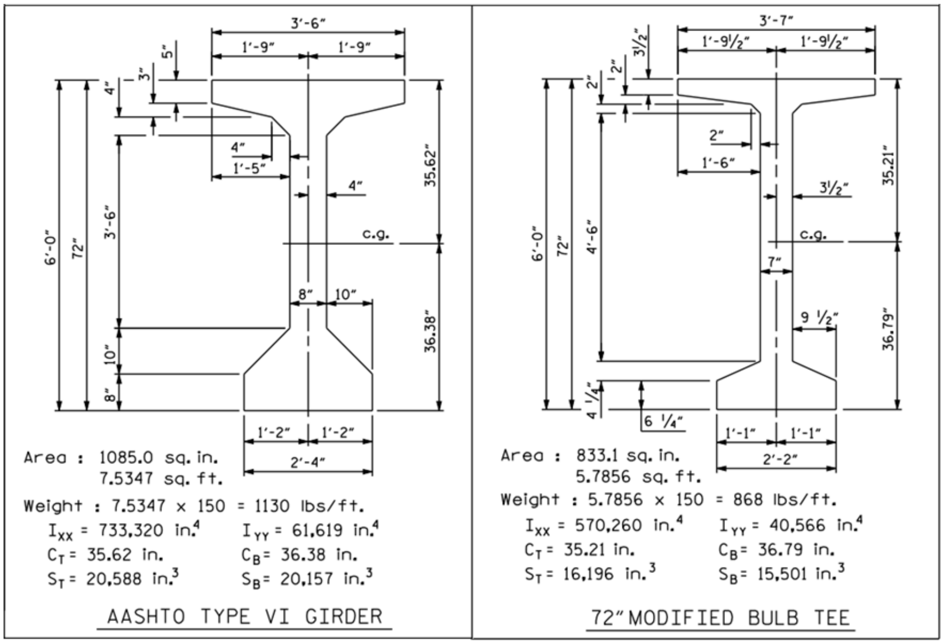


Figure 79 AASHTO Prestressed Precast Girder Types (2 of 2).

Girder Strength: Girder strengths considered were: 5, 10, 15, and 20 ksi. The 10 ksi strength concrete represents typical practice for precast construction today, while the 5 ksi concrete strength occurs in older bridge construction practices. The 15 and 20 ksi concrete strengths represent high strength concrete girders to be used in future bridges.

Slab Strength: Slab strengths selected were: 2, 4, 6, and 8 ksi. The strength of 4 ksi represents a value typically used for bridge construction, while the other values are included to account for lower and higher strengths that can be typically expected.

Slab Depth: Slab depths selected were: 8, 10, and 12 inches. These depths are typical for current bridge construction practices, with a typical value of 10 inches assumed.

Transverse Slab Cracked Moment of Inertia: Slab cracked moments of inertia selected were: 50, 100, 150, 200, and 250 in^4. A range of acceptable slab cross-sections was created while varying slab depth, steel content, and steel location according to the NCDOT Structures Management Unit Manual. Cracked moments of inertia due to positive and negative moments were calculated for each of these cross-sections. These values ranged from approximately 50 in^4 to 160 in^4 for a slab concrete strength of 4ksi. The higher values of 200 and 250 in^4 represent the possibilities of stronger cross-sections that have a higher steel content or stronger concrete. Though the cracked moments of inertia induced by positive and negative moments varied, this difference was neglected in the bridge models due to the added complexity and minimal difference likely to occur.

3.5.2.2 Continuous Span Bridge Model Parameters

Continuous bridges were modeled by varying the number of spans and their lengths while assuming typical values for all other parameters. The bridge span length ratios (SLR) considered were: 1:1, 1:2, 1:3, 1:1:1, 1:2:1, 1:3:1, 1:1:1:1, 1:2:2:1, and 1:3:3:1. For each of these span length ratios three models were created using 50, 100, and 150 ft as the maximum span length. For example, a bridge with a maximum span length of 100 and a span-length ratio of 1-2-2-1 would have four spans with lengths 50 ft, 100 ft, 100 ft, and 50 ft.

3.6 BridgeMaker

3.6.1 Program Overview

In order to quickly and accurately create bridge models for analysis, the NCSU team created a helper program called BridgeMaker. BridgeMaker allows the user to quickly create a plane-grillage model of straight and non-skewed PPC slab-on-girder bridges. The program accepts inputs in terms of vehicle files, total bridge length, span length ratios, girder types and spacing, slab depth and cracked moment of inertia, number of lanes, and the strength of the slabs and girders. From these inputs and user specified vehicles, BridgeMaker creates a text file that can be imported into SAP2000 for analysis.

BridgeMaker models bridges using the plane-grillage analysis method where a mesh of representative elements is created based on bridge properties. Longitudinal elements are modeled to represent girders and contributing portions of the deck slab accounting for their stiffness and material properties. Transverse elements are modeled to represent the slab's properties alone and to transmit loads to the girders. It is assumed that the slab is cracked longitudinally, representing the worst-case scenario where a superload exceeds a majority of the slab's capacity for transferring demands between girders. The resulting mesh of frame elements is less stiff than an uncracked model, which conservatively estimates the worst case of girder demands before girder cracking occurs.

The team chose to neglect the stiffness of secondary elements such as sidewalks, parapets, and diaphragms. Based on prior work by Eamon and Nowak (29) this assumption is typically conservative. While most bridge bent and abutment connections impart additional stiffness to the bridge, connections were modeled as frictional supports without any moment resistance. This approach typically provides conservative results and attempts to model bridge abutment fixities without adequate calibration. This will provide unconservative results in some cases of bridge geometries and superloads.

Each of these assumptions imparts a range of conservativism for results calculated when using BridgeMaker models. Analysis results for shorter bridges are expected to be more conservative than those for longer bridges, for both simply supported and multi-span bridges.

3.6.2 Initial Model Development

Prior to switching to analyses using AASHTO LFD loadings, initial sensitivity analyses for BridgeMaker utilized Vehicle 4 and the HL-93 design load from the AASHTO LRFD Bridge Design Specification (35). The HL-93 load is a notional load comprised of an HS truck, a tandem vehicle, and a lane load. Analyses were run on bridges of varying span lengths while changing the method for resolving wheel loads, longitudinal load distribution of vehicle loads, and model refinement level.

Method for resolving wheel loads into bridge loads: In order to be modeled, vehicles must be resolved into point loads and distributed loads to be applied during analysis. While each wheel could be modeled as a point load, this is computationally intensive and sensitivity tests suggested a simpler method of converting wheel pairs into a single point load located at the geometric center of each transverse wheel-pairing. This simplified modeling method reduced the number of loads by half and resulted in less than 1% difference in moment demands. Reducing paired wheels into a single load was selected for use in future analyses.

Since the modular superload vehicles have many closely spaced wheels along a single axle-line, a test vehicle was created using a distributed load for each line of wheels. This method produced results with up to an unrealistic 300% reduction in demands along external girders, and was eliminated from further analyses.

Longitudinal load distribution of vehicle loads: Most of the superload permits received from NCDOT OSOW for analysis indicated that an even longitudinal distribution of load is assumed. For example, when considering a 1000-kip vehicle load on a 10-axle trailer, permit applicants assume an axle-line weight of 100 kips. To test the effect of other load distributions, a triangular load distribution was created from the test vehicle for comparison to the equal distribution typically assumed. Figure 81 shows an example of an equal distribution and the triangular distribution. Note that the vertical axes are scaled differently, however each vehicle weighs the same amount.

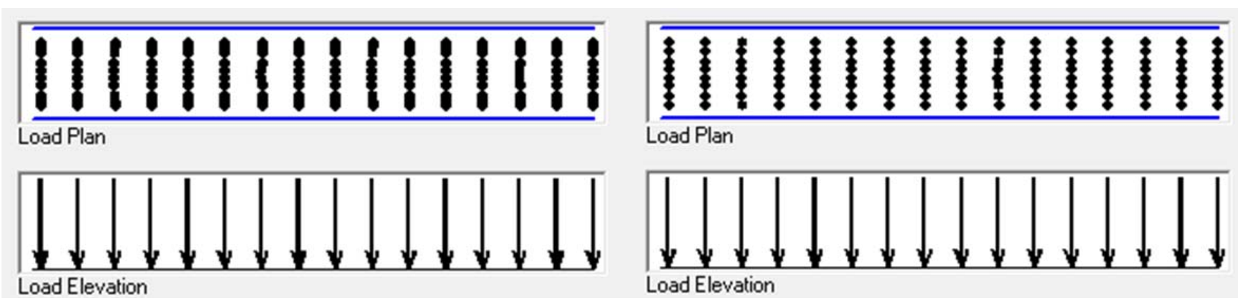


Figure 80 Resolving a Superload into Point Loads Using Individual Wheels (left) and Wheel Pairs (right).

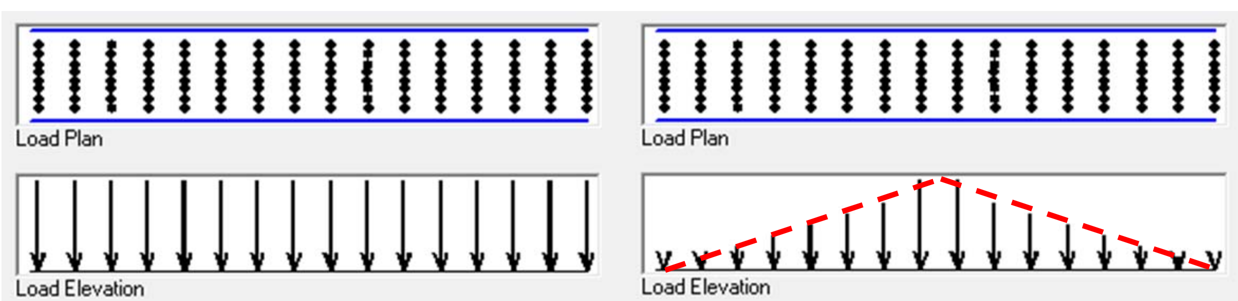


Figure 81 Uniform Load Distribution (left) and Triangular Load Distribution (right) of a Superload Truck.

Results showed up to a 10% difference in demands between the triangular and equal distribution of loads. Differences in demands were largest for exterior girders and longer spans. While modeling both distributions in future analyses was initially considered, the data gathered from the superload weighing at Shearon Harris and Garner, as well as data provided by NCSHP suggests that the vehicles have a degree of control over the weight distribution to prevent an extreme load imbalance. We concluded modeling a series of representative superload vehicles with varying axle geometries would be more beneficial.

Transverse load distribution of vehicle loads: The superload weightings performed at Shearon Harris provided data for the driver and passenger side axle weights for the outer tire loads. From this data, we observed that superloads can distribute their weight unevenly across axles if the payload is not properly centered on the vehicle. The difference of axle loads was only 6.3% for the worst case, but even this could lead to additional demands on girders under the heavier side. Attempts were made to replicate uneven transverse loading with BridgeMaker and SAP2000, however SAP2000 does not support vehicles that are non-symmetrical across their axles. This difference was neglected in this report, but quantifying the effects of imbalanced superloads could provide useful information if examined in future research.

Model refinement level: When modeling bridges using BridgeMaker, the girders and slab are resolved into representative beam elements in the transverse and longitudinal directions. To determine the effect of mesh refinement on results, models were created with varying span lengths and longitudinal elements. Elements were limited to 2, 5, and 10 ft. The demands' variance was nearly negligible for all load cases and bridge spans. A maximum segment length of 10 ft was used in future analyses to reduce the number of elements and in doing so, the computational costs also decreased significantly.

3.7 Analysis Results

3.7.1 Introduction

During initial testing of BridgeMaker, it became evident that superloads could impart significant demands on both the exterior girders and their adjoining girders. This led to gathering data for "transition" girders, referring to the girders that lie adjacent to the external girders. External girders refer to the girders that run along the outside edges of the bridge, while internal girders refer to the girder found closest to the centerline of the bridge. For each girder, maximum positive moments were found across each span and maximum negative moments found over each bent. From these moments, the HS-Equivalent Vehicle Ratings were calculated. These ratings represent the equivalent weight of an HS vehicle in tons that produces the same demand. HS-equivalent vehicle weights from SAP2000 analyses of plane-grillage models were calculated using Equation (1):

$$HS_{eq} = \left[\frac{M_{SL} * IM}{M_{HS} * IM} \right] * W_{HS} \tag{1}$$

HS_{eq} is the HS-equivalent weight for a given superload, while M_{SL} and M_{HS} are moment demands for the superload and HS loading. The term IM represents impact factors, which can be canceled out, resulting in Equation (2):

$$HS_{eq} = \left[\frac{M_{SL}}{M_{HS}} \right] * W_{HS} \tag{2}$$

For example, on a given bridge a superload causes a moment demand of 1000 kip*ft, while an HS-15 vehicle causes a moment demand of 500 kip*ft. The resulting HS-equivalent rating for the superload in this case would be an HS-30, as seen below (3).

$$HS_{eq} = \left[\frac{1000}{500} \right] * 15 = HS - 30 \tag{3}$$

After the calculation of HS-equivalent vehicle weights from the SAP2000 data, similar values were calculated using the modified NCDOT OSOW permitting process. PERM6 is an in-house program that calculates moment demands for a given superload and a HS-15 vehicle for a range of simply supported span lengths. The program then calculates the HS-equivalent vehicle weight for the superload across a range of span lengths. For continuous bridges, the longest span length is selected, and the resulting HS-equivalent vehicle weight is multiplied by a factor of 1.2 to account for the possibility of negative moment regions controlling. Below, Equation (4) represents how PERM6 calculates the HS-equivalent vehicle weights. The term GDF represents the girder distribution factor calculated according to AASHTO Standard Specifications (22). Once terms cancel, Equation (4) becomes Equation (2), above.

$$HS_{eq} = \left[\frac{M_{SL} * GDF * IM}{M_{HS} * GDF * IM} \right] * W_{HS} \tag{4}$$

Since the girder distribution factors from the 2002 AASHTO Bridge Design Specifications include multiple lane presences for a single lane vehicle and have different distribution factors for one or two-lane bridges, only one lane-width of a superload is analyzed using PERM6. The girder distribution factors in AASHTO Bridge Design Specification were created using standardized one-lane vehicles, and account for the likelihood of multiple vehicles passing simultaneously to create maximum demands. Early test analyses revealed that this method was likely extremely unconservative for two-lane superloads. ***As a result, this division of superloads into a single lane-width was not done when calculating the HS-equivalent vehicle weights using the NCDOT OSOW program PERM6***. Instead, entire two-lane superloads were analyzed for comparison with one-lane superloads. This only affects results for superloads that are wider than a single lane (12 ft): Vehicle 2b, 4, and 5a.

After calculating HS-equivalent vehicle weights from the SAP2000 plane-grillage models and the NCDOT OSOW program PERM6, a factor of conservatism is calculated by dividing the PERM6 value by the SAP2000 value. This conservatism ratio is the factor by which current NCDOT practices over or under estimate demands due to a superload. As such, values between +1.0 and -1.0 are unconservative when compared to values calculated using the grillage model analysis.

Graphs for moment demands, HS-equivalent vehicle weights, and conservatism factors for all bridges analyzed are displayed below and discussed. Since a majority of the same conclusions can be made from the moment demands and the HS-equivalent vehicle weights, generalized conclusions from the moment demand are provided with their associated graphs located in APPENDIX B section B.1. Afterwards, results for the HS-equivalent vehicle weights and conservatism ratios are broken down by the parameter varied. Graphs are displayed side-by-side for external, transition, and internal girders where applicable per case, with a diagram indicating where on the girder the values occur.

3.7.2 Overall Results

Figure 82 shows the moment demands for all bridges analyzed. Positive moment demands were found to be typically two to three times higher than the negative moments. This trend is observed for all superloads and the HS-15 Truck. It is noted that Vehicle 2b's demands are lower than Vehicle 2a's, evidence that the wider wheel base on Vehicle 2b due to its expandable axles helps distribute loads across the bridge superstructure. Similarly, Vehicle 5b's demands are higher than Vehicle 5a's demands, suggesting that the outrigger dollies on Vehicle 5a also helps distribute the load across the bridge superstructure.

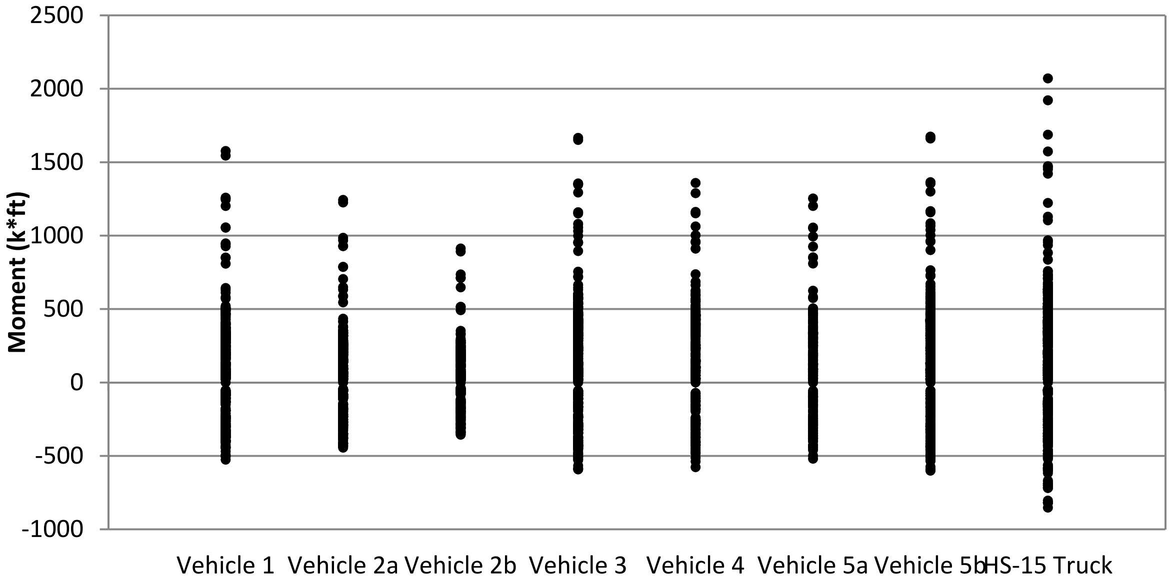


Figure 82 Moment Demands for all Bridges Analyzed.

Figure 83 displays the equivalent HS-vehicle weights calculated for all bridges analyzed. Immediately observable is that while the positive moment demands were higher than the negative moment demands, the opposite is true for HS ratings. In each case, the negative HS-equivalent vehicle weights are typically larger than the positive HS-equivalent vehicle weights. This occurs because of the difference in the distribution of loads between the superloads and the notional HS-15 load, which makes logical sense given that the superloads are typically longer than the HS truck. While the HS loading does have a lane loading included to account for longer vehicles or heavy traffic, it typically controls only for longer bridges (approximately 200 ft or longer, depending on the number of spans and their arrangement).

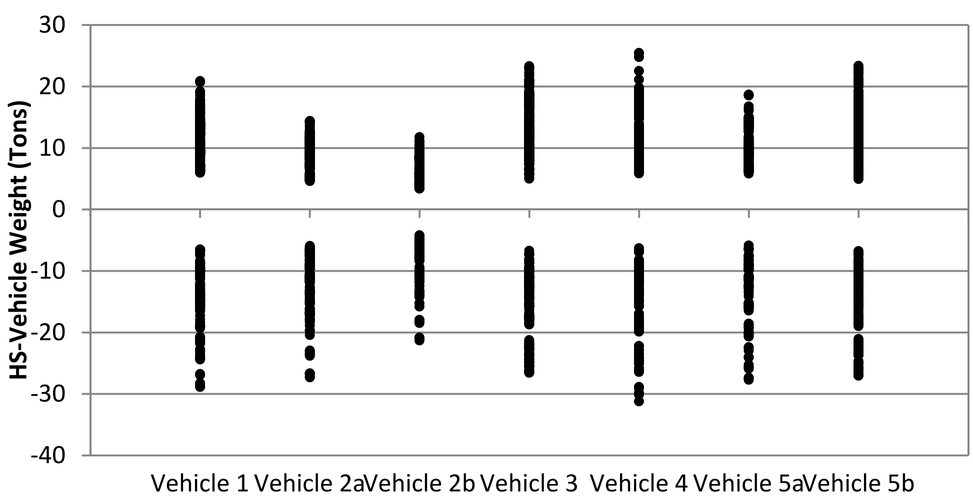


Figure 83 HS-Vehicle Weights for all Bridges Analyzed.

Figure 84 displays the conservatism factors calculated for all bridges analyzed. The dashed lines bound the region of unconservatism. Data points within this area represent instances where the HS-Vehicle Weight calculated by the plane-grillage method using SAP2000 is underestimated by the PERM6 calculation. Each vehicle's demands are unconservatively estimated for a number of bridges and overly conservative for other bridges. Due to the number of data points displayed on the graph and the resulting congestion, data is further broken down below by which girder the demands occur on.

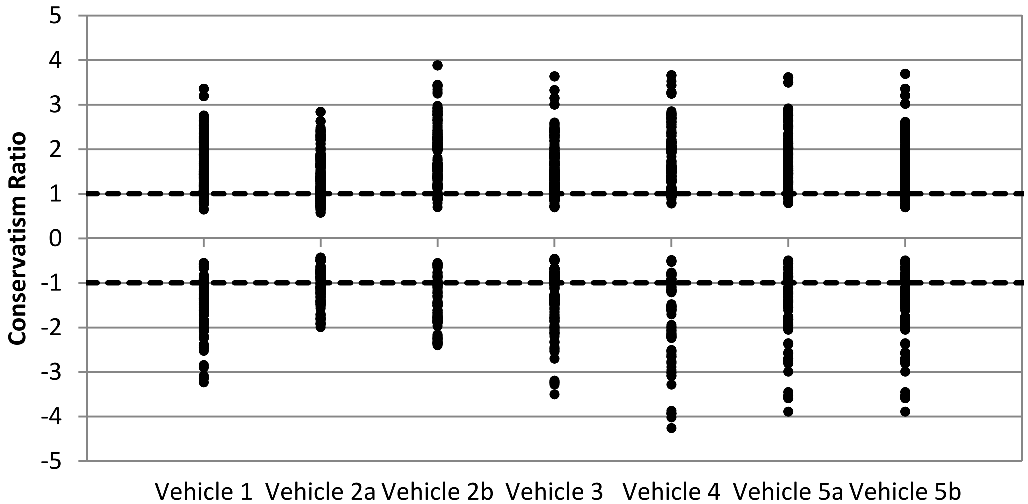


Figure 84 Conservatism Factors for all Bridges Analyzed.

Figure 85 displays conservatism ratios for moment demands on the external girders. NCDOT OSOW's current methods of analysis poorly estimate the superload's demands on external girders. Many of the superloads have their positive and negative demands underestimated by up to 50%. While a wider wheelbase appears to help distribute load across the external girders for Vehicle 2 (the drop-deck gooseneck), there is less of a difference between Vehicle 5 (modular with and without outriggers). There is little difference between the results for Vehicle 3 and Vehicle 5b, despite Vehicle 5b having an additional modular axle-line and less distance between the pull truck and modular trailer.

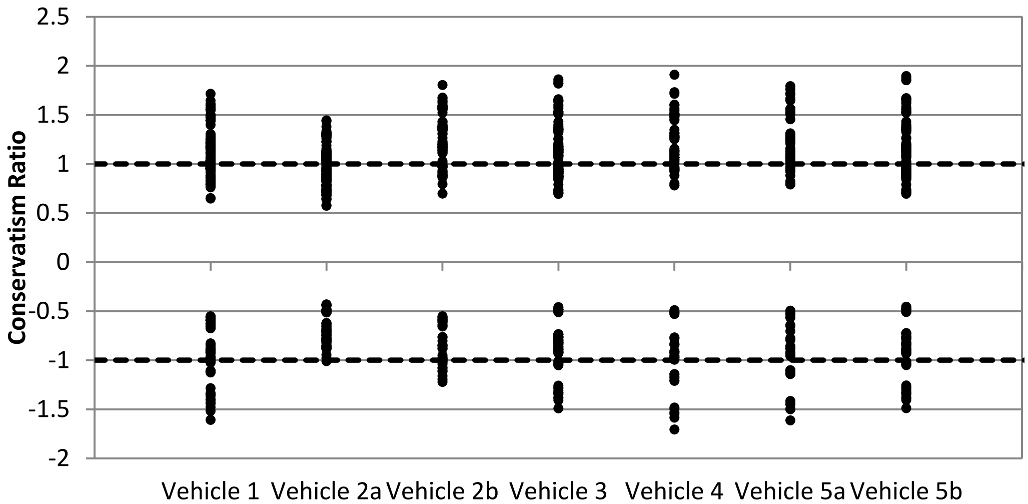


Figure 85 Conservatism Ratios for External Girders on all Bridges Analyzed.

Figure 86 displays conservatism ratios for transition girders. Overall, a majority of positive demands are estimated conservatively, though several instances of negative moment demands are under-estimated by up to 33%. Again, Vehicle 2b's results are more favorable than Vehicle 2a, and Vehicle 3 and Vehicle 5b results appear nearly identical.

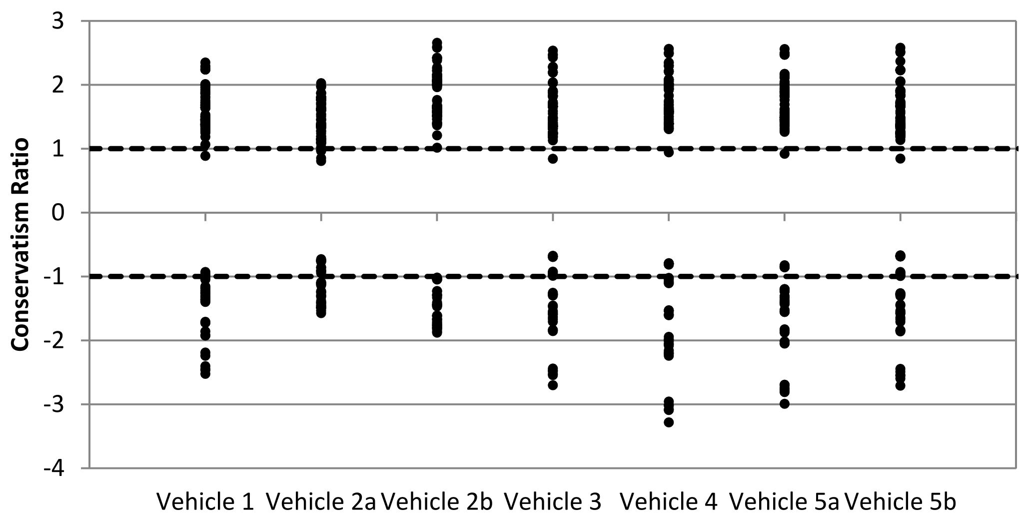


Figure 86 Conservatism Ratios for Transition Girders on all Bridges Analyzed.

Figure 87 displays conservatism ratios for demands on internal girders. Overall, NCDOT OSOW's current method of analysis predicts superload demands for internal girders fairly well. Negative moment demands were still underestimated for several cases involving the drop-deck gooseneck and one-lane modular vehicles (Vehicles 2a, 3, and 5b), though there are less instances where this occurs.

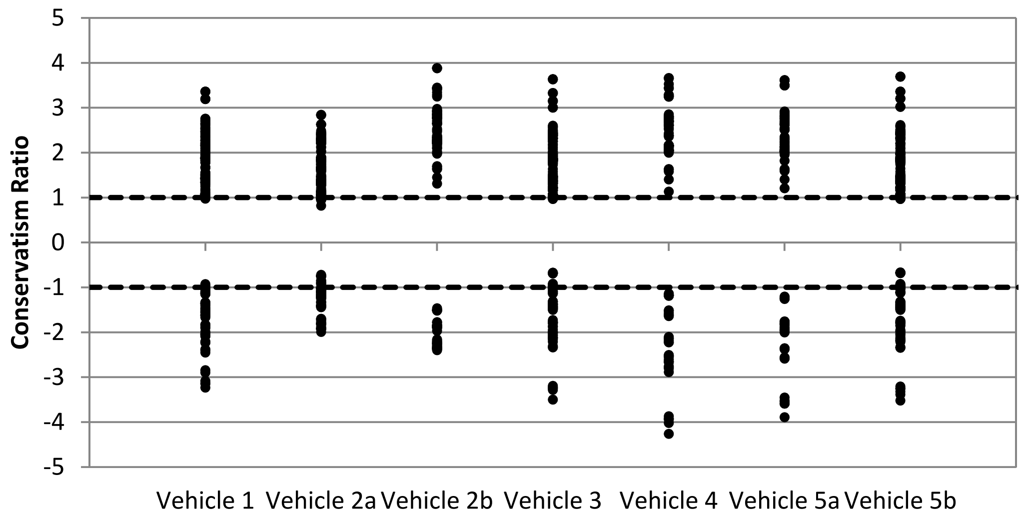


Figure 87 Conservatism Ratios for Internal Girders on all Bridges Analyzed.

Figure 88 and Figure 89 show conservatism ratios separately for one and two-lane bridges. Vehicles 2b, 4, and 5a do not appear in Figure 88 due to the fact that they are too wide for a one-lane bridge. Noting that these vehicles' demands are still underestimated by a large margin in some cases, the choice to not analyze the wider superloads as a single lane width is justified. If a single lane-width of each superload to be analyzed using PERM6, the resulting demands would be less accurate.

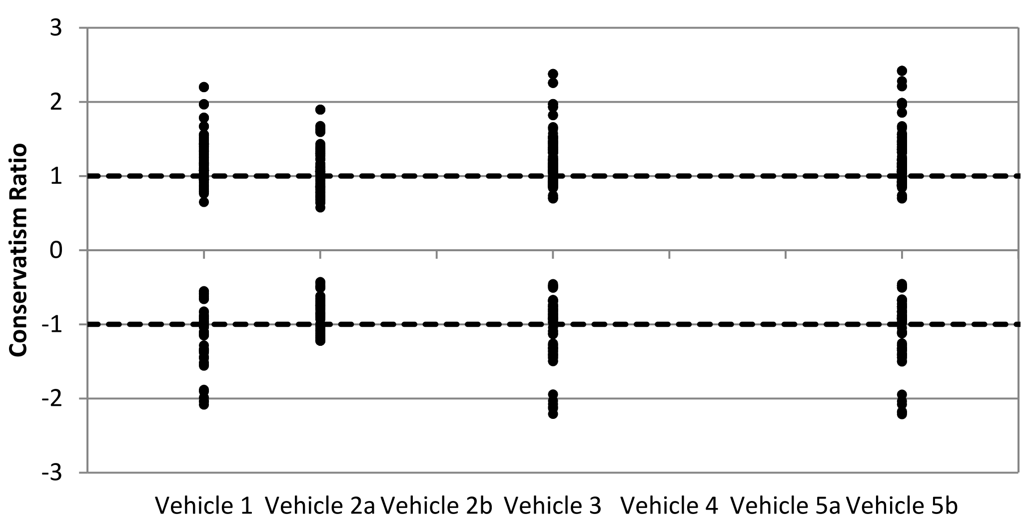


Figure 88 Conservatism Ratios for all girders on One-Lane Bridges.

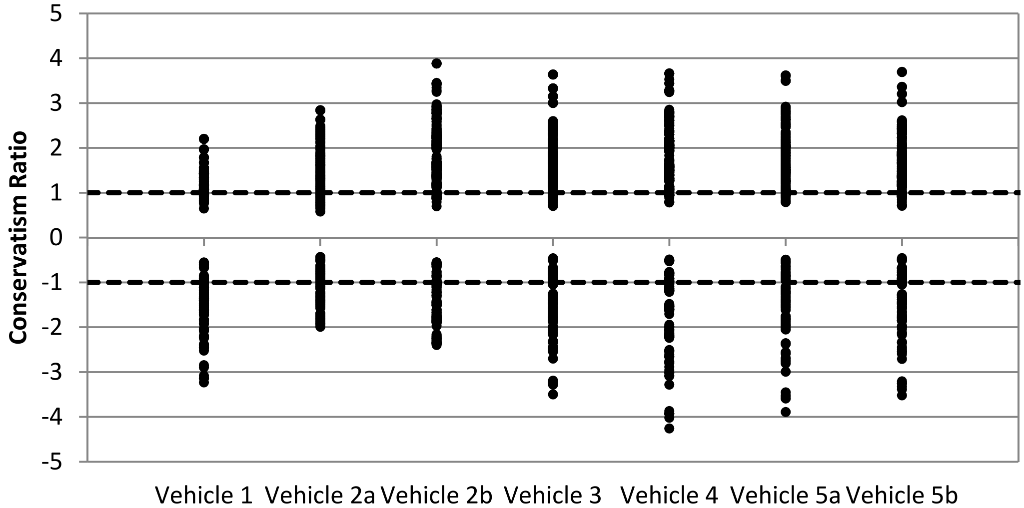


Figure 89 Conservatism Ratios for all girders on Two-Lane Bridges.

3.7.3 Moment Demands and HS-Equivalent Vehicle Weight Results

Figures displaying moment demands calculated for the superloads and HS-15 loading are located in APPENDIX B section B.1, while figures displaying the superload's HS-equivalent vehicle weights are located in APPENDIX B section B.2. Graphs are broken down by the parameter varied, with graphs for external, transition, and internal girder demands located next to each other for direct comparison. Note that the demands displayed are per 100 kip of GVW. Relative demands of the superloads are discussed below.

On one-lane bridges, calculated positive and negative moment demands from least to greatest were typically as follows: Vehicle 2a, Vehicle 1, Vehicle 3, and Vehicle 5b. Vehicle 3 and 5b cause nearly identical demands in every case, though this is expected due to their similarities in load distribution. As previously mentioned, Vehicle 5b has one additional axle-line and a shorter distance between the pull truck and the modular trailer. For shorter bridges, positive demands for Vehicle 1 typically controlled over those of Vehicle 3 and 5b. Moment demands due to HS-15 loading result in demands on internal girders that closely follow the maximum demands generated by the superloads. For external girders, the demands from the HS-15 loading are much less, falling between the values for Vehicles 1 and 5b. This leads to the HS-equivalent vehicle weights being much higher on external girders than those calculated for internal girders. This difference in values between girders highlights the difference in transverse load distribution between superloads and the HS-15 loading.

On two-lane bridges, calculated positive and negative moment demands from least to greatest were typically as follows: Vehicle 2b, Vehicle 2a, Vehicle 1, Vehicle 5a, Vehicle 3, Vehicle 5b, and Vehicle 4. Demands for Vehicles 3 and 5b are nearly identical, while Vehicles 1 and 5a exhibit similar demands for transition and internal girders. Vehicle 5a causes slightly higher demands than Vehicle 1 on external girders. For shorter bridges, positive demands for Vehicle 1 typically controlled over those of Vehicles 3 and 5b. HS-15 demands are typically much larger than superload demands for internal and transverse girders, while falling between Vehicle 5a and 5b's demands for external girders. This difference results in HS-equivalent vehicle weights calculated for external girders to be much larger than the transition and internal girders.

3.7.4 Conservatism Ratio Results

3.7.4.1 Results for One-Lane Simply Supported Bridges

Table 33 contains the lowest conservatism ratios for each group of bridges tested. Values above 1.0 are conservative, while values below 1.0 are unconservative when compared to results from the plane-grillage model. Internal girder demands are accurately predicted by the modified method in most cases, while external girder demands are under predicted by up to 36%.

Table 33 Worst-Case Conservatism Ratios for One-Lane Simply Supported Bridges

	Parameter						
Girder	Slab Depth	Girder Strength	Slab Strength	Girder Type	Slab Inertia	Girder Spacing	Span Length
External (+)	0.851	0.842	0.842	0.680	0.826	0.687	0.641
Internal (+)	1.057	1.054	1.054	1.043	1.043	1.031	0.957

Figure 90 through Figure 96 contain graphs of conservatism ratios for the one-lane simply supported bridges analyzed. Each figure contains the results from a group of bridges varying a single parameter. There are few differences observed between the responses for different superload vehicles on the internal girders. On external girders, Vehicle 1's demands are better approximated than the demands from Vehicles 2a, 3, and 5b. Varying girder and slab concrete strength, slab depth, and cracked moment of inertia of transverse slab elements had little impact on the accuracy of the modified NCDOT OSOW method. Span length, girder type, and girder spacing typically only affected the accuracy of the estimates of the external girder demands. Shorter span lengths, larger girder sizes, and smaller girder spacings caused progressively less accurate results. Vehicles 2a, 3, and 5b's demands were most often severely under-estimated for bridges modeled with these parameters.

A one-lane bridge model with a girder spacing of 8 ft was created and analyzed, but was neglected deleted due to the demands being an order of magnitude higher than the others. This was likely a result of a mismatch between the superload movement discretization and the model mesh, or problem in either BridgeMaker or SAP2000.

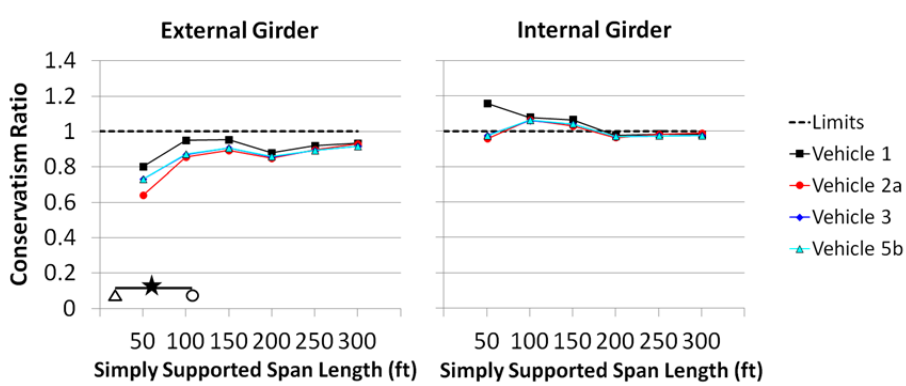


Figure 90 Conservatism Ratios of One-Lane Bridges with Varying Span Lengths.

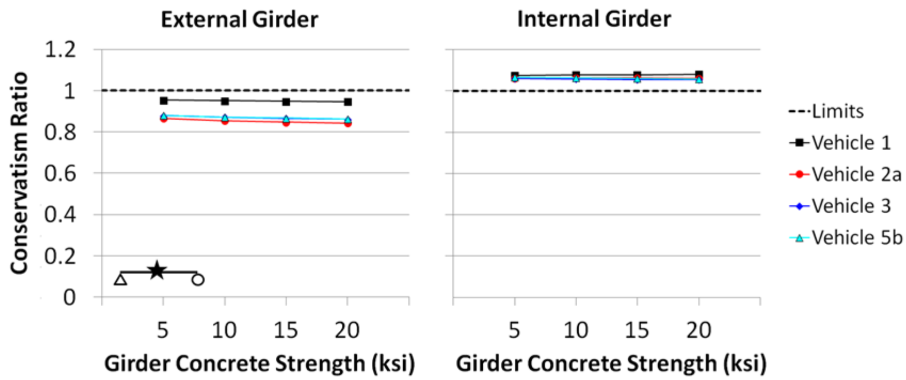


Figure 91 Conservatism Ratios of One-Lane Bridges with Varying Girder Strengths.

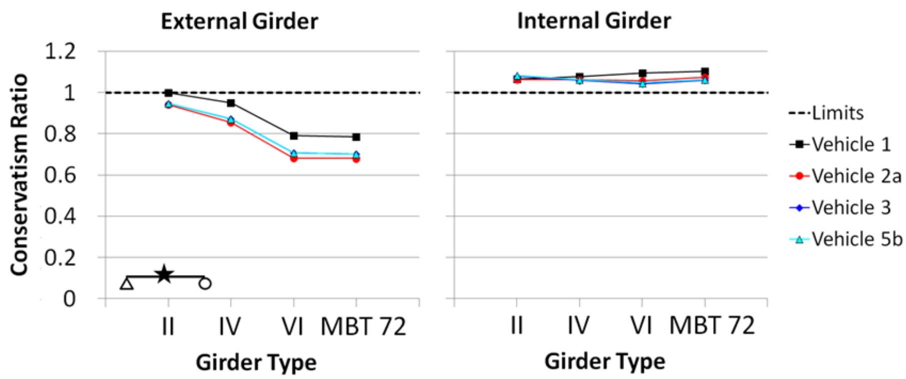


Figure 92 Conservatism Ratios of One-Lane Bridges with Varying Girder Types.

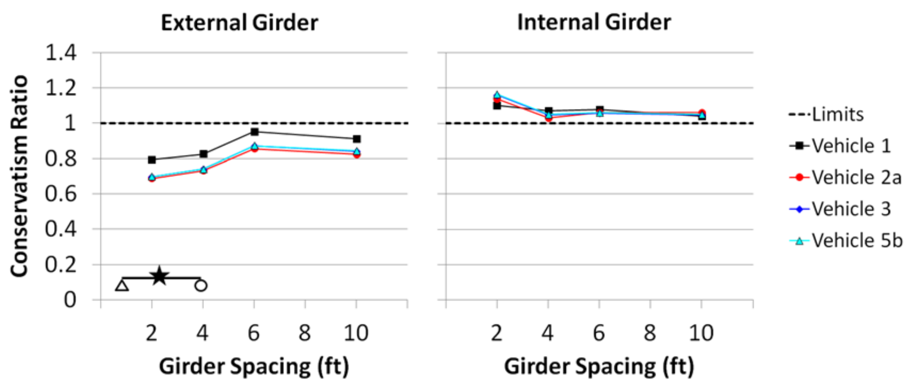


Figure 93 Conservatism Ratios of One-Lane Bridges with Varying Girder Spacing.

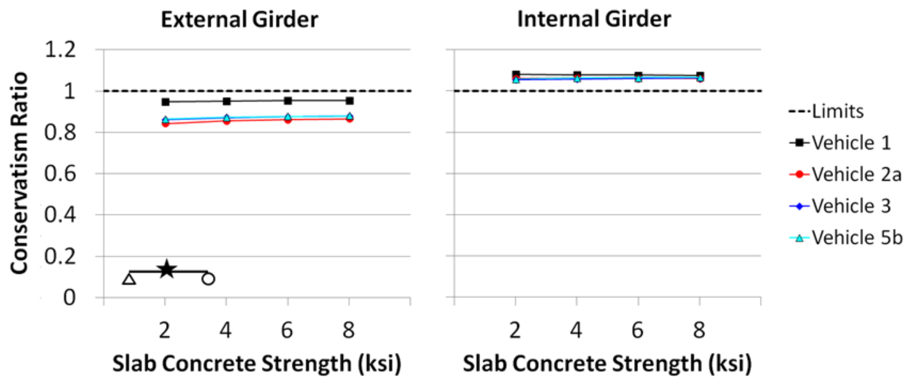


Figure 94 Conservatism Ratios of One-Lane Bridges with Slab Concrete Strength.

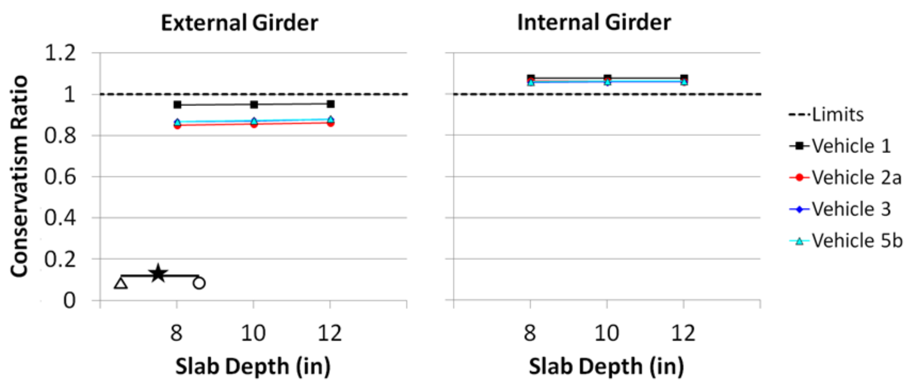


Figure 95 Conservatism Ratios of One-Lane Bridges with Slab Depth.

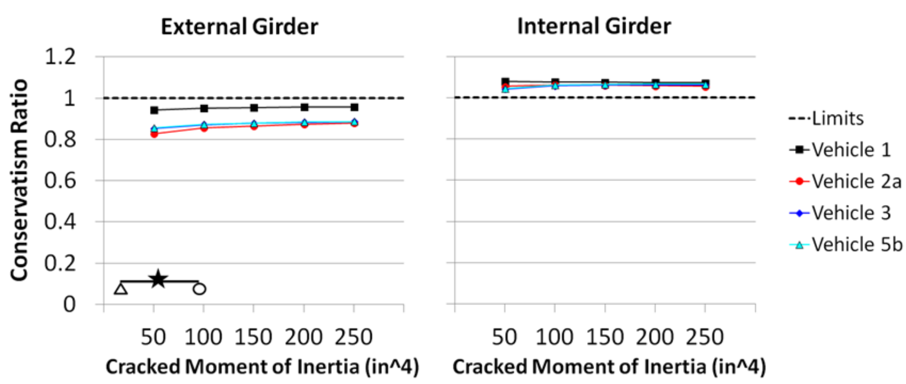


Figure 96 Conservatism Ratios of One-Lane Bridges with Varying Cracked Moment of Inertia of Slab.

3.7.4.2 Results for Two-Lane Simply Supported Bridges

Table 34 contains the lowest conservatism ratios for each group of bridges tested. Values above 1.0 indicate the modified NCDOT OSOW method is conservative when compared to results from the plane-grillage model, while values below 1.0 are unconservative.

Table 34 Worst-Case Conservatism Ratios for Two-Lane Simply Supported Bridges

	Parameter						
Girder	Slab Depth	Girder Strength	Slab Strength	Girder Type	Slab Inertia	Girder Spacing	Span Length
External (+)	0.907	0.897	0.897	0.683	0.878	0.718	0.927
Transition (+)	1.342	1.317	1.317	1.224	1.261	0.807	1.155
Internal (+)	1.830	1.804	1.804	1.733	1.762	1.683	0.986

Figure 97 through Figure 103 show conservatism ratios calculated for the two-lane simply supported bridge analyses. In most cases, internal and transition girders are conservatively estimated with one exception; extremely narrow girder spacings result in under-predicting demands up to 20% for transition girders. Similar to their one-lane counterparts, changing girder and slab concrete strength, slab depth, and cracked moment of inertia of transverse slab elements were found to have relatively little effect on the accuracy of the modified NCDOT OSOW's method. Shorter span lengths, larger girders, and smaller girder spacings result in less conservative estimates of superload demands, with extreme cases resulting in estimates up to 33% less than those predicted by the plane-grillage model. With the exception of cases involving Type VI or MBT 72 girders, a majority of the severely under-estimated are due to Vehicles 2a, 3, and 5b.

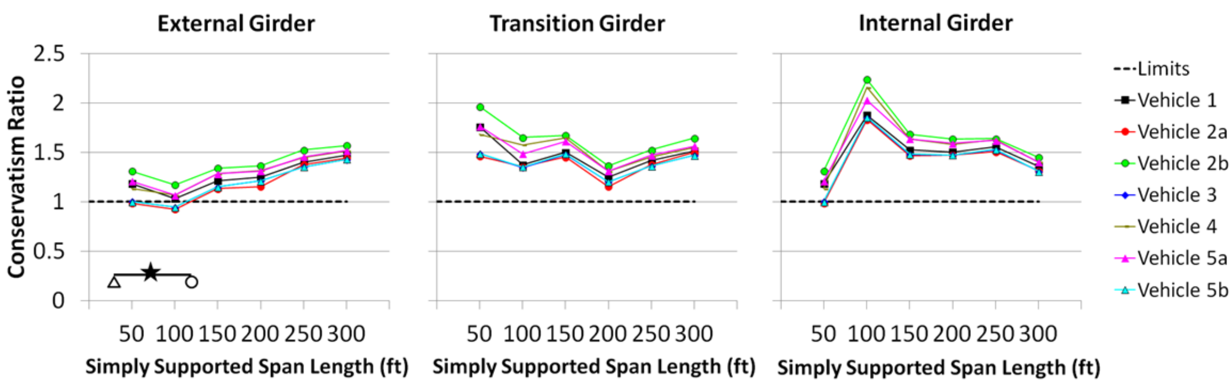


Figure 97 Conservatism Ratios of Two-Lane Bridges with Varying Span Lengths.

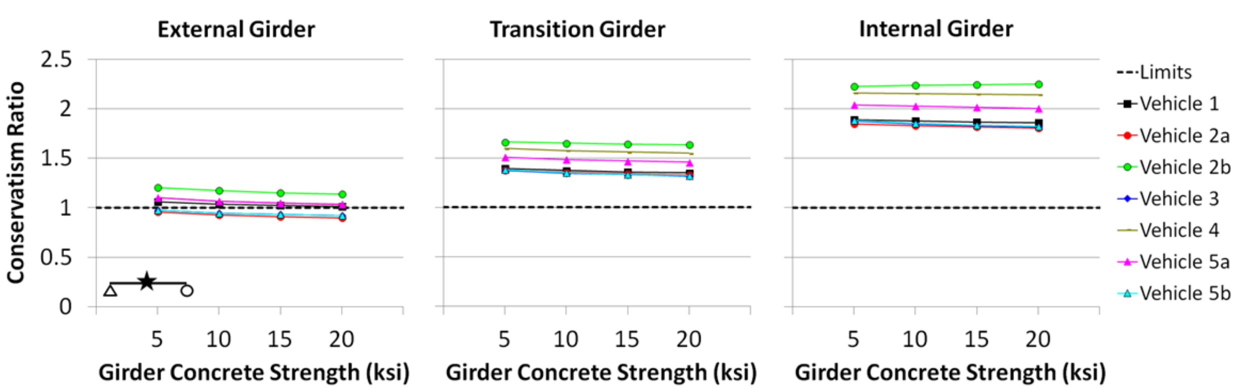


Figure 98 Conservatism Ratios of Two-Lane Bridges with Varying Girder Strengths.

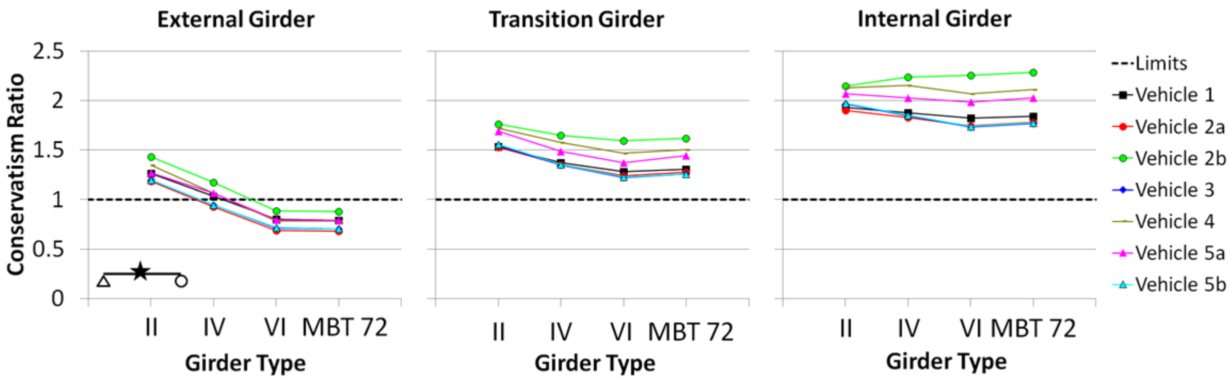


Figure 99 Conservatism Ratios of Two-Lane Bridges with Varying Girder Types.

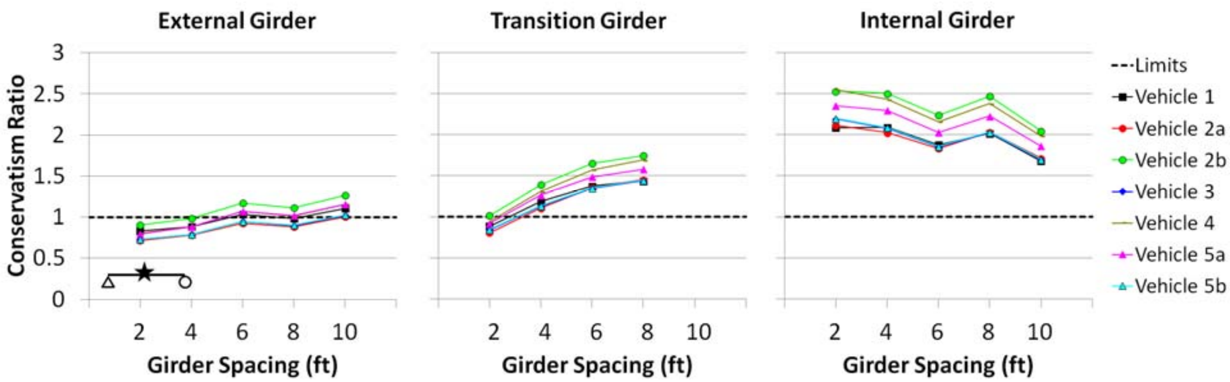


Figure 100 Conservatism Ratios of Two-Lane Bridges with Varying Girder Spacing.

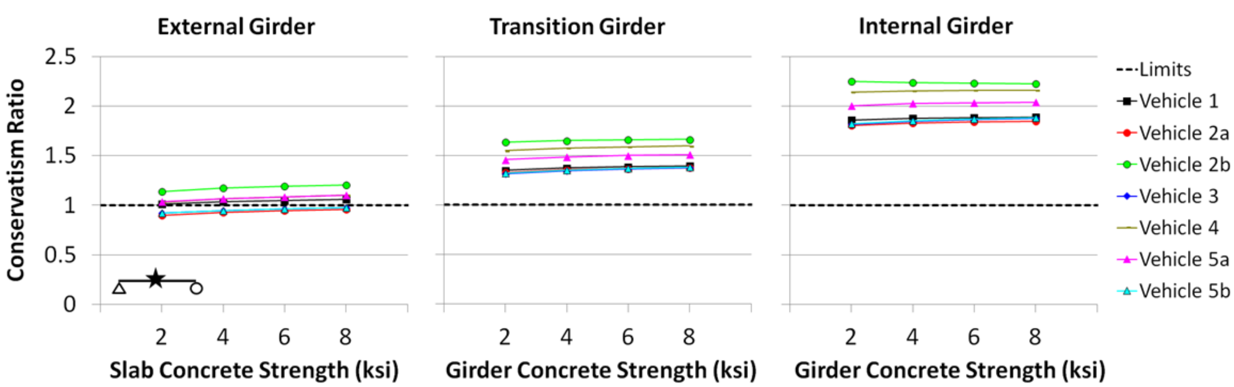


Figure 101 Conservatism Ratios of Two-Lane Bridges with Varying Slab Strength.

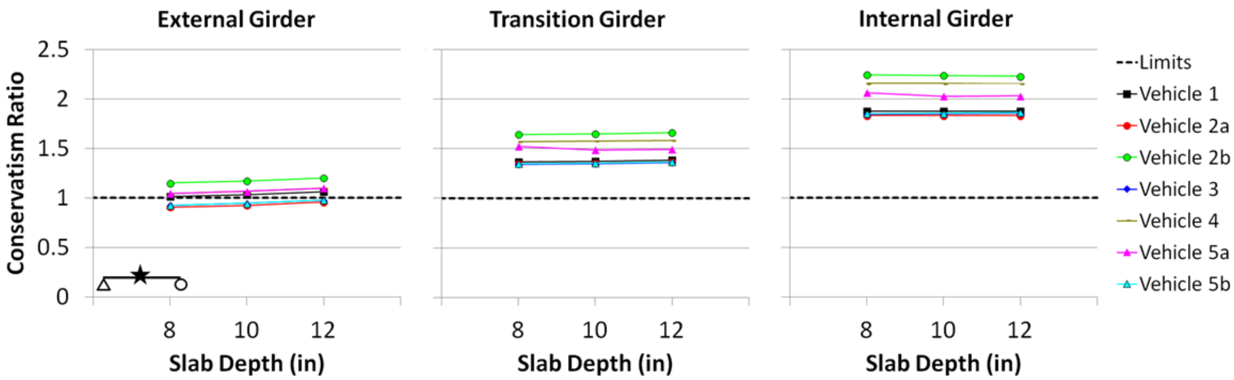


Figure 102 Conservatism Ratios of Two-Lane Bridges with Varying Slab Depth.

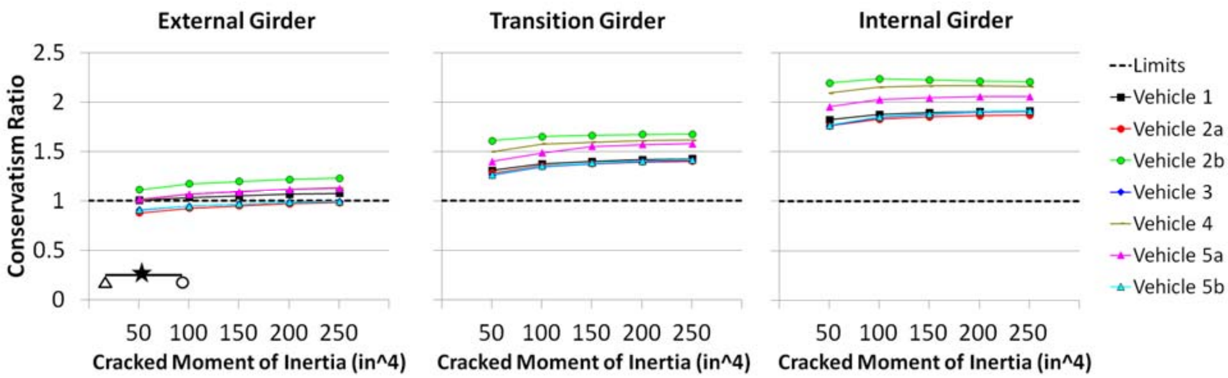


Figure 103 Conservatism Ratios of Two-Lane Bridges with Varying Cracked Moment of Inertia of Slab.

3.7.4.3 Results for One-Lane Continuous Bridges

Table 35 and Table 36 contain the worst-case conservatism ratios for each group of one-lane continuous bridges modeled. Table 35's values are grouped by span length ratio and Table 36's values are grouped by number of spans. Values above 1.0 indicate the modified NCDOT OSOW method is conservative when compared to results from the plane-grillage model, while values below 1.0 are unconservative. Demands were more underestimated for shorter bridges. Positive demands were more accurately estimated than negative demands. Internal girder demands were more accurately estimated than external girder demands. The following sub-sections are broken down by number of spans, with each section containing specific observations and figures for the bridge models analyzed.

Table 35 Worst-Case Conservatism Ratios for One-Lane Continuous Bridges, by Span Length Ratios

	4 spans			3 spans			2 spans		
Demands	1:1:1:1	1:2:2:1	1:3:3:1	1:1:1	1:2:1	1:3:1	1:1	1:2	1:3
External (+)	0.710	0.640	0.575	0.728	0.706	0.729	0.775	0.707	0.723
External (-)	0.479	0.439	0.439	0.476	0.621	0.693	0.430	0.650	0.715
Internal (+)	1.066	0.977	0.821	1.118	1.011	0.952	1.164	1.010	0.948
Internal (-)	0.680	0.681	0.670	0.671	0.849	0.891	0.666	0.912	0.932

Table 36 Worst-Case Conservatism Ratios for One-Lane Continuous Bridges, by Number of Spans

	Number of Spans		
Demands	4	3	2
External (+)	0.575	0.706	0.707
External (-)	0.439	0.476	0.430
Internal (+)	0.821	0.952	0.948
Internal (-)	0.670	0.671	0.666

Figure 106 through Figure 113 contain graphs of conservatism ratios calculated for the one-lane continuous bridges with 2, 3 or 4 spans of varying lengths. For both external and internal girders, estimates for negative moments were underestimated by a larger amount than for positive moments. External girder moments were also under predicted by a larger amount than internal girder moments. Shorter span lengths of bridges result in poorer estimates of demands for a majority of the cases analyzed. The influence of span length on accuracy of demand estimates is more pronounced for negative moments than positive moments. Vehicle 2a is least conservatively estimated for all one-lane continuous bridges modeled. The accuracy of estimating demands for Vehicles 1, 3, and 5b vary bridge to bridge, though Vehicles 3 and 5b exhibit the same load distributions in all one-lane continuous analyses considered.

3.7.4.4 Two Span Bridges

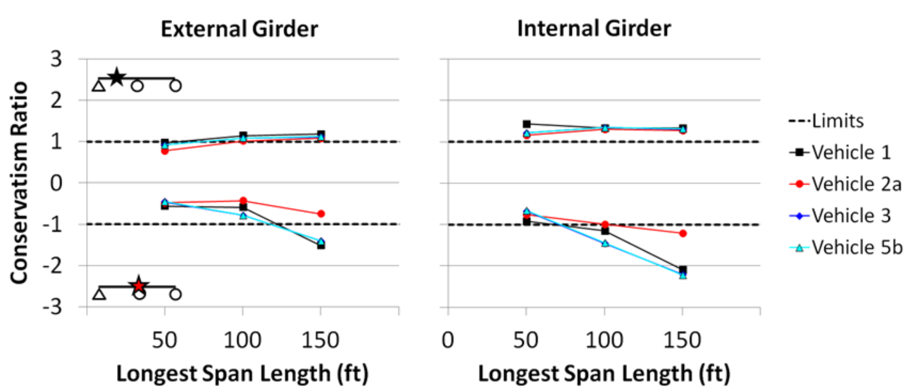


Figure 104 Conservatism Ratios for One-Lane Bridges with an SLR of 1:1 and Varied Span Lengths.

Figure 105 Conservatism Ratios for One-Lane Bridges with an SLR of 1:2 and Varied Span Lengths.

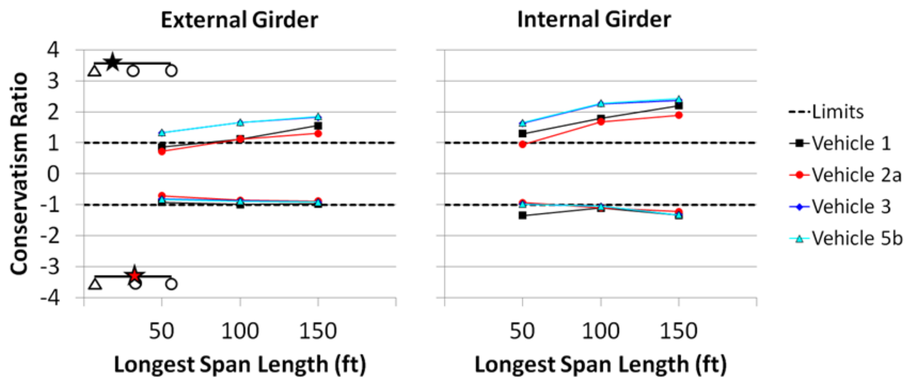


Figure 106 Conservatism Ratios for One-Lane Bridges with an SLR of 1:3 and Varied Span Lengths.

3.7.4.5 Three Span Bridges

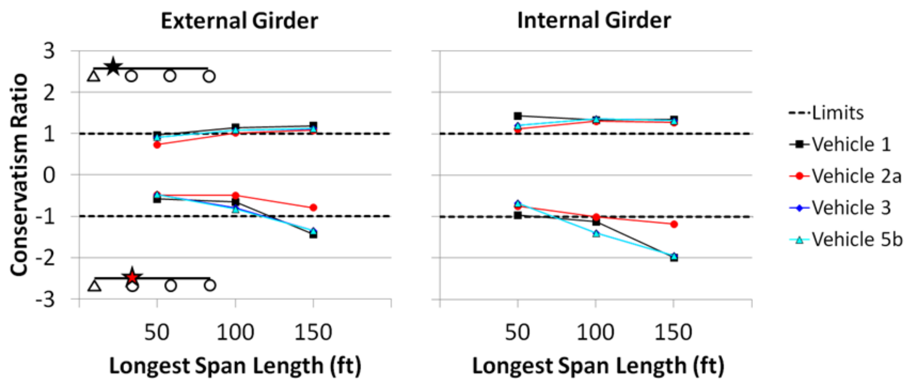


Figure 107 Conservatism Ratios for One-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (1 of 2).

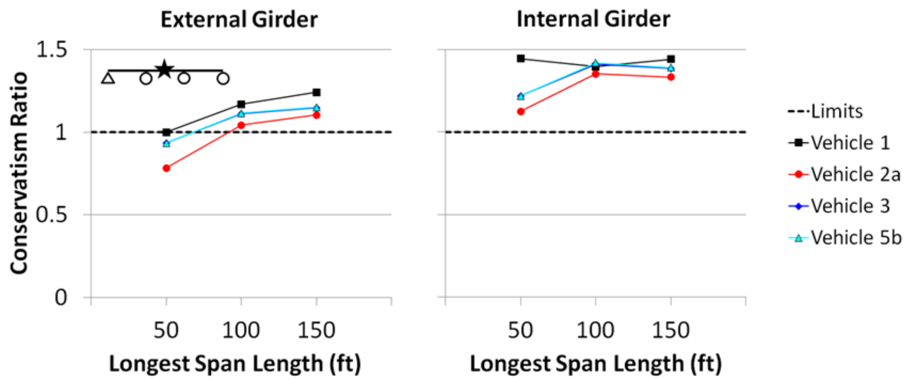


Figure 108 Conservatism Ratios for One-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (2 of 2).

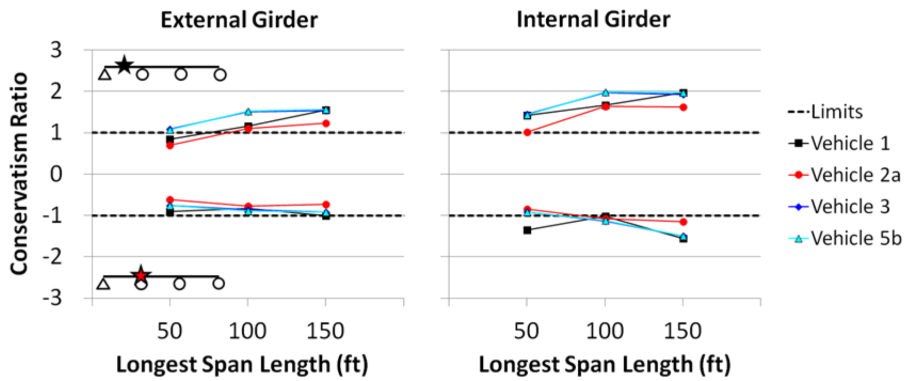


Figure 109 Conservatism Ratios for One-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (1 of 2).

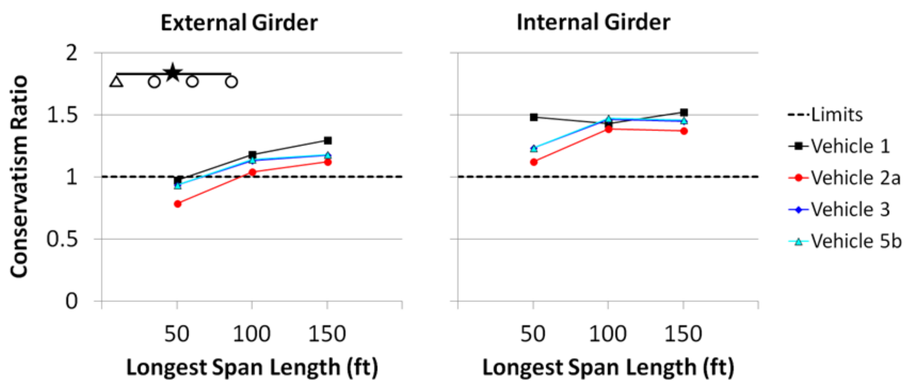


Figure 110 Conservatism Ratios for One-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (2 of 2).

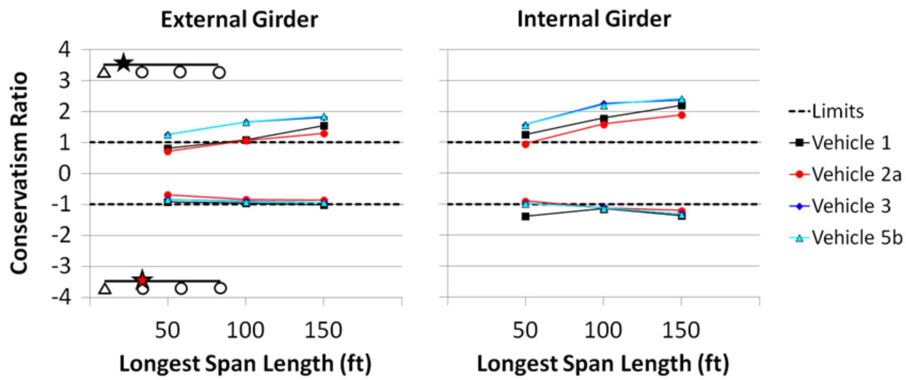


Figure 111 Conservatism Ratios for One-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (1 of 2).

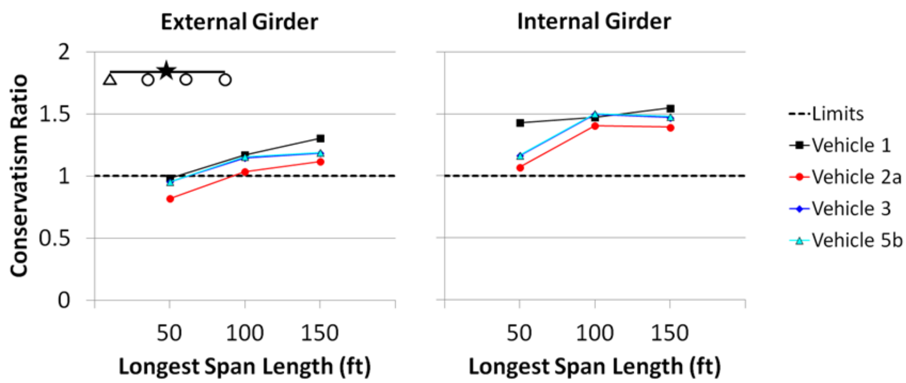


Figure 112 Conservatism Ratios for One-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (2 of 2).

3.7.4.6 Four Span Bridges

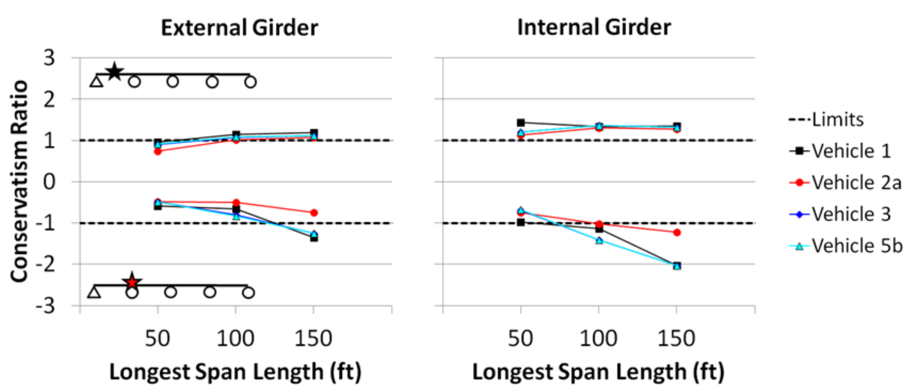


Figure 113 Conservatism Ratios for One-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (1 of 2).

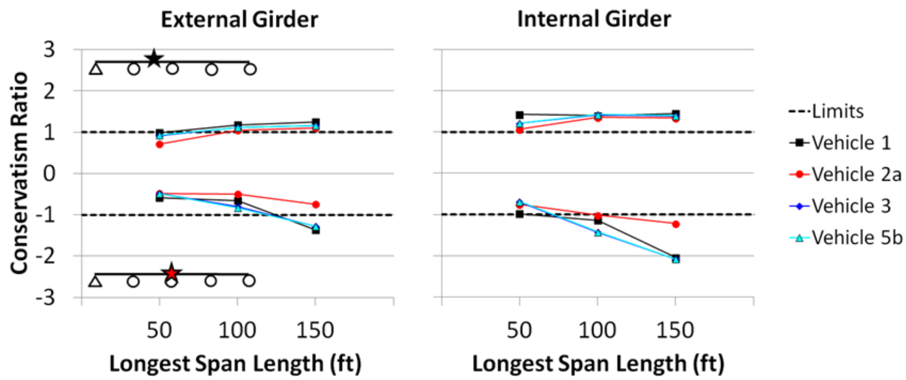


Figure 114 Conservatism Ratios for One-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (2 of 2).

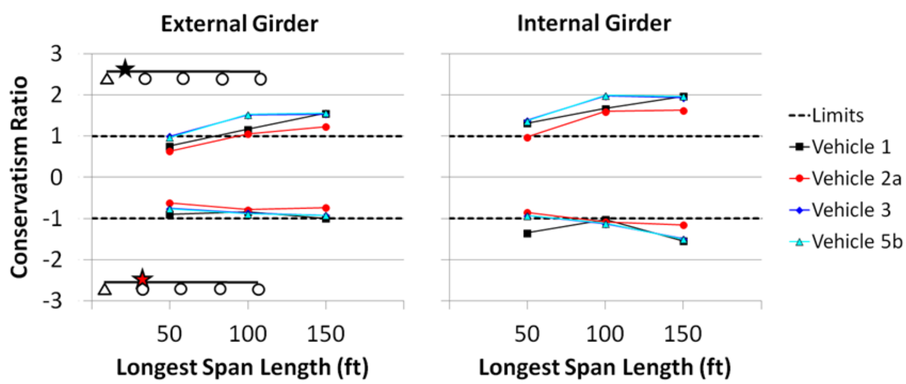


Figure 115 Conservatism Ratios for One-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (1 of 2).

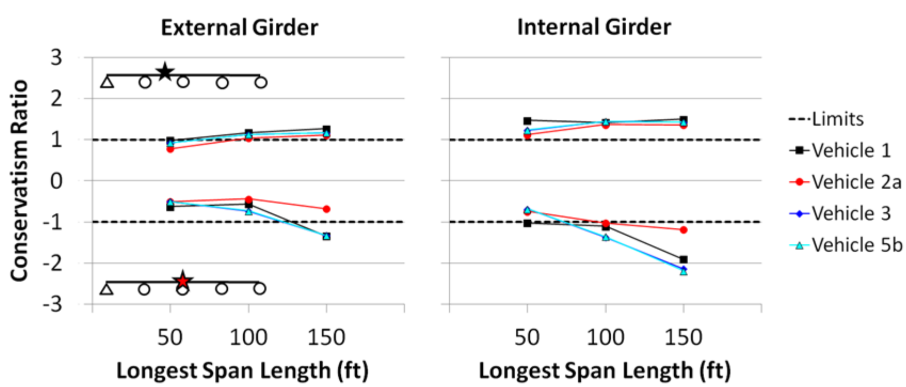


Figure 116 Conservatism Ratios for One-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (2 of 2).

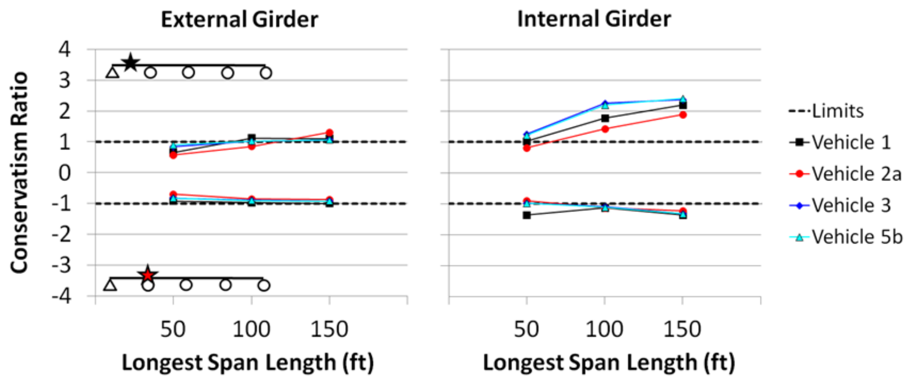


Figure 117 Conservatism Ratios for One-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (1 of 2).

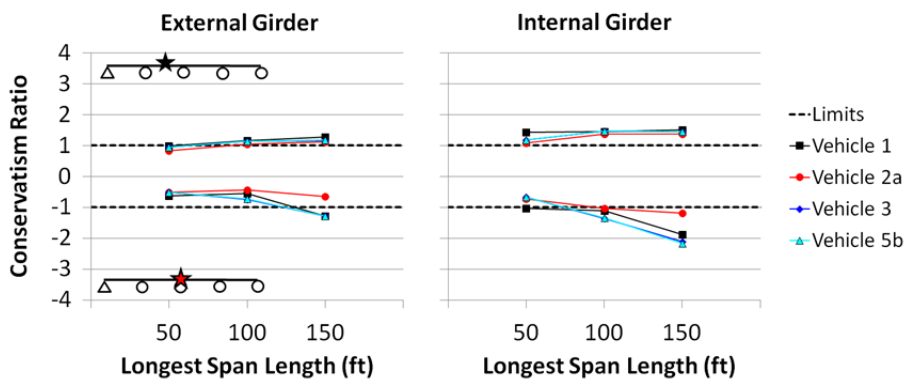


Figure 118 Conservatism Ratios for One-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (2 of 2).

3.7.5 <u>Results for Two-Lane Continuous Bridges</u>

Table 37 and Table 38 contain the lowest conservatism ratios for each group of two-lane continuous bridges modeled. Table 37 displays values for analyses grouped by span length ratio. Table 38 values are grouped by number of spans. Values above 1.0 indicate the modified NCDOT OSOW method is conservative when compared to results from the plane-grillage model, while values below 1.0 are unconservative. Demands were more underestimated for shorter bridges. Positive demands were more accurately estimated than negative demands. Internal girder demands were more accurately estimated than external girder demands. The following sub-sections are broken down by number of spans, with each section containing specific observations and figures for the bridge models analyzed.

Table 37 Worst-Case Conservatism Ratios for Two-Lane Continuous Bridges, Detailed

	4 spans			3 spans			2 spans		
Demands	1:1:1:1	1:2:2:1	1:3:3:1	1:1:1	1:2:1	1:3:1	1:1	1:2	1:3
External (+)	0.714	0.650	0.580	0.731	0.717	0.737	0.780	0.719	0.738
External (-)	0.481	0.441	0.440	0.478	0.634	0.698	0.432	0.658	0.719
Transition (+)	1.088	0.990	0.854	1.142	1.017	0.965	1.191	1.022	0.970
Transition (-)	0.686	0.685	0.674	0.675	0.858	0.900	0.668	0.921	0.947
Internal (+)	0.714	0.789	0.834	0.789	0.789	0.821	0.780	0.755	0.782
Internal (-)	1.015	1.014	0.982	1.004	1.247	1.313	0.986	1.343	1.389

Table 38 Worst-Case Conservatism Ratios for Two-Lane Continuous Bridges, by Number of Spans

	Number of Spans		
Demands	4	3	2
External (+)	0.854	0.965	0.970
External (-)	0.674	0.675	0.668
Transition (+)	0.854	0.965	0.970
Transition (-)	0.674	0.675	0.668
Internal (+)	0.714	0.789	0.755
Internal (-)	0.982	1.004	0.986

Figure 119 through Figure 133 contain graphs of conservatism ratios calculated for the two-lane continuous bridges with 2, 3 or 4 spans of varying lengths. For both external and internal girders, estimates for negative moments were underestimated by a larger amount than for positive moments. External girder moments were also under-predicted by a larger amount than internal girder moments. Shorter span lengths of bridges result in poorer estimates of demands for a majority of the cases analyzed. The influence of span length on accuracy of demand estimates is more pronounced for negative moments than positive moments. Vehicle 2a is least conservatively estimated for all one-lane continuous bridges modeled. The accuracy of estimating demands for Vehicles 1, 2b, 3, 4, 5a and 5b vary bridge to bridge, though Vehicles 3 and 5b exhibit the same load distributions in all two-lane continuous analyses considered.

3.7.5.1 Two Span Bridges

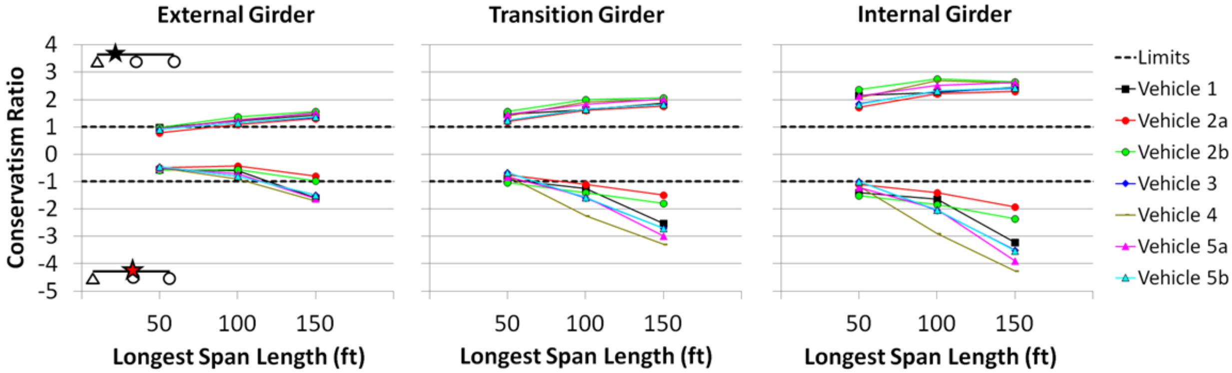


Figure 119 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:1 and Varied Span Lengths.

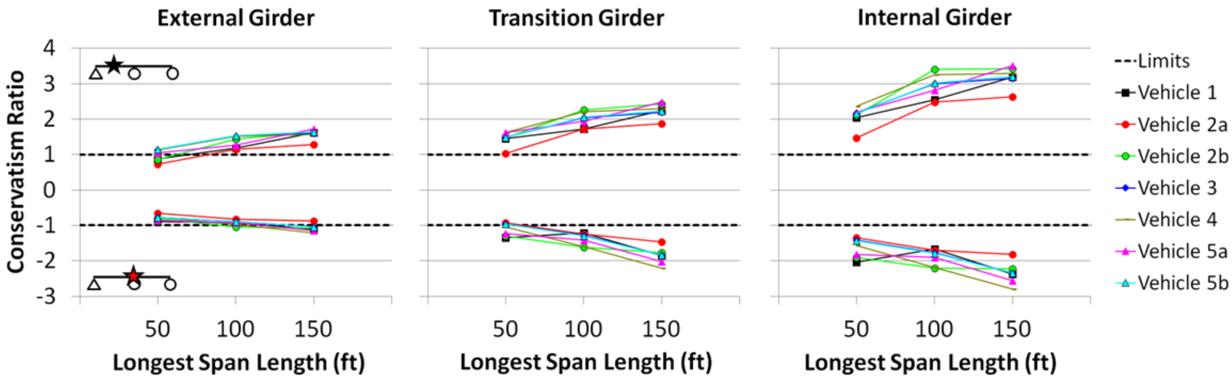


Figure 120 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:2 and Varied Span Lengths.

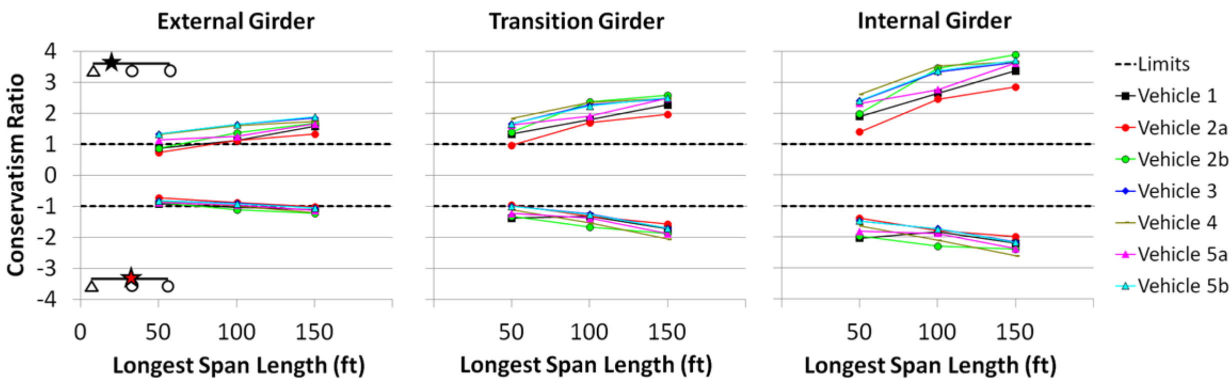


Figure 121 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:3 and Varied Span Lengths.

3.7.5.2 Three Span Bridges

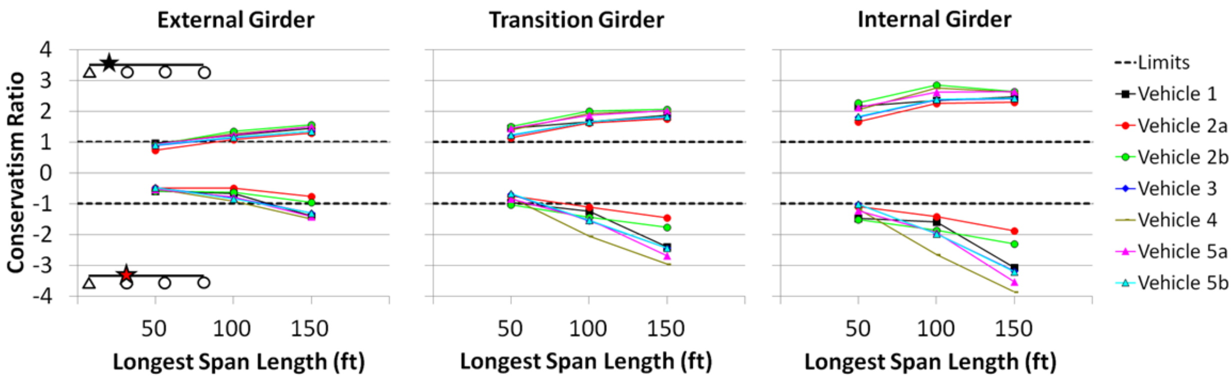


Figure 122 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (1 of 2).

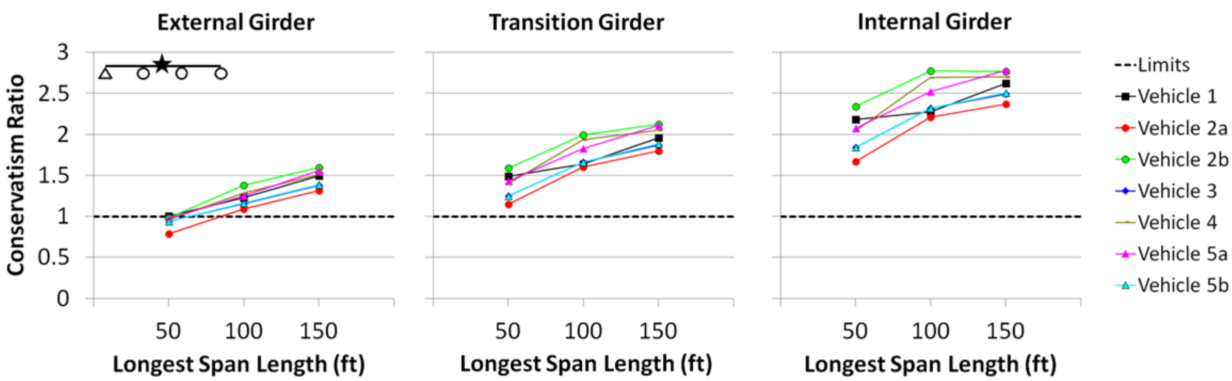


Figure 123 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (2 of 2).

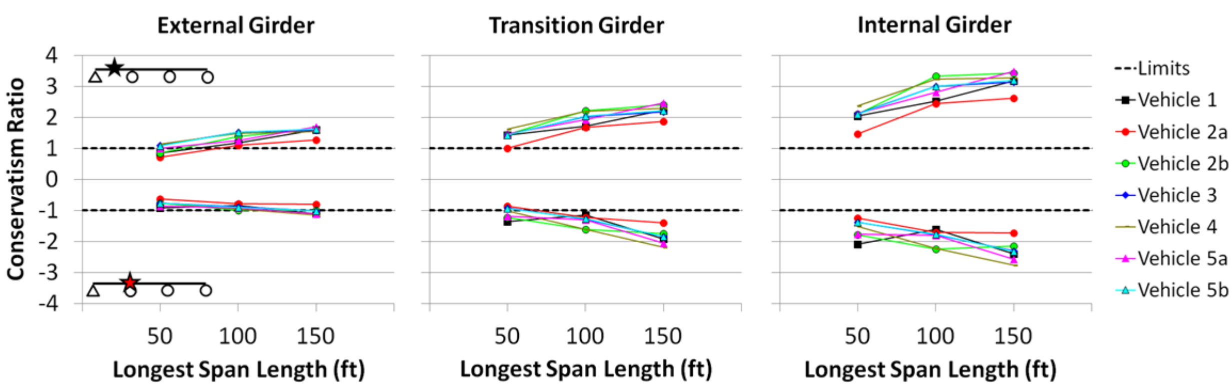


Figure 124 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (1 of 2).

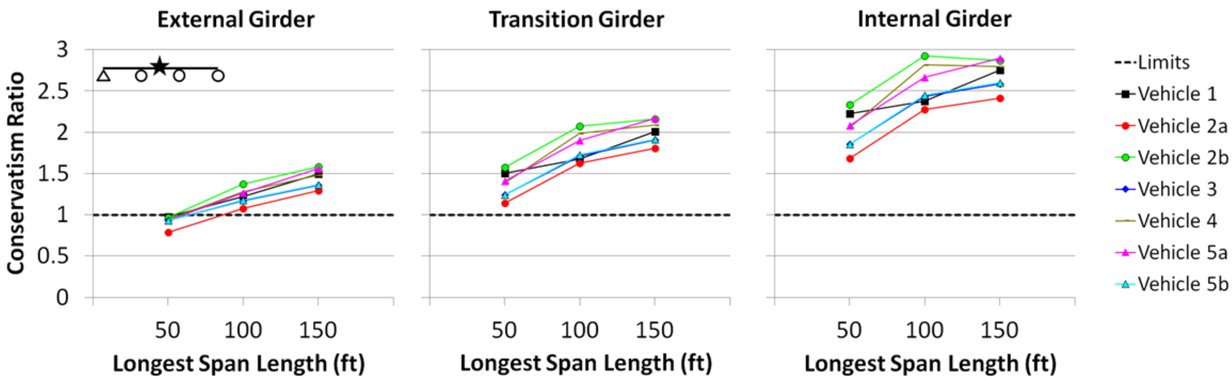


Figure 125 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (2 of 2).

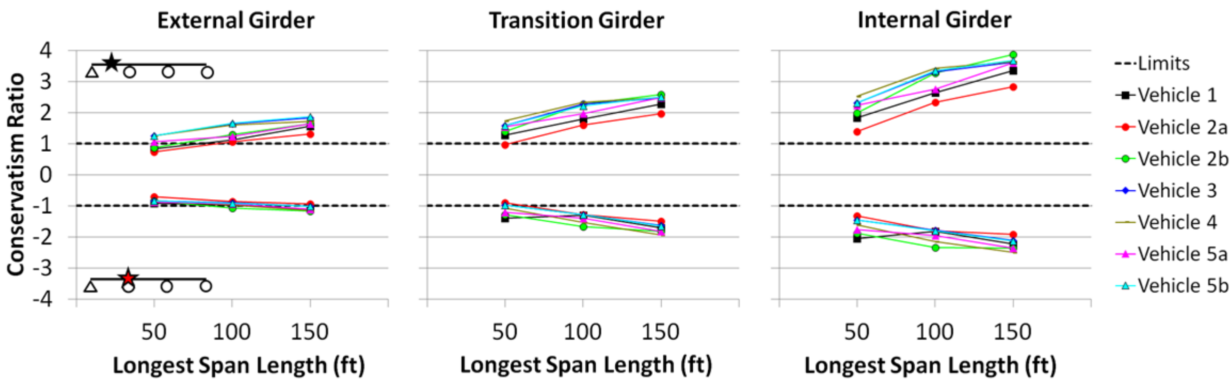


Figure 126 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (1 of 2).

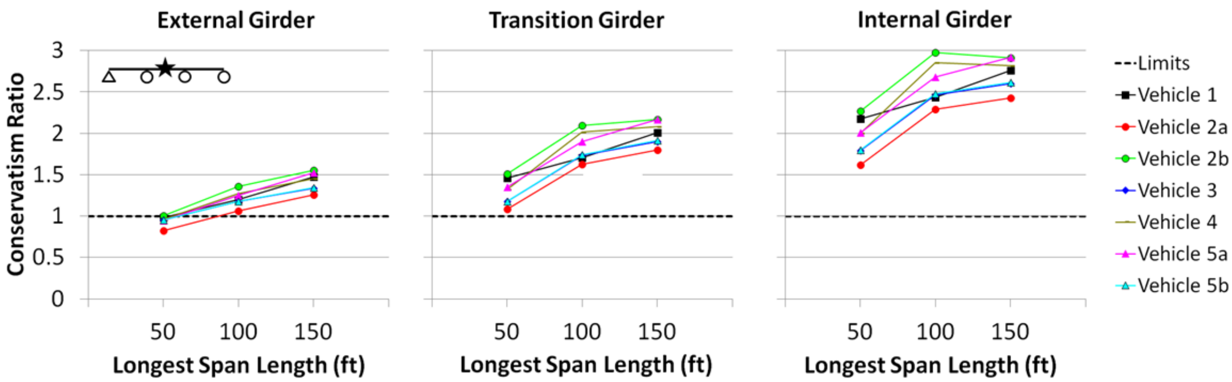


Figure 127 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (2 of 2).

3.7.5.3 Four Span Bridges

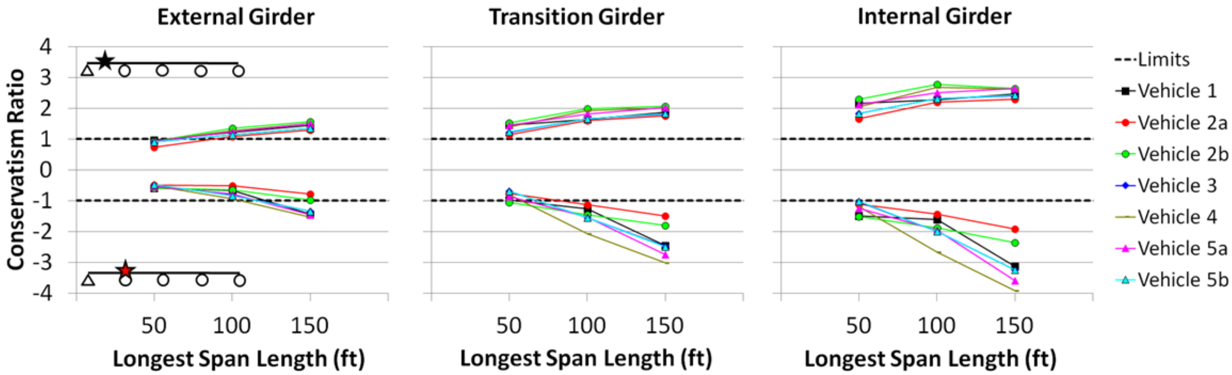


Figure 128 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (1 of 2).

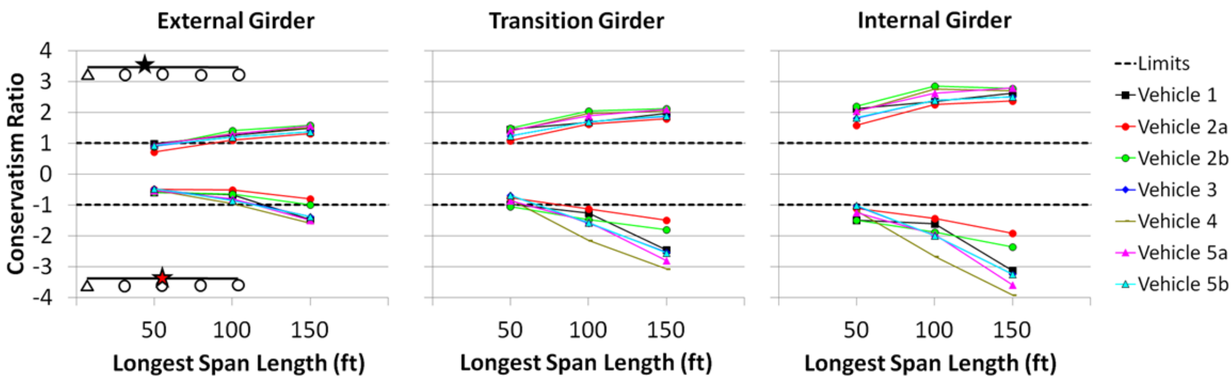


Figure 129 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (2 of 2).

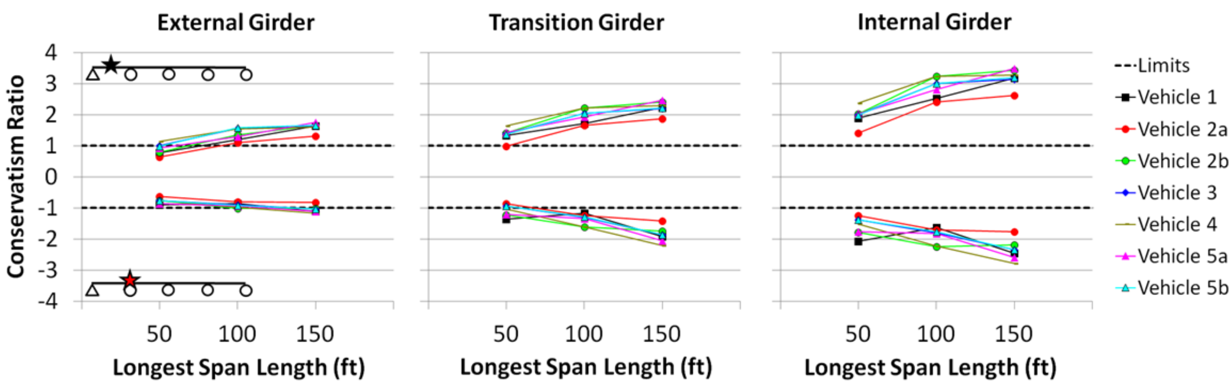


Figure 130 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (1 of 2).

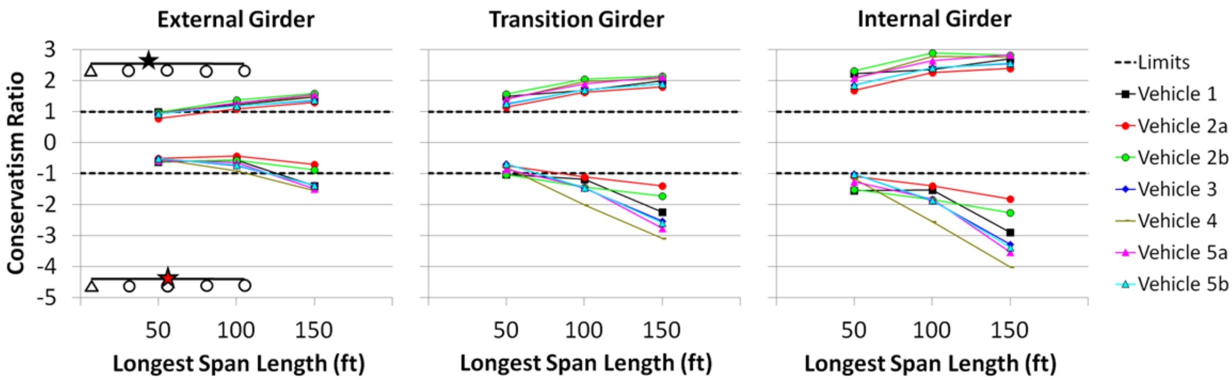


Figure 131 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (2 of 2).

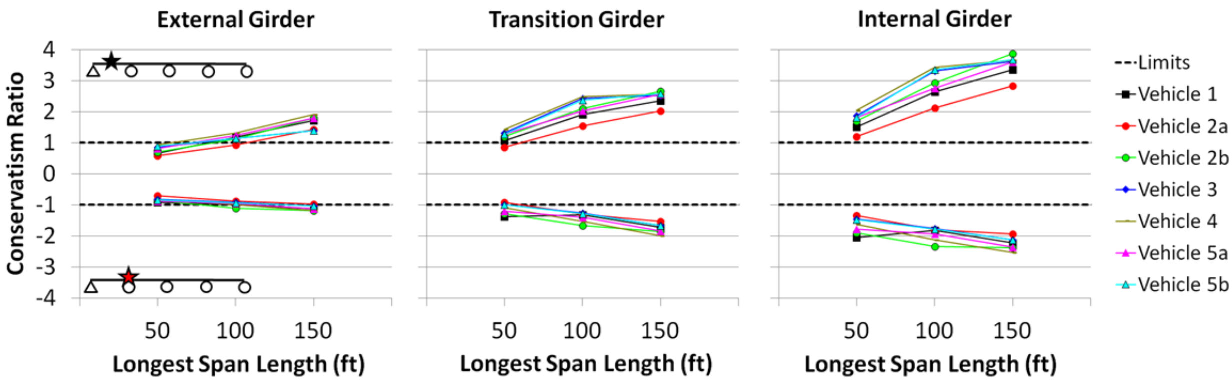


Figure 132 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (1 of 2).

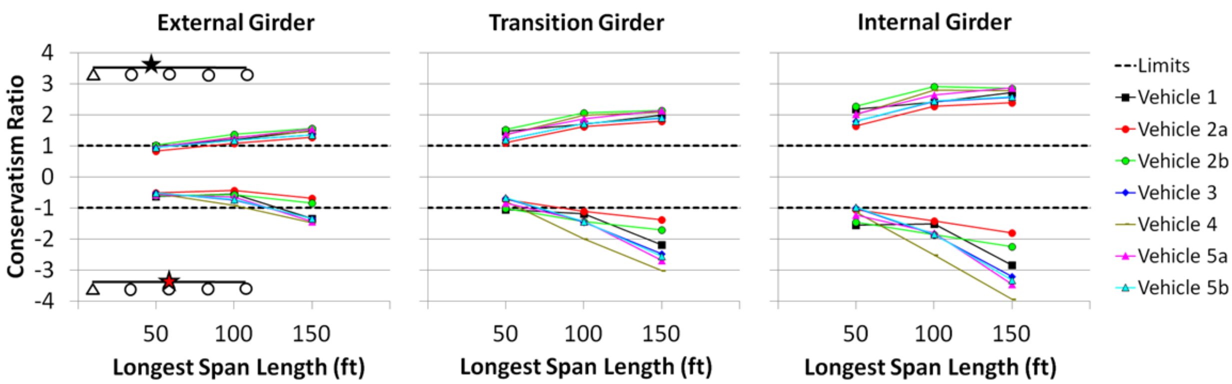


Figure 133 Conservatism Ratios for Two-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (2 of 2).

3.8 Future Research Recommendations

This study focused on a sample of prestressed precast concrete slab-on-girder bridges with a defined range of parameters. While the approach utilized provided a reasonable cross-section of samples to gather initial data regarding the behavior of superloads on bridges, more detailed sampling is necessary to gain results with a statistical significance. Results showed that girder strength, slab strength, slab depth, and slab cracked moment of inertia have little effect on superload load distributions, and can be neglected in future analyses. Modeling sidewalks, diaphragms, and parapets would also reduce the conservatism found in this study's results, as shown by work done by Zokaie *et al*. (27).

Beyond modeling additional parameters, the inclusion of additional types of bridges such as steel I-beam or concrete slab bridges is recommended. Only straight, non-skewed PPC slab-on-girder bridges were modeled in this study. Expanding the sample to include additional types of bridges, such as steel beam or concrete slab bridges, as well as skewed and curved bridges would provide a more definitive estimate of the accuracy of NCDOT OSOW's permitting process for a wider range of bridges. To select a series of representative bridges a more refined method of sampling such as Latin Hypercube Sampling (LHS) should be used to prevent an excessively large sample size. BridgeMaker can be modified to accommodate a majority of these additional model parameters, and LHS is available through a variety of commercial statistical packages, whose results can be "fed" into BridgeMaker to create the analysis models desired.

3.9 Summary and Conclusions

Models for 116 bridges with varying properties were created and analyzed under seven superload vehicles. Moment demands and HS-equivalent vehicle weights were calculated using plane-grillage models and the NCDOT OSOW program, PERM6. Conservatism ratios were calculated using a modified method of NCDOT OSOW's current permitting process. By analyzing an entire two-lane superload vehicle instead of a single lane width, the modified method conservatively accounts for the entire vehicle's demands.

Results indicate that in cases where superloads are to be permitted, the entire vehicle should be analyzed using PERM6 to limit the underestimation of demands. Analyzing only part of the superload can cause significant errors in some cases. While AASHTO girder distribution factors were derived to account for multiple lanes of loading, their demands were found to be poorly applicable to superloads. Superload vehicles can exert much larger demands on external and transition girders than typical HS-vehicle loads.

For the bridge geometries considered, the modified NCDOT OSOW analysis method underestimates superload demands by up to 57% on external girders and 33% on internal girders. Despite this finding, no bridge failures due to superload passages have been observed by the NCDOT to date. This is likely due to the conservative assumptions made when modeling the bridges, as well as additional factors of safety inherent within code-designed bridges. It should be noted that as superloads continue to increase in weight and size, relying upon the unquantified overstrength of bridges may lead to damage to the superstructure or failure of the bridge. As a result of this, additional research into quantifying the uncertainty of the current NCDOT permitting and the associated variations of superloads is highly recommended.

Due to the large differences seen in the demand distribution of AASHTO design loads and superloads, it is recommended that if possible, superloads should be limited to passage along the center of a bridge. In many cases, current NCDOT OSOW practices under predicted demands for external girders by a factor of 2, which could result in failure for sufficiently large superloads. Where there is an instance of a superload whose outer wheels extend over the outer-most girders, it is recommended that the superload be re-routed along a wider bridge, or a more detailed analysis performed to prevent damage to or failure of the external girders.

For a majority of the bridges considered, wider axle-lines appeared to distribute their loads more evenly than narrow axle-lines. Comparing the results of Vehicles 2a and 2b and Vehicles 5a and 5b, we recommend that superloads with the ability to increase their axle-line width (through the use of extendable axles or outrigger dollies) should be required to do so when crossing bridges. In cases where an increase in vehicle width causes the superload's wheels to pass over the external girders of a bridge, The NCSU team defers judgment to NCDOT OSOW, whose prior experience provides greater working knowledge.

CHAPTER 4. PAVEMENT IMPACT ANALYSIS

This chapter will cover the pavement impacts analysis for a sample vehicle for each of the five superload configurations identified for use in this study. The organization of this chapter is as follows: a discussion of the background and problem, a discussion of the scope and objectives, a literature review of superload pavement impacts, a discussion of pavement analysis methods, presentation of data and analysis of pavement impacts, and lastly conclusions drawn from the data.

4.1 Background and Problem Definition

Large construction projects in NC often bring with them the need for extremely large equipment to be transported to the construction sites. Specialized heavy haul trucks, designated as superloads in NC, are used to transport the equipment over NC roadways. In order for a superload to operate on public roads, an operator must obtain a permit from the NCDOT OSOW. A single large construction project can require 50 or more superloads for completion and these superload vehicles often use the same roads going to and from the construction site. The size of these superloads may cause significant impacts on the ultimate life of the highway pavement and its ride quality.

According to the NCDOT the OSOW unit processes 150 to 200 superload permits per month. Each superload permit application is initially checked against a number of requirements to see if they automatically qualify for a permit without further study. If the application does not pass the checks for pavement, NCDOT OSOW sends the permit application to the NCDOT Pavement Management Unit (PMU) for approval of the requested route for the truck configuration. Currently the NCDOT PMU does not have a standardized documented procedure for approval of superloads. Extensive analysis for superload route and truck configuration approval is currently challenging for the PMU due to limited availability of information on current pavement structure and material strength for any given road segment without time consuming and expensive testing. The existing PMU practice is to compare the requested superload tire loads to current legal tire loads, and if the superload tire load is not significantly greater than the legal limit it is considered acceptable. If it is significantly higher than current legal tire loads, the amount of standard truck traffic that uses the route is determined from previous traffic counts. If there is currently a significant amount of standard truck traffic on the route, it is considered acceptable. If not, approval of the route is requested from the District Engineer for the applicable district. The District Engineer can request a bond equaling the estimated resurfacing costs for the route, if there is concern for damage to the pavement structure. The PMU can also request the truck configuration be changed to include more axles to distribute the weight of the load. More extensive analysis for superload route and configuration approval is currently challenging for the PMU due to limited availability of information on current pavement structure for any given road segment.

Permit applicants typically assume that the total weight of a superload is distributed to each axle-line, even in instances where the load is confined to one part of the trailer and/or the load is not a uniform mass. The actual distribution of load strongly depends on the assumed stiffness, geometry, and lateral and longitudinal orientation of the truck as it travels. Despite these assumptions, the current NCDOT OSOW permitting policy does not require verification of the gross vehicle weight (GVW) or individual axle weights with scales to weigh the superloads.

The chapter will seek to infer if the PMU needs to account for variations in axle weight distribution for each superload configuration type when reviewing superload applications.

4.2 Objectives and Scope

This chapter will focus on estimating the pavement impacts of a single pass of a superload on NC roadways. Five representative superload trucks, one for each superload configuration as defined in section 1.4, have been selected for the pavement analysis portion of this study. The pavement impact analysis will focus on secondary roads since there is a higher perceived risk of damage due to weaker pavement structures for these roads.

4.3 Literature Review

4.3.1 Superload Pavement Damage Types

The Texas Department of Transportation (TxDOT) identifies five main types of pavement damage related to superloads in their *Pavement Design Guide (36)*.

1. Shearing of the pavement surface occurs when tires slide across the pavement during a turn.

Figure 134 Example of Surface Shear *(36)*.

2. Rutting or cracking is caused by superloads exceeding the capacity of the pavement structure, often in conjunction with weakened subgrade or base layers due to inadequate drainage or heavy rainfall.

Figure 135 Example of Rutting *(36)*.

3. Peeling of seal coats or asphalt overlays happens when superloads move across recently applied seal coats and asphalt.

Figure 136 Example of Seal Coat Peeling *(36)*.

4. Bleeding of seal coats or asphalt overlays may also occur when superloads move across recently laid seal coats and asphalt.

Figure 137 Example of Seal Coat Bleeding *(36)*.

5. Shear failure of the edge of the pavement is caused by outside tires tracking on or near the edge of the pavement.

Figure 138 Example of Edge Shear *(36)*.

TxDOT believes that only a single pass of a superload increases the risk of pavement failure. Field studies of multiple superload moves demonstrate that tire loads of 6000 pounds or greater and gross vehicle weights of 500,000 pounds or greater were the most likely to damage the roadway. For loads that exceed either a 6000 tire load or a total weight of 500,000 TxDOT requires an in-depth pavement analysis for the superload route to determine the likelihood for pavement damage. Loads under both of these limits are seen as not likely to cause damage and do not require a pavement analysis. These limits were developed empirically by comparing tire loads, gross vehicle loads and observed pavement damage *(36)*.

4.3.2 Pavement Impact

The Virginia Transportation Research Council (VTRC) in an effort to review the adequacy of the Virginia overweigh permit fee structure developed a simple method to analyze pavement damage due to different types of vehicles. A group of five VTRC engineers reviewed the roadway maintenance needs budget and attributed a percentage of each item to load related damage using engineering judgment. WIM data was used to find the average Equivalent Single Axle Load (ESAL) for each vehicle class. This was then multiplied by the average daily vehicle miles traveled for each vehicle class, as supplied by the Virginia DOT, resulting in daily ESAL-miles. The total load damage related budget was then divided by the total daily ESAL-miles times 365 to produce a cost of roadway damage per ESAL-mile. This can then be used to estimate the roadway damage caused by an overweight permitted truck by converting it into ESAL-miles based on axle weights and projected distance traveled *(37).*

Saraf, Ilves, and Majidzadeh, in *Effect of Heavy Vehicle Weights on Pavement Performance*, completed a study of four sites in Lucas County, Ohio, to determine the effects on pavement performance from heavy vehicles. The sites were selected for their frequency of heavy permitted loads. During the two-year study, detailed traffic data was collected twice a year using WIMs and pavement distress data including cracking, faulting, Mays roughness, and PSI. The authors converted the traffic to ESALs using AASHTO equivalency factors and compared predicted distresses from ESALs to the measured distresses. They determined that the AASHTO equivalency factors were not sufficient to predict the pavement impacts of heavy vehicles and new conversion factors should be developed for each distress type *(38)*.

Huang in Pavement Analysis and Design determined that equivalent axle load factors (EALF) depend on the failure type utilized. Using KENPAVE software he found that the EALF used for fatigue cracking is different from the EALF used for rutting. Due to complex interaction between many variables, EALF values are difficult to predict and vary widely depending on conditions such as axle spacing and pavement structure. He notes that using the ESAL conversion factors developed from the AASHTO Road Test though widely used is only a rough approximation since these use only one EALF for all modes of damage *(39)*.

Jeong Ho Oh, et.al used five years for field monitoring data to show that the most common type of pavement damage caused by the movement of superload in Texas is damage to seal coats less than five weeks old. Field studies also showed that damage to seal coats depended not only on age of the seal coat, but on grade of the roadway, temperature of the road surface and seal coat mix properties. It was found that surface temperature was the most significant feature affecting seal coat damage and that temperatures above 50°C were the most likely to cause peeling of the seal coat during a superload move, though other factors could not be ignored. Through these field studies, a mechanistic-empirical model was developed and calibrated to predict probability of damage seal coats given seal coat properties and age, grade of the roadway, surface temperature of the pavement and tire load. This model was implemented in a program Mechanistic-Empirical Seal Coat Damage Evaluation Program (M-E SDEP). The M-E SDEP program was tested in several case studies and found to be reasonably accurate for predicting seal coat damage due to superload movements *(40).*

Jooste and Fernando in 1992 monitored three heavy vehicle moves in Victoria, TX. The gross weight of the three trucks ranged between 254,000 pounds and 108,000 pounds. Field-testing of the route was completed to determine pavement structure and material properties. A

Multi-Depth Deflectometer was installed on a section of the route and pavement response was measured as the heavy loads passed over that section. Visual inspections of the route were completed before and after the moves, and no damage was found. It was concluded that the pavement structure had sufficient strength to carry the loads. The data collected on the pavement properties and response to the heavy loads was analyzed and it was determined that the pavement deflections measured during the moves corresponded well with mechanistic linear elastic layered theory *(41)*.

Jooste and Fernando developed a procedure to analyze route adequacy for "super heavy" vehicles for TxDOT. They posit that because superloads have relatively few repetitions when compared to other traffic, long-term pavement impacts were of less concern than immediate impacts. They developed their analysis procedure to assess the potential for rapid shear failure of a pavement structure due to a single superload pass. For this pavement failure type, the limiting factor for a superload truck is the tire load. A model for assessing the risk of rapid shear failure was created using MOHR-Coulomb yield criterion and detailed information on pavement structure and materials. This model has been implemented through the creation of PALS, Program to Analyze Loads Super Heavy. It is noted that without detailed information on the pavement structure and materials, the PALS software should not be used. The model underlying PALS is very sensitive to these inputs and inaccurate pavement data would produce unreliable results. Consequently, they developed a series of charts with the PALS software for an initial analysis of the superload route. These charts require only general characterization of the pavement structure and provide conservative estimates for wheel loads that would cause rapid shear failure. The analysis procedure designed by Jooste and Fernando use these charts as an initial first stage check with the use of the PALS software as a follow up second stage in-depth analysis for superload route approval. If the wheel loads are determined to be acceptable using the conservative charts then no further analysis is needed. If the wheel loads do not pass the chart requirements, detailed information must be collected on the pavement structure and analysis completed using the PALS software *(41)*. The PALS software has since been updated to PALS 2.0, which includes analysis for edge shear *(43)*.

4.4 Analysis Method Selection

The ability to analyze the stress and strain reasonably within the pavement structure is a key to the pavement performance prediction. Considering the complexity of variations in traffic loading, material properties, and climate, numerous methods have been used to predict pavement performance. For the flexible pavement analysis, the analysis tool should be able to treat asphalt concrete as viscoelastic materials since asphalt concrete exhibits significant viscoelastic characteristics especially under a moving load.

Many computer-modeling programs were considered for use in this study. General commercial finite element programs such as ANSYS and ABAQUS are expensive and inefficient for analyzing an entire truck with multiple moving axles and tires. These programs have limited usability for asphalt materials since the material parameters from experimental characterization are not accepted for modeling. Traditional pavement analysis programs such as KENPAVE and 3D-Move Analysis were also investigated for use in this study. They were discarded as options because they are not capable of accommodating the special truck configurations required for an analysis of superloads, which can have over 15 lines of axles (each with up to 16 tires) that are considered in this report. The Mechanistic-Empirical Pavement

Design Guide (MEPDG), a more contemporary program, was also explored for use in the superload pavement analysis. At the time, the special axle configuration module of the program was inoperable due to a suspected software bug; therefore, it was not capable of analyzing the special truck configurations required for superloads. The program was also developed to analyze traffic loading over time and thus cannot be used to calculate the stress-strain response under a single pass of a vehicle.

Also reviewed were the two programs from TxDOT, M-E SDEP and PALS, discussed in the previous section. The M-E SDEP program, developed for TxDOT to predict the seal coat damage potential from a superload vehicle, was calibrated for TX pavement materials and climate; therefore, it is not immediately apparent that it would produce reliable results for NC superloads. Although the general guideline of avoiding allowing a superload to operate on a seal coat less than five weeks old, is advisable for NC. TxDOT allowed the research team access to their PALS software and training materials. Reiterated several times in the training was the need for detailed and current data on pavement structure and materials for accurate results. As a result, it was determined that this software would hold negligible value for the NCDOT PMU because detailed pavement data is not readily available without labor intensive field testing. Instead, the conservative charts, developed by Jooste and Fernando with the PALS software, for assessing probability of rapid shear failure were selected for use in this study. These charts require only general pavement characteristics and are less labor intensive.

The pavement impact analysis for this study was completed in four parts. (1) The AASHTO ESAL conversion factors are used to convert the superloads into number of equivalent 18-kip single axles as an initial simple analysis, since AASHTO ESALs are well known and easy to calculate. (2) A program, LVECD (Layered ViscoElastic Continuum Damage) was selected for the pavement response modeling and analysis. Developed at NCSU, this program was initially written for analyzing pavement response and performance (including thermal cracking, fatigue cracking, and rutting) under traffic loading of normal trucks. It was then modified to accommodate the special geometric configurations of the overload trucks while keeping the algorithms and assumptions the same as for normal trucks. The goal of this portion of the analysis is to convert a superload truck to an equivalent number of the standard 18-kip single axle, a value known as the ESAL (equivalent single axle load), based on the concept of equivalent damage (either fatigue or permanent deformation) caused to the pavement. (3) The wheel load charts developed by Jooste and Fernando with the PALS software are used to determine the risk of immediate damage from a superload due to rapid shear failure. (4) A case study was performed for a route that was used by a one-million pound configuration 4, doublewide modular superload. This vehicle was not weighed during the study, as noted in chapter 2, and no other weight data was found for this configuration. Therefore, to compensate for this lack of weight data for analysis an interview was conducted with an NCDOT inspector who inspected the route before and after the superload move. A case study written.

4.5 Vehicle Selection

Five vehicles were selected for use in the pavement analysis portion of this study, one representative vehicle for each of the five superload configurations defined in chapter 1.

The first superload vehicle, Truck-1, is the Progress Energy 13-axle mobile transformer truck, shown in Figure 139. This truck was selected for study as the configuration 1 truck because it is known to operate in NC and was weighed by the research team, therefore carrier estimated and measured axle weight data was available. For pavement modeling and analysis, axle spacings and carrier estimated axle weights were taken from the truck schematic diagram supplied to the NCDOT as part of the superload permit application process. This schematic is supplied for reference in APPENDIX C of this report.

Figure 139 Truck-1: Progress Energy Mobile Transformer Truck.

The configuration 2 truck selected for the pavement analysis (truck-2) is a 19 axle-line dual-lane drop-deck gooseneck truck, shown in Figure 140, from the January 2012 NC weight citation in Polk County, NC. This truck was selected for study because this is the only configuration 2 vehicle for which measured axle weight data was available, which also operated in NC. Since this weight data was from a NC citation individual axle weights were not available, as only axle group weights are reported. It was assumed that the weight of an axle group would distribute equally to each axle in that group. For pavement modeling and analysis, axle spacings and carrier estimated axle weights were taken from the truck schematic diagram supplied to the NCDOT as part of the superload permit application process. This schematic is supplied for reference in APPENDIX C of this report.

Figure 140 Truck-2: 19 Axle-Line Dual-Lane Transporter.[38]

The configuration 3 truck selected for pavement analysis, truck-3, was an 11 axle-line truck-towed singlewide modular unit, shown in Figure 141. Guy M. Turner operated this truck in late February of 2012 internally at the Shearon Harris power plant moving transformers across plant property. This truck was weighed three times by the research team and provided good weight data for this superload configuration. Since this truck operated only on plant property, no

[38] Picture Source: NC SHP

superload permit was needed and thus there is not an available truck schematic with carrier estimated axle weights. The estimated axle weights used in this study were estimated by the research team for reference only and are not to be considered representative of the weights that would be submitted in a permit application. A Guy M. Turner employee noted that they were operating the truck with heavier axle weights than they would if they were traveling on public roadways. Additionally when weighing the truck, only the outside tires were weighed for safety concerns and the inside tires were assumed to carry the same weight. Data on the axle and tire spacings was not available but were assumed to be the same as other Goldhofer brand modular units. Therefore, for this analysis axle and tire spacings on similar previously permitted Goldhofer units were used.

Figure 141 Truck-3: 11 Axle-Line Singlewide Modular, Shearon Harris Plant.[39]

The configuration 4 superload truck selected for this study, truck-4, was a 16 axle-line doublewide modular unit, shown in Figure 142. Guy M. Turner operated this truck in September of 2011 in Wayne County, NC, transporting a power generator from a rail siding to a Progress Energy plant. This unit could not be weighed, as discussed in chapter 2, but was chosen for study because of the extreme weight of the vehicle - over one million pounds. Additionally, this truck was operated on NC roadways in Wayne County, and a case study was completed for this truck. For pavement modeling and analysis, axle spacings and carrier estimated axle weights were taken from the truck schematic diagram supplied to the NCDOT as part of the superload permit application process. This schematic is supplied for reference in APPENDIX C of this report. Given that no measured weight data for this truck was collected, the pavement impact analysis will focus only on the carrier estimated weights, which assumes an equal weight distribution to each axle.

[39] Photo courtesy of Progress Energy

Figure 142 Truck-4: 16 Axle-Line Self-Propelled Doublewide Modular.[40]

The last vehicle selected for study, Truck-5, was a superload configuration 5. It was a 22 axle-line towed truck with a singlewide modular unit with outriggers, shown in Figure 134, operated by Guy M. Turner. There were no opportunities to collect axle weight data available for any configuration 5 truck during this study. This truck was selected for the pavement study due to its high gross weight of 887,500 pounds and the company operating this truck is a project partner that operates in NC. For pavement modeling and analysis, axle spacings and carrier estimated axle weights were taken from the truck schematic diagram supplied to the NCDOT as part of the superload permit application process. This schematic is supplied for reference in APPENDIX C of this report. Given that no measured weight data for this truck was collected, the pavement impact analysis will focus only on the carrier estimated weights, which assumes an equal weight distribution to each axle. The truck was also analyzed with and without the dollies to determine if they mitigate damage to pavement structures.

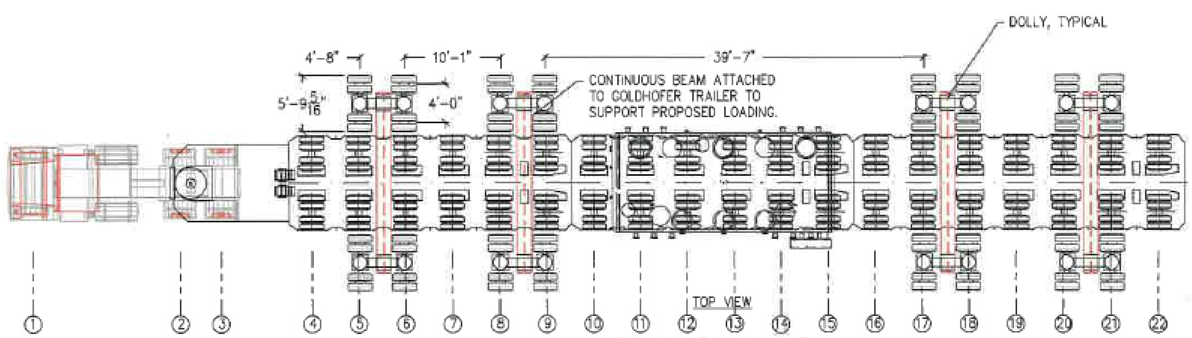


Figure 143 Truck-5: 22 Axle-Line Singlewide Modular with Outriggers.[41]

As a reference for comparison in the pavement impact analysis, a standard legal 80,000-pound tractor-trailer was also analyzed. The “standard normal truck” is a five-axle truck with a steer axle weighing 12,000 pounds, a tandem drive axle weighing 32,000 pounds, and trailer tandem axle weighing 36,000 pounds.

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[40] Picture Source: NCDOT
[41] Source: NCDOT

For each truck with measured weight data, it was assumed that the measured weight would distribute equally to each subpart. For example, if weights for an axle-line group were the level of measured weight data, it was assumed that this weight would distribute equally to each axle-line, and from each axle-line to each axle, and from each axle to each tire.

4.6 AASHTO ESAL Analysis

The AASHTO axle load equivalency factors have been used for many years by numerous agencies as part of pavement design and analysis. Though many agencies are pushing towards more mechanistic analysis programs the AASHTO ESAL method is still widely used.

As a quick initial analysis, each superload truck identified for study was converted to ESALs using the AASHTO equivalency factors. The axle load equivalency factors tables found in appendix D of the 1993 AASHTO Guide for Design of Pavement Structures (44) were used to convert each truck in to ESALs. However, with any quick method the AASHTO ESAL method has several limitations. The axle load equivalency factors tables were created from data collected through the AASHTO Road Test completed in the 1960s, which was limited in scope. The Road Test used only one subgrade and local paving materials for the test section and these were in a single area so only a limited set of climatic conditions were experienced. The test used identical loads and a limited set of axle configurations to accumulate traffic and not mixed traffic as would be seen on a normal roadway (45). The limited nature of the axle configurations is of special concern in this instance since superload vehicles commonly have non-standard axle configurations with large axle groups and/or closely spaced axles. This may lead to complex stress interactions in the pavement that are not accounted for by the AASHTO factors.

For the analysis, a pavement structural number of 4.0 and a terminal serviceability of 2.0 were assumed. Each axle in an axle-line was considered a separate axle and quad axle groupings were treated as two tandem axle groups. The modular units (trucks 3, 4, and 5) due to their close axle spacing were considered to have successive groups of triple axles (tridems). Truck-5 was analyzed with and without the dollies, and for the analysis without the dollies the weight of the dollies was subtracted from the gross weight of the truck and the new gross weight was assumed to distribute equally to all axles. Trucks 1 and 2 were analyzed using the carrier estimated axle weights and the measured axle weights. Truck 3 was analyzed using weights estimated by the research team and measured weights. The estimated weights for this truck are for reference only and are not indicative of weights that would be requested for a permit. The results are summarized in Table 39 below.

Truck-1, the 13-axle mobile transformer, had an estimated gross weight of 228,700 pounds and a measured gross weight of 227,840 pounds. The average estimated tire load was 4,574 pounds while the average measured tire load was 4,557 pounds. The ESALs estimated for this truck using the AASHTO method are 7.93 ESALs based on estimated weights and 7.54 ESALs based on measured weights. As shown in chapter 2 of this report, this truck did not have an equal weight distribution and the measured axle weights showed eight overweight axles and five underweight axles as compared to carrier estimates. By the AASTO ESAL method, the variations in measured axle weight as compared to the estimated weights do not produce a significant change in the pavement impacts estimated for this vehicle, since the ESALs from the measured weights versus ESALs from estimated weights are nearly identical. The estimated average tire load was slightly higher than the average measured tire load. Since, stresses in pavement structures are directly relatable to tire loads, the ESAL estimates follow the same pattern. Comparing this truck to the standard normal truck, it can be seen that this truck would cause the damage of approximately 3.14 standard trucks, while having a gross weight approximately 2.85 times that of a standard truck. This indicates that this truck causes slightly more damage per pound of gross weight than a standard truck.

Table 39 AASHTO ESALs (Estimated/Measured)

	Truck-1	Truck-2	Truck-3	Truck-4	Truck-5		S.N.T.
					w/ dollies	w/out dollies	
Gross weight (lb)	228700/ 227840	607000/ 558200	483747/ 468300	1012600/ ---	887500/ ---	851340/ ---	80000/ ---
No. of tires	50	120	88	256	226	162	18
Average tire load (lb)	4574/ 4557	5058/ 4652	5497/ 5322	3955/ ---	3927/ ---	5255/ ---	4444/ ---
AASHTO ESALs	7.93/ 7.54	30.92/ 22.95	28.03/ 32.45	20.70/ ---	33.91/ ---	42.41/ ---	2.41/ ---

Note: Estimated/Measured indicates that the first value in a cell is based on estimated weights and the second value is based on measured weights. S.N.T. stands for standard normal truck.

Truck-2, the 19 axle-line drop-deck gooseneck, had an estimated gross weight of 607,000 pounds and a measured gross weight of 558,200 pounds. The average estimated tire load was 5,058 pounds while the average measured tire load was 4,652 pounds. The ESALs estimated for this truck using the AASHTO method are 30.92 ESALs based on estimated weights and 22.95 ESALs based on measured weights. As discussed in chapter 2, this truck had a relatively uniform weight distribution across the trailer and the measured axle-line weights showed 3 overweight lines and 16 underweight lines as compared to carrier estimates. Since this carrier overestimated gross weight by almost 50,000 lbs and most axle-line were significantly under estimated weights, the calculated ESALs based on estimated weights provides an overestimation of pavement damage. As with the last truck, the lower ESAL value for the measured weights corresponds with a lower average tire load. This truck would cause the same amount of pavement damage as 9.52 standard normal trucks while weighing only 6.98 times a standard 80,000-pound truck. This indicates that this truck causes more damage per pound of gross weight than a standard truck.

Truck-3, the 11 axle-line singlewide modular, had an estimated gross weight of 483,747 pounds and a measured gross weight of 468,300 pounds. The estimated weight was estimated by the research team and is for reference only. A Guy M. Turner employee stated during the weighing of this truck that if they were seeking a superload permit they would overestimate weights to allow themselves a cushion. The average estimated tire load was 5,497 pounds while the average measured tire load was 5,322 pounds. The ESALs estimated for this truck using the AASHTO method are 28.03 ESALs based on estimated weights and 32.45 ESALs based on measured weights. From chapter 2, it can be seen that this truck had a relatively uniform weight distribution within a suspension grouping but was non-uniform between front and rear suspension groupings. The ESALs based on measured weights are significantly higher than the ESALs based on estimated weights, even though the average tire load was lower. This is due to the rear axle-lines carrying significantly more weight than the front. The average tire load for the front six axle-lines was 4470 pounds while the average tire load for the rear five axle-lines was

6343 pounds. With the rear axle-lines carrying approximately 2000 pounds more weight per tire than the front, the potential pavement damage increased significantly. This truck had an estimated pavement impact equivalent to that of 13.46 standard normal trucks while only weighing 5.85 times that of a standard truck, indicating that this vehicle would cause more damage per pound of gross weight than a standard truck. It should be noted that this truck only operated on private property. A Guy M. Turner official stated during the weighing that because of this they were operating with heavier axle weights than they would if they were operating on public roadways. It was also noted that because this was on private property that the load had not been centered as carefully as it would have been had they been operating on NC roadways, which would account for the uneven weight distribution.

Truck-4, the 16 axle-line doublewide modular, had an estimated gross weight of 1,012,600. This truck was not able to be weighed due to extenuating circumstances; therefore, the analysis will necessarily only focus on the carrier estimated weights. The average tire load was 3,955 pounds and the estimated ESALs for this truck are 20.70. This truck has a lower estimated pavement impact than truck-3 does, while carrying more than twice the weight. This is due to truck-4 having almost 3 times the number of tires than truck-3 and thus a lower average tire load. Truck-4 has an estimated pavement impact equivalent to 8.59 standard normal trucks, while carrying 12.66 times the weight. This indicates that this truck has a lower pavement impact per pound of gross weight than a standard truck.

Truck-5, the 22 axle-line singlewide modular with dollies, had an estimated gross weight of 887,500 pounds with the dollies and 851,340 pounds without the dollies. The estimated average tire load was 3,927 pounds with the dollies and 5,255 pounds without the dollies. The estimated ESALs for this truck are 33.91 with the dollies and 42.41 without the dollies. Though the dollies add extra weight to the vehicle, they reduce the pavement damage caused by this vehicle by spreading the load out through more contact points, thus emphasizing the need for lower tire loads to mitigate the impact to the pavement structure. This truck has the equivalent pavement impact of 14.07 standard normal trucks while weighing only 11.09 times a standard truck with the dollies being used. This truck has the equivalent pavement impact of 17.60 standard normal trucks without the dollies while weighing 10.64 times a standard truck with the dollies being used. This illustrates that if dollies are an option to spread out the load through more contact points, they should be used to keep tire loads low. With the dollies used, this truck had a smaller pavement impact per pound of gross weight than a standard truck.

4.7 LVECD Modeling Analysis

In the framework of the LVECD program (Figure 144), asphalt concrete is treated as a linear viscoelastic material, and the base and subgrade as linear elastic. The response at a point within the pavement structure is obtained by linearly superimposing the responses at this point from all tires. Here superposition is allowed since pavement materials are assumed linear mechanically (either linear viscoelastic or linear elastic) within the program. Yet, first, the response under a tire located at the center of the lane should be obtained, which is the most basic calculation in the program.

The LVECD program is now only at a research level and still under development. The current version supports the analysis for stress-strain response and fatigue performance while rutting analysis and other mechanisms such as healing and aging are not included for now. The input parameters for asphalt materials are anticipated to be determined through dynamic modulus test for response analysis, and uniaxial cyclic fatigue test for fatigue performance prediction. For now the effects of fatigue/rutting damage on the material properties/pavement structure are ignored, which means the stress redistribution effect due to damage is not considered in the current analysis. The pavement layers are assumed to be fully bonded at the interface in the program. Figure 144 shows the flowchart of fatigue performance analysis. More details of LVECD programs can be found in *Layered Viscoelastic Continuum Damage Program (44), Int. J. Pavement Eng. (47),* and *Accelerated Pavement Performance Modeling Using Layered Viscoelastic Analysis (48)*.

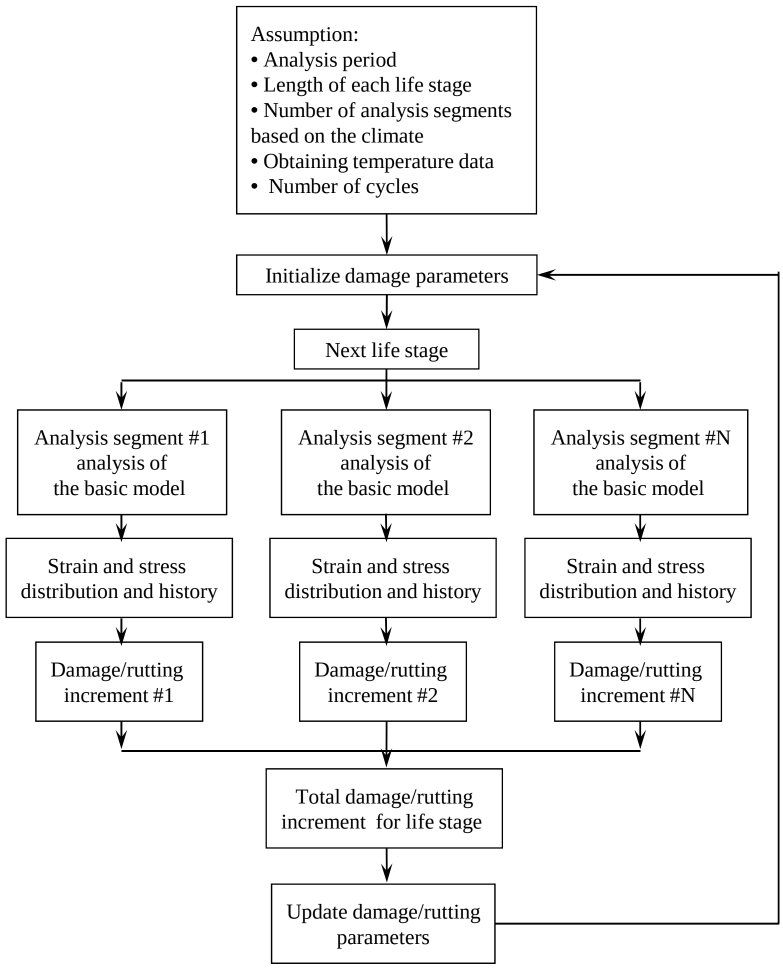

Figure 144 Scheme of LVECD Framework for Pavement Performance Analysis *(48)*.

4.7.1 Truck Configuration Inputs

Since the first and most basic step in LVECD is to calculate the pavement stress and strain response under a moving wheel, it is crucial to input the exact location information of each tire of a truck. Given this, LVECD utilizes a coordinate system for locating all tires with its origin located at the center of the truck rear axle, y-axis along the traffic direction, and x-axis directed transversely to the side of the pavement. Since all tires are considered individually, the tire load can be varied accordingly, and thus different load distribution patterns across the truck can be captured easily. LVECD truck inputs, Table 60 to Table 66 given in APPENDIX C, shows the truck configuration information for superload trucks 1-5 and the standard normal truck as traffic input for the LVECD program. The standard normal truck is used as the reference for a better understanding of the impacts for superload trucks. Note: For any truck with a symmetrical loading only data for one side is shown.

4.7.2 Materials and Pavement Structure

Since the main interest of this section is the impact of superload trucks on secondary roads, a relatively thin asphalt pavement structure is used. This structure is comprised of three layers: 4-inch Superpave-9.5B asphalt concrete (which is commonly used in North Carolina), 6-inch aggregate base, and the subgrade. As a composite of elastic aggregate and viscous asphalt binder, asphalt concrete usually exhibit elasticity, viscosity, and plasticity depending on the temperature and loading frequency.

Regarding the lane width, instead of 12 feet as commonly employed in pavement analysis program, 24 feet is used here since some of the trucks need two lanes to operate. Even though other superload trucks have widths less than one lane, there is very little lateral clearance to pavement to the side or the adjacent lanes. Therefore, considering the safety issues, it is assumed that all the analyzed overload trucks will occupy two lanes in operation regardless their actual width. Finally, the same lane width is assumed for the standard normal truck and the standard single axle for consistency considering the fact that 24 feet versus 12 feet will result in very small difference in pavement response.

4.7.2.1 Asphalt Concrete

Linear viscoelastic property

In the framework of LVECD, asphalt concrete is treated as a linear viscoelastic material, the constitutive relation of which is usually characterized experimentally through the dynamic modulus test. The measured dynamic modulus test data will be used to construct master curves by fitting a sigmoidal function, as described by Equations 5 through 7:

$$\log\left(\left|E^*\right|\right) = \delta + \frac{\alpha}{1+e^{\beta+\gamma\log(f_r)}} \tag{5}$$

$$f_r = f / a_T \tag{6}$$

$$\log a_T = \alpha_1 T^2 + \alpha_2 T + \alpha_3 \tag{7}$$

where $|E^*|$ is the dynamic modulus, f_r is the reduced frequency (loading frequency at the reference temperature), f is the physical loading frequency, a_T is the shift factor at temperature T, and δ, α, β, γ, α_1, α_2, and α_3 are the fitting parameters.

To facilitate the numerical implementation, the dynamic modulus master curve represented by Equations 5 through 7 is then converted to the relaxation modulus, as expressed by the Prony series:

$$E(t) = E_\infty + \sum_{i=1}^{m} E_i e^{-t/\rho_i} \tag{8}$$

where t is the time period after the load initiation, E_∞ is the equilibrium modulus, E_i's are the Prony coefficients physically representing the individual spring stiffness in the Wiechert model, and ρ_i's are the relaxation times of each component Maxwell model in the Wiechert model.

For linear viscoelastic materials, the responses are loading time/frequency- and temperature-dependent, and thus, the material behavior is dependent not only on the current loading input but also on the loading history. Generally, linear viscoelastic constitutive relationships are described by convolution integrals:

$$\sigma = \int_0^t E(t-\tau)\frac{d\varepsilon}{d\tau}d\tau \tag{9}$$

$$\varepsilon = \int_0^t D(t-\tau)\frac{d\sigma}{d\tau}d\tau \tag{10}$$

where $E(t)$ and $D(t)$ are the relaxation modulus and creep compliance, respectively, and τ is the integration variable for time.

In the current analysis, the dynamic modulus test has been completed at North Carolina State University (NCSU) on similar asphalt material (Superpave-9.5B) used here, seen in Figure 145. The resulting shift factors and Prony coefficients as the input for the LVECD program are listed in Table 40 and Table 41, respectively.

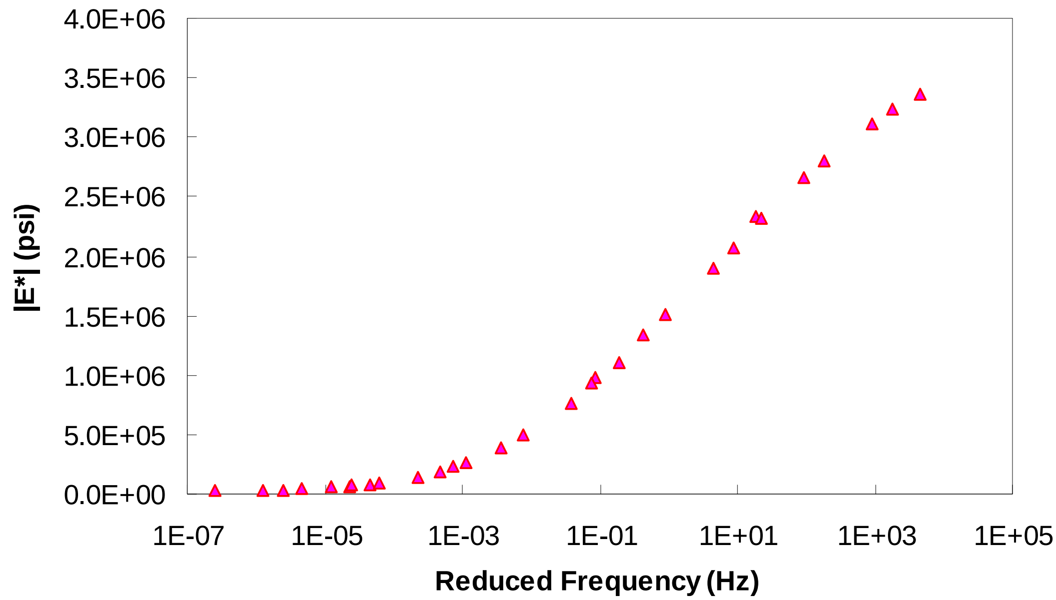

Figure 145 Dynamic Test Result of Superpave-9.5B.

Table 40 Shift Factors at Reference Temp = 41°F

α_1	α_2	α_3
2.129E-4	-0.0992	3.708

Table 41 Prony Coefficients for the Relaxation Modulus at Reference Temp = 41°F

i	ρ_i (second)	E_i (psi)	i	ρ_i (second)	E_i (psi)
1	2E+16	6.77E+01	18	2E-01	5.99E+05
2	2E+15	3.45E+01	19	2E-02	6.40E+05
3	2E+14	8.35E+01	20	2E-03	5.40E+05
4	2E+13	1.43E+02	21	2E-04	4.02E+05
5	2E+12	2.55E+02	22	2E-05	2.73E+05
6	2E+11	4.53E+02	23	2E-06	1.75E+05
7	2E+10	8.08E+02	24	2E-07	1.08E+05
8	2E+09	1.45E+03	25	2E-08	6.60E+04
9	2E+08	2.61E+03	26	2E-09	3.96E+04
10	2E+07	4.77E+03	27	2E-10	2.35E+04
11	2E+06	8.93E+03	28	2E-11	1.40E+04
12	2E+05	1.73E+04	29	2E-12	8.25E+03
13	2E+04	3.48E+04	30	2E-13	4.87E+03
14	2E+03	7.30E+04	31	2E-14	2.87E+03
15	2E+02	1.54E+05	32	2E-15	1.70E+03
16	2E+01	3.03E+05	33	2E-16	1.03E+03
17	2E+00	5.00E+05	E_∞		5.06E+04

Since the response of asphalt concrete is frequency dependent, and thus speed dependent, the normal operation speed used in analysis for each vehicle is listed as follows:

Table 42 Normal Vehicle Speed used in Analysis (mph)

Truck-1	Truck-2	Truck-3	Truck-4	Truck-5		Standard Normal Truck/18-kip Axle
				W/ Dollies	W/out Dollies	
55	25	20	3	20	20	55

<u>Empirical relationships for fatigue and rutting</u>

Currently, the LVECD program is able to conduct fatigue performance predictions (the permanent deformation or rutting prediction is still under development). It is able to evaluate and rank different pavement structure designs subject to the same traffic and environment, or compare the damage caused by different types or volumes of traffic and environments in the same pavement, in terms of the so called damage factor. (More severe fatigue damage gives a lower damage factor.) However, there are two unavoidable difficulties in applying this LVECD approach to the superload truck analysis:

- The fatigue/rutting performance analysis requires the entire truck configuration information (tens of axle lines and hundreds of wheels) which will significantly lengthen the computation time in order for the numerical convergence normally for analyzing a 10 to 15-year design period.

- Even if the fatigue damage factors in a pavement cross section are obtained, how they should be used to convert the truck to an equivalent number of standard single axles is still not clear. That is to say, it is considered that a single number should be assigned to the cross section representing the whole damage caused by the truck traffic, but how this representative number can be calculated based on the damage factor of all material points in the cross section is still unknown.

Therefore, in the present report, for both fatigue and permanent deformation models the traditional empirical relationships are used. For the fatigue relation, the so-called *S-N* (strain-number of cycle to failure) relationship is expressed as *(49)*:

$$N_f = k_1 \cdot \varepsilon^{k_2} \tag{11}$$

where,

N_f	=	number of loading cycle to failure
ε	=	tensile strain at the bottom of asphalt layer
k_1, k_2	=	regression constants.

Uniaxial cyclic fatigue tests on common Superpave-9.5B mixtures have been done at NCSU laboratory and the *S-N* relationship can be extracted as follows:

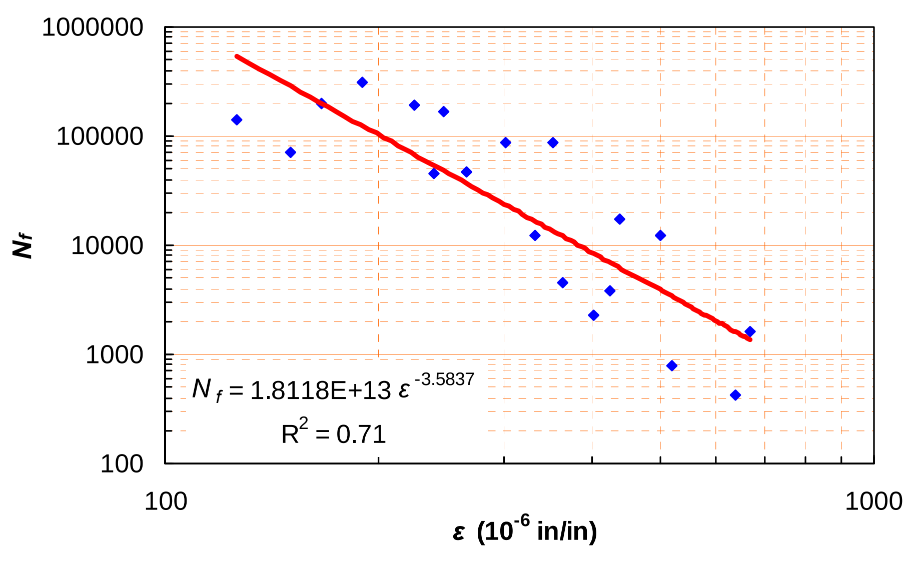

Figure 146 *S-N* relationship for Superpave-9.5B.

Equation 11 is shown as a straight line in the log-log space. It is found from the above figure that the regression coefficients are k_1 = 1.8118E+13, and k_2 = -3.5837.

As for the calculation of permanent deformation, the asphalt material is divided into several sublayers and the rutting is estimated at the mid-depth of each sublayer, and finally the overall permanent deformation for the pavement system is the sum of permanent deformation for each individual sublayer, mathematically expressed as *(50)*:

$$RD = \sum_{i=1}^{n} \varepsilon_p^i h^i \tag{12}$$

where,

RD	=	Rut depth, i.e. permanent deformation
n	=	Number of sublayers for asphalt materials
$\varepsilon_p^{\ i}$	=	Total plastic strain in sublayer i
h^i	=	Thickness of sublayer i.

Note that the permanent deformation from aggregate base and subgrade in the present analysis is ignored while the contribution from asphalt layer is considered only. In Equation 12, the plastic strain in each sublayer is modeled using the following empirical relationship *(50)*:

$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 T^{a_2} N^{a_3} \tag{13}$$

where,

ε_p	=	Accumulated plastic strain at N repetitions of load (in/in)
ε_r	=	Resilient strain of the asphalt material as a function of mix properties, temperature and time rate of loading (in/in); here obtained from LVECD
N	=	Number of load repetitions
T	=	Temperature (°F)
a_i	=	Nonlinear regression coefficients.

Note that as compared to MEPDG, the resilient strain in Equation 13 is calculated in a layered viscoelastic system instead of a layered elastic system. In the LVECD program, ε_r under one pass of an axle group will be computed using constant uniform temperature field, which is 104°F. In addition, the stress redistribution due to rutting damage is not captured in the program, and thus ε_r for a specific axle does not change with pass of trucks and is calculated only once for predicting the permanent deformation.

On the other hand, as a non-material empirical model, the coefficients (a_i) in Equation 13 depend on many other conditions besides material itself. This relationship tells a nonlinear (power) relationship between accumulated plastic strain (ε_p) and number of load repetitions (N). To simplify the analysis, it is assumed that all coefficients are the same for all trucks and the standard axle. Combined with the constant temperature used (104°F) and if we evaluate the impact of a truck versus standard axle using the same number of pass of each, Equation 13 can be reduced to:

$$\varepsilon_p = A \cdot \varepsilon_r \tag{14}$$

Where the constant A is the same for different trucks and different sublayers. Substitution of Equation 14 into Equation 12 assuming the same thickness (Δh) of each sublayer gives:

$$RD = \left(A \cdot \Delta h\right) \sum_{i=1}^{n} \varepsilon_r^i \tag{15}$$

where ($A\Delta h$) is the same for each truck and the standard axle and from now on, $\sum_{i=1}^{n} \varepsilon_r^i$ is denoted *rut depth coefficient*, which is proportional to the permanent deformation and thus computed in the rutting analysis.

4.7.2.2 Base and Subgrade

Base and subgrade are considered as linear elastic materials with the constitutive relations characterized by Hooke's law. The elastic modulus for aggregate base is 40000 psi, and 12000 psi for subgrade. Fatigue cracking and permanent deformation are not considered for base or subgrade.

4.7.3 ESAL CONVERSION

4.7.3.1 Strain History of Axle Groups

Axle groups

As stated previously, if the pavement response to an entire truck is analyzed at a time, even though the tire-to-tire response interaction can be captured, the expense would be a much lengthened computation time in order for a stabilized numerical results. However, on the other hand, if only one axle line is calculated every time, the response interaction will be ignored.

Due to these reasons, as an intermediate approach, all the axle lines are grouped into several axle groups and then analyzed one by one for each vehicle. This way, most interaction effects will be covered and the analysis time will be reduced to an acceptable length. The grouping results are shown in LVECD Truck Inputs

Table 60 to Table 66 in APPENDIX C. The following grouping rules are adopted:

- If several axle lines are closely spaced and relatively far away from other lines, then they are grouped into one axle group. See Truck 1, 2, and the standard normal truck for example.
- If multiple axle lines of similar configurations are nearly evenly spaced, then three lines are grouped consecutively until the rear of the truck. See Truck 3, Truck 4, and Truck 5 without dollies, for example.
- For the trailer of Truck 5 with dollies, since they are heavily loaded and closely distributed, seven lines are grouped including four with dollies and three without dollies, considering the potentially strong response interaction due to the additional dollies. See Table 65.

Time period of strain analysis

For base and subgrade layers treated as elastic materials, their response depends only on the current loading magnitude, while for asphalt concrete, the response is temperature and loading time,(vehicle speed) dependent. For the fatigue analysis, the temperature is chosen as 68°F (20°C). The reason is that most fatigue deterioration occurs at moderate temperatures, whereas at high and low temperatures, the pavement distress is dominated by permanent deformation and low temperature cracking, respectively. As for the permanent deformation analysis 104°F (40°C) is used.

After temperature and loading frequency (Table 42) are prescribed, the strain response of the pavement structure is determined. Consider a pavement cross section. When an axle group with four lines (e.g. Truck-4 Axle Group-5) passes over it, the transversal tensile strain history of a material point at the bottom of the asphalt layer in the section can be represented by Figure 147. As illustrated, each axle line corresponds to a strain peak at different times. Note that although quite similar, these four peak values are different due to the history-dependence of linear viscoelasticity model. If a layered elastic system is employed, the resulting peaks should have the same magnitude for the same axle load, and the strain will drop back to zero promptly when the axle group leaves.

Figure 147 has demonstrated that in order to acquire the strain history, a time period corresponding to the horizontal axis is needed. Yet it should be kept in mind that according to the above, the response does not depend on the chosen time period here, and the time period is nothing more than a window for us to observe the whole strain history of all axle lines in a group. Therefore, this period should be long enough for the axle group to fully pass the cross section, whereas on the other hand, it should not be too long to increase the number of time steps and thus the analysis time.

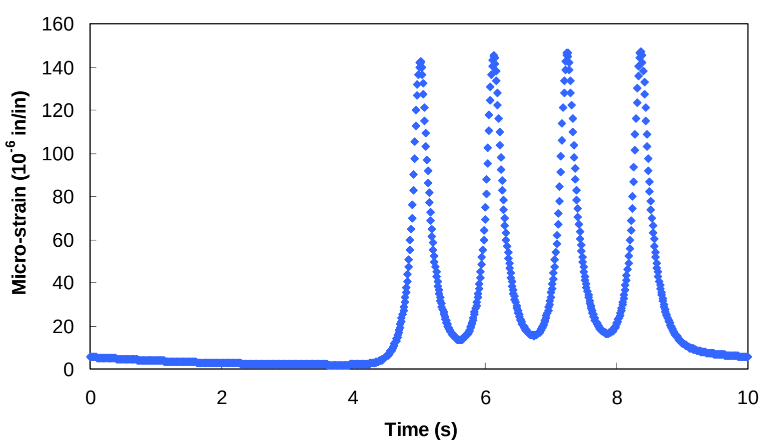

Figure 147 Transversal Strain Response at the Bottom of Asphalt Layer by an Axle Group of Four Lines.

As an example for the permanent deformation analysis, the vertical strain response at the mid-depth of each sublayer for the same axle group as used for Figure 147 is shown in Figure 148.

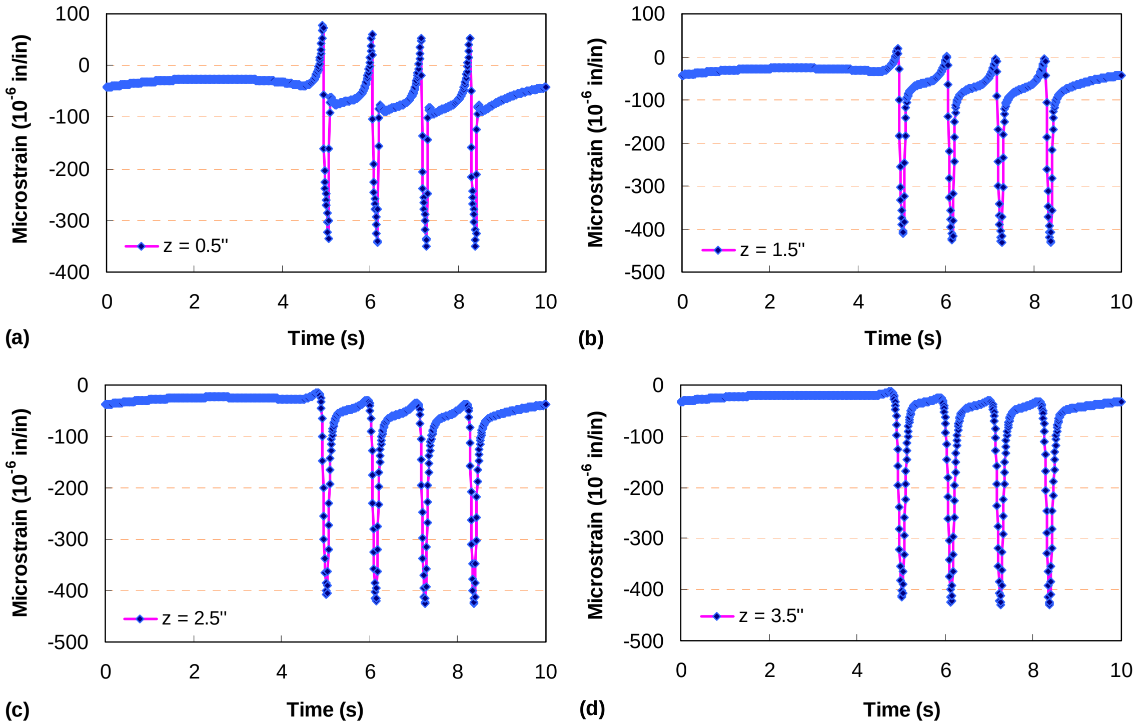

Figure 148 Vertical Strain Response at the Mid-depth of Each Sublayer by an Axle Group of Four Lines.

4.7.4 Strain profile across the pavement width

Now the response analysis for each axle group can be performed. Since the transverse tensile strain at the bottom of asphalt layer is of interest for fatigue analysis, by comparing different positions, it is found that for the material point right under where a tire is located, the tensile strain level is higher than its surrounding area. The same situation is true for vertical strain in rutting. This way, by plotting the strain history at one of these material points, the time corresponds to each peak can be determined. This is the time moment when each axle line causes the largest tensile strain or damage at the bottom of asphalt layer. For example, the time moments that should be obtained for Axle Group-5 in Truck-4 shown in Figure 147 are 5.02, 6.14, 7.25, and 8.37s.

Afterwards, for the fatigue analysis, the transversal strain contour for the whole cross section corresponding to these time moments are generated in the LVECD and exported as Excel files including node coordinates and strain levels. Only the nodal information for the bottom of asphalt layer (z = 4 inch) will be extracted to construct the strain profile across the width of the pavement for these time moments. For example, for Axle Group-5 in Truck-3 the strain profile for the first axle line (t = 5.02s) is shown in Figure 149.

Similarly, for the rutting analysis, the time moment corresponding to peak compressive (negative) vertical strains at each depth are obtained from Figure 148 and then used to generate the vertical strain profile across the pavement width caused by each axle line in a group. See Figure 150 as an example.

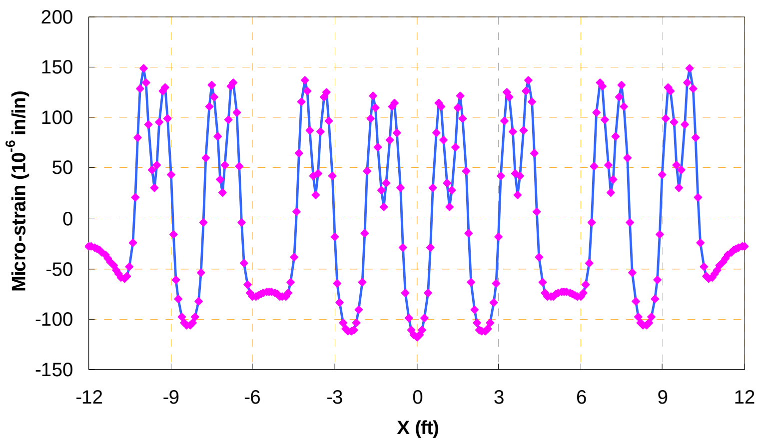

Figure 149 Transversal Strain Profile at Bottom of HMA Across the Pavement Width for a 16-Tire Axle-Line.

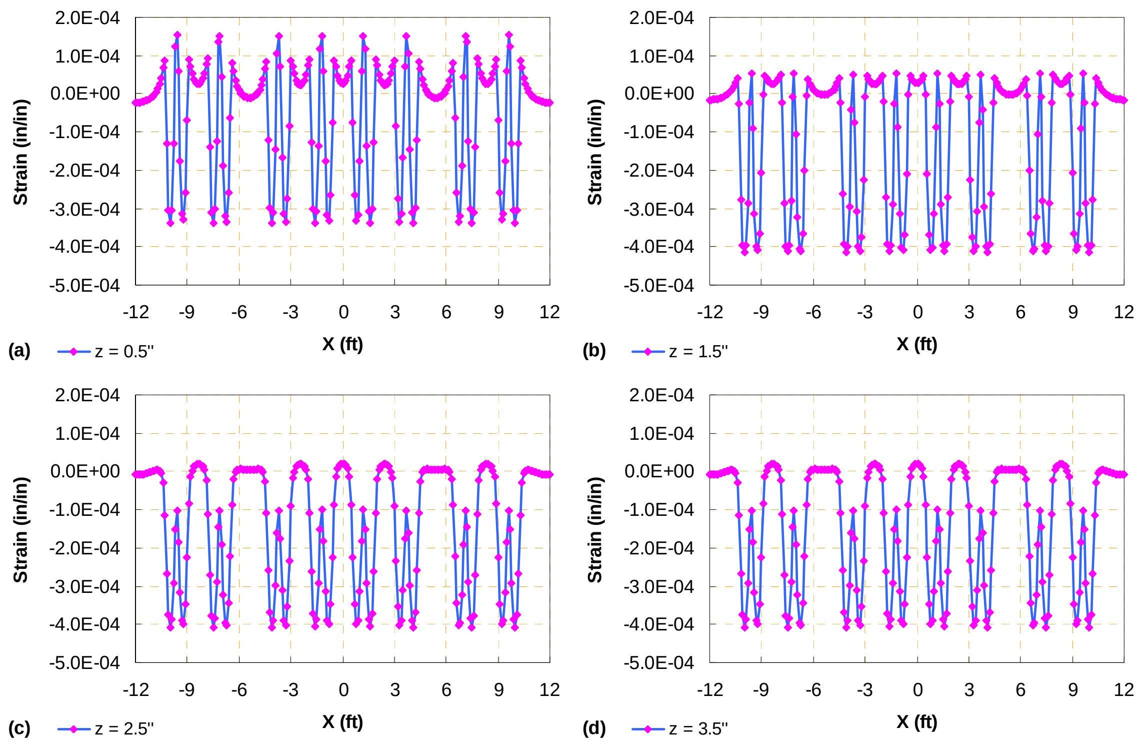

Figure 150 Vertical Strain Profile Across the Pavement Width at Different Depths for a 16-Tire Axle-Line.

Note that in Figure 149 and Figure 150 the *x*-axis is now the pavement width. It is clear that each tire corresponds to each strain peak as shown above. In Figure 149, compressive strain occurs between dual tires since materials in this region are pushed from both sides.

4.7.5 Fatigue Damage Profile and Rut Depth Coefficient across the Pavement Width

After the maximum strain at the bottom of asphalt layer caused by every axle line is obtained, Equation 7 is used to compute the fatigue life for the material points across the pavement width. The fatigue damage caused by one pass of a truck is calculated based on Miner's Law as (50):

$$D = \frac{1}{N_f} \tag{16}$$

Therefore, the profile of the maximum damage caused by each axle line can be generated as shown in Figure 151 as an example following Figure 149.

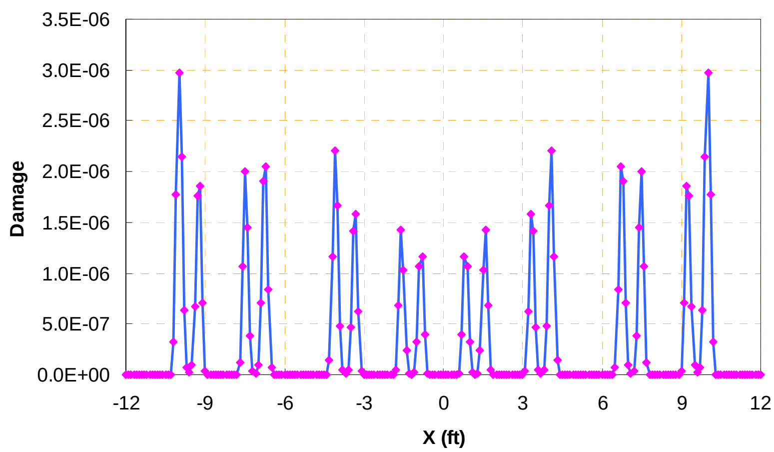

Figure 151 Fatigue Damage Profile Across the Pavement Width Due to a 16-Tire Axle-Line.

For the permanent deformation, the rut depth coefficient for each axle line is found by superimposing the vertical strain profiles for different depths. Figure 152 below shows an example following Figure 150.

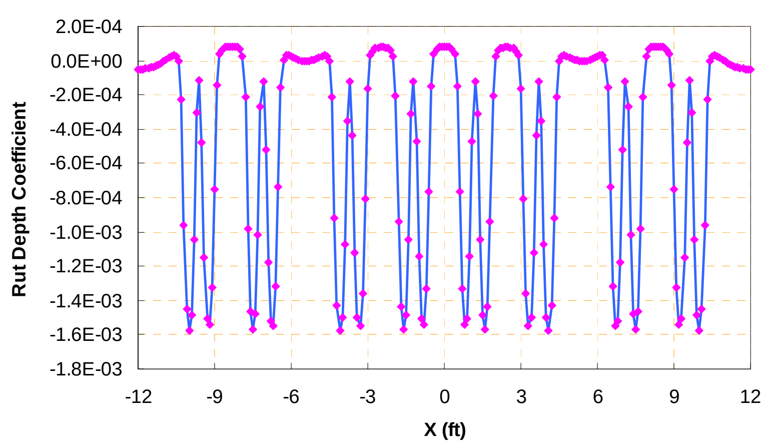

Figure 152 Rut Depth Coefficient Across the Pavement Width for a 16-Tire Axle-Line.

4.8 ESAL for Fatigue

Following the procedures described above, for every truck, the damage profile for all axle lines are generated and then superimposed (ignoring traffic wander) to give the profile of the damage caused by one pass of the whole vehicle. Figure 153 shows the damage profile for each truck plotted against the standard 18-kip axle as a comparison. Similarly, the profile of rut depth coefficient can be generated and shown in Figure 154.

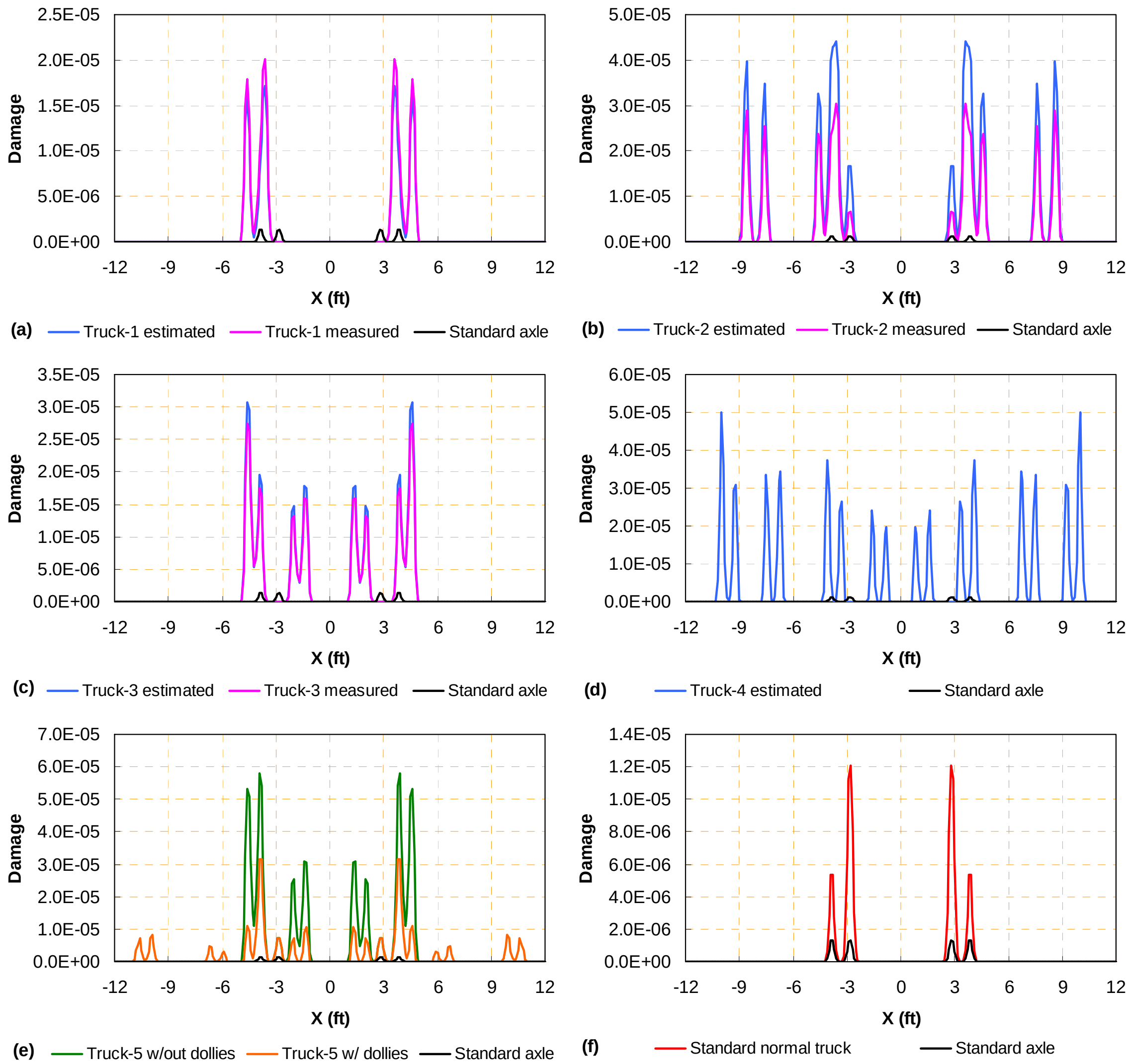

Figure 153 Fatigue Damage Profile for Study Trucks Versus 18-kip Single Axle.

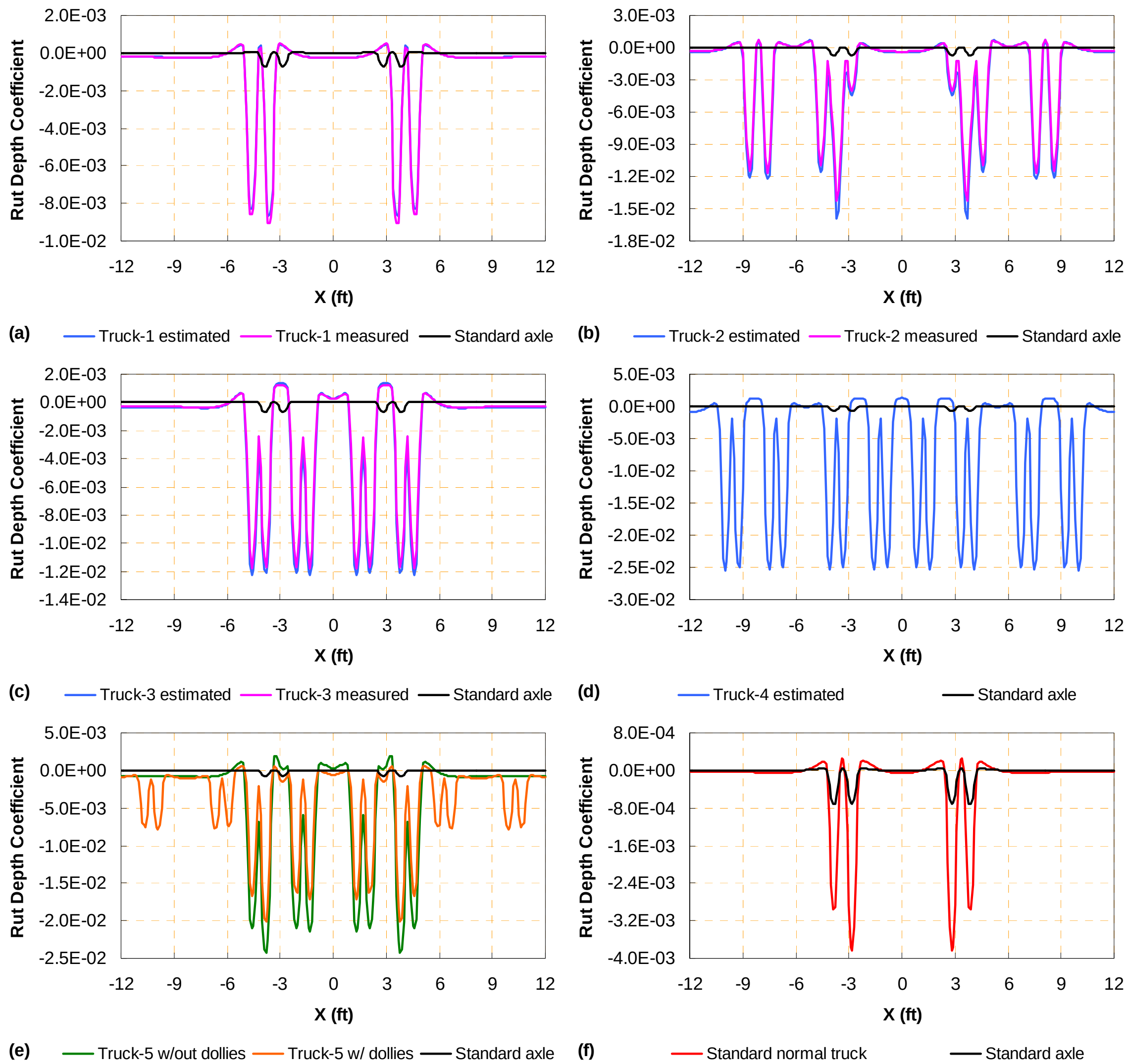

Figure 154 Profile of Rut Depth Coefficient for Study Trucks Versus 18-kip Single Axle.

For the fatigue-based ESAL calculation, two types of conversion are suggested here:

- Compare the damage maximum of a truck with the maximum from the standard axle, and the quotient would be the equivalent number in the sense of fatigue damage. This approach is derived from viewing the pavement as an assembly of material points and thus the pavement fails as soon as any point reaches its fatigue life.
- Compare the area under the damage profile of a truck to that of the standard axle, and the quotient would be the equivalent number in the sense of fatigue damage. Here we consider the pavement as a whole and thus the damage to the whole pavement is used in the conversion.

Here both methods are used for the fatigue analysis. For the rutting-based ESAL conversion, also both maximum and area-based methods are adopted. Note that area in the profile of rut depth coefficient can be either positive or negative just as rut and hump observed in the field, respectively. Thus in the area-based method the sum of absolute values of both positive and negative areas are used. The ESAL based on fatigue and permanent deformation are listed in Table 43.

Table 43 ESAL for Fatigue and Permanent Deformation (Estimated/Measured)

		Truck-1	Truck-2	Truck-3	Truck-4	Truck-5		S.N.T.
						w/ dollies	w/out dollies	
Configuration	Gross Weight (lb)	228700/ 227840	607000/ 558200	483747/ 468300	1012600 / ---	887500/ ---	851340/ ---	80000/ ---
	No. of Tires	50	120	88	256	226	162	18
	Average Tire Load (lb)	4574/ 4557	5058/ 4652	5497/ 5322	3955/ ---	3927/ ---	5255/ ---	4444/ ---
ESAL Based on Fatigue	Based on Maximum	13.09/ 15.33	33.62/ 23.19	23.46/ 20.93	38.07/ ---	50.15/ ---	44.16/ ---	9.22/ ---
	Based on Area	14.76/ 17.37	75.99/ 48.55	33.92/ 30.52	76.17/ ---	63.16/ ---	72.28/ ---	6.95/ ---
ESAL Based on Permanent Deformation	Based on Maximum	12.18/ 12.68	22.28/ 19.94	17.23/ 16.54	35.65/ ---	28.25/ ---	33.97/ ---	5.36/ ---
	Based on Area	14.94/ 15.46	42.89/ 37.10	40.19/ 35.98	128.43/ ---	68.39/ ---	71.68/ ---	4.87/ ---

Note: S.N.T. stands for Standard Normal Truck.

As shown in Table 43, the ESALs calculated with LVECD are significantly higher than ESALs calculated by the AASHTO method, in the previous section. This is indicative of the findings of Saraf, Ilves, and Majidzadeh, in *Effect of Heavy Vehicle Weights on Pavement Performance (38)*, and Huang, in *Pavement Analysis and Design (39)*, in which AASHTO ESAL equivalency factors are found inadequate for predicting the pavement damage caused by heavy trucks. Therefore, the AASHTO method for calculating ESALs is determined to be inadequate for assessing the potential pavement damage caused by superloads. However, as noted in the AASHTO analysis, the ESALs calculated using LVECD show that for truck-1, truck-2, and truck-3, the ESALs based on measured weights are close to or less than ESALs based on estimated weights. Therefore, for superload permit approval it seems that using carrier estimates would provide a reasonable basis for analysis.

Estimated ESALs for each damage type increased when based on area of damage rather than the point of maximum damage. Superload trucks, to accommodate extra axles and wheels, are commonly wider than normal trucks and therefore cause damage to a wider portion of the pavement structure, indicated by the ESALs based on area. Although, damage to the pavement structure at a point would be more indicative to damage within the normal wheel paths, indicated by ESALs based on maximum, may be of more concern since wheel paths are subject to a greater frequency and level of stresses caused by traffic loading. For most trucks, the ESAL estimates were higher for permanent deformation than for fatigue when based on area. However, ESALs based on fatigue are higher than ESALs based on permanent deformation for every truck when based on point of maximum damage. Although, since ESALs based on the point of maximum damage are of more concern this indicates that NC roads are at a higher risk over the long term for fatigue cracking damage from superload passes.

There seems not to be a direct correlation between the truck gross weight and the ESAL. This is reasonably due to the arrangement of increased number of tires in most axle lines, which helps better distribute the truck weight and thus reduce the damage caused to the pavement. Thus, tire load is of greater concern for pavement damage than gross weight. Although, as seen by the ESAL estimates based on areas, superloads with higher gross weights generally cause more damage to the pavement structure as a whole because they have more contact points over a larger area than lesser weight trucks. For further perspective, the gross weight and ESALs for each truck were divided by the respective values for the standard normal truck to get equivalent number of standard normal trucks and are provided in Table 44 below.

Table 44 Equivalent Number of Standard Normal Trucks (Estimated/Measured)

		Truck-1	Truck-2	Truck-3	Truck-4	Truck-5	
						w/ dollies	w/out dollies
# S.N.T. by Gross Weight		2.86/ 2.85	7.59/ 6.98	6.05/ 5.85	12.66/ ---	11.09/ ---	10.64/ ---
# S.N.T. by ESAL Based on Fatigue	Based on maximum	1.42/ 1.66	3.65/ 2.52	2.54/ 2.27	4.13/ ---	5.44/ ---	4.79/ ---
	Based on area	2.12/ 2.50	10.93/ 6.99	4.88/ 4.39	10.96/ ---	9.09/ ---	10.40/ ---
# S.N.T. by ESAL Based on Permanent Deformation	Based on maximum	2.27/ 2.37	4.16/ 3.72	3.21/ 3.09	6.65/ ---	5.27/ ---	6.34/ ---
	Based on area	3.07/ 3.17	8.81/ 7.62	8.25/ 7.39	26.37/ ---	14.04/ ---	14.72/ ---

Note: S.N.T. stands for Standard Normal Truck.

As illustrated in Table 44, number of equivalent standard normal trucks based on the point of maximum damage for fatigue and permanent deformation are lower than those based on gross weight. This suggests that every superload vehicle type analyzed causes less damage per pound of gross weight than a standard normal truck does when based on point of maximum damage. On the other hand, the number of equivalent trucks when based on area is generally larger than equivalent number of standard trucks based on gross weight. This indicates that damage from superload trucks to the entire pavement structure is larger per pound of gross weight than a standard truck. This is necessarily true because superloads are larger than standard trucks to accommodate more axles and thus impact a greater area of the pavement.

4.9 Rapid Shear Failure Chart Analysis

As discussed in the literature review section, Jooste and Fernando developed a procedure to analyze route adequacy for “super heavy” vehicles for TxDOT. They developed their analysis procedure to assess the potential for rapid shear failure of a pavement structure due to a single superload pass. For this pavement failure type, the limiting factor for a superload truck is the tire load. A model for assessing the risk of rapid shear failure was created using MOHR-Coulomb yield criterion and detailed information on pavement structure and materials. This model has been implemented through the creation of PALS, Program to Analyze Loads Super Heavy. It is noted that without detailed information on the pavement structure and materials, the PALS software should not be used. The model underlying PALS is very sensitive to these inputs and inaccurate pavement data would produce unreliable results. Consequently, they developed a series of charts with the PALS software for an initial analysis of the superload route. These charts require only general characterization of the pavement structure and provide conservative estimates for wheel loads that would cause rapid shear failure *(41)*.

The charts are organized by subgrade and base strength and the material parameters used to derive the charts and for choosing the correct chart for analysis is provided below.

Table 45 Pavement Material Parameters *(41)*

Layer Description	Non-linear Material Constants			Resulting Range of Moduli (MPa)	Cohesion (kPa)	Angle of Friction
	k_1	k_2	k_3			
Asphalt Surface	10000 to 15000	0.1	0.0	790 to 2070	938.0	0.0°
Weak Base	1000	0.6	-0.3	62 to 235	49.0	50.0°
Stabilized Base	20000 to 25000	0.1	0.0	1500 to 3200	621.0	40°
Weak Subgrade	300	0.0	-0.3	48 to 62	41.0	30°
Stiff Subgrade	900	0.0	-0.3	90 to 138	103.0	30°

The same pavement structure as used in the LVECD analysis was used for this portion of the analysis as well and is as follows: 4-inch (102 mm) asphalt concrete, 6-inch (152 mm) aggregate base with an elastic modulus of 40000 psi (276 MPa), and the subgrade with an elastic modulus of 12000 psi (83 MPa). From the above table, it can be seen that these values fall between weak and stabilized base and weak and stiff subgrade; therefore, the chart for weak base and weak subgrade is used to remain conservative.

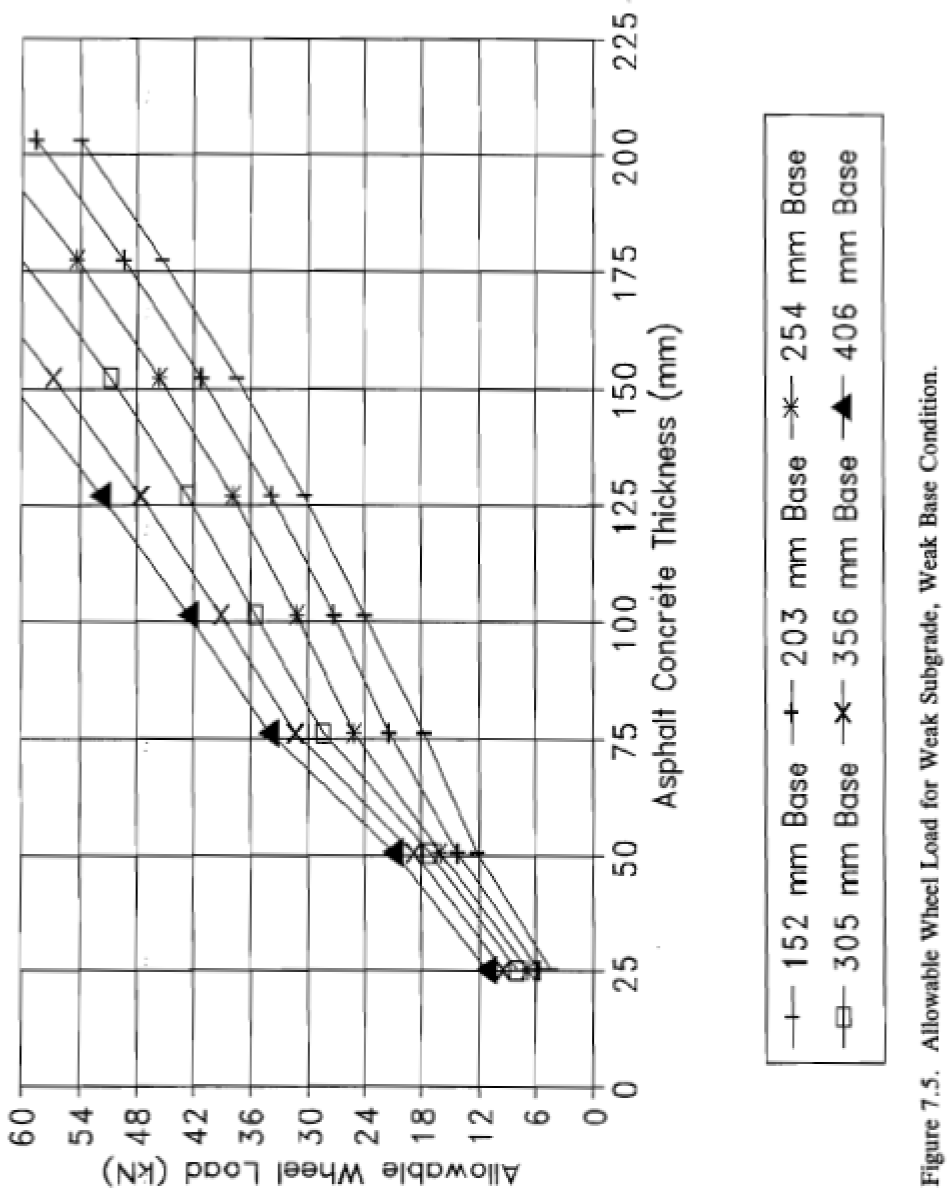

Figure 155 Weak Base, Weak Subgrade *(41)*.

From the chart, it can be seen that the allowable wheel load for this pavement structure is approximately 5395 pounds (24 kN). Table 46 below contains the maximum estimated and measured wheel load for each truck.

Table 46 Maximum Wheel Loads (Estimated/Measured)

	Truck-1	Truck-2	Truck-3	Truck-4	Truck-5		S.N.T.
					w/ dollies	w/out dollies	
Maximum Wheel Load (lb)	5700/ 6940	7500/ 6050	5497/ 6700	3955/ ---	8250/ ---	8250/ ---	6000/ ---
Maximum Wheel Load (Ignoring Steer Axle) (lb)	4958.5/ 5385	5000/ 5137.5	5497/ 6700	3955/ ---	5500/ ---	5500/ ---	4500/ ---

As can be seen from the table all the trucks, except Truck-4, have maximum wheel loads that exceed the allowed wheel load of 5,395 pounds from the chart. This maximum wheel load occurred on the steer axle for Trucks 1, 2, 5 and the standard normal truck. This increased wheel load on the steer axle is due to the steer axle having only two tires instead of four like the other axles. This does not indicate that rapid shear failure of the pavement is imminent, as the chart is very conservative, but it does indicate that for a weak pavement structure such as this that extra caution should be taken before approving the superload route. Ignoring wheel loads from steer axles only Truck-3 and Truck-5 have wheel loads exceeding the allowable wheel load of 5,395 pounds. Truck-3 greatly exceeds the wheel load limit, causing a higher potential for immediate damage to the pavement structure. Although as noted previously, this truck operated on private property and heavier axle loads than would be permitted on public roadways were used. Truck-5 was only 105 pounds over the allowable limit illustrated by the charts and thus given the conservative nature of the charts would most likely be tolerable. This analysis shows that for a weak pavement structure consideration should be given to reducing steer axle loads, since steer axles provide less contact area with the pavement to carry the load.

It is also worth mentioning that while Table 46 suggests that the maximum wheel load of the standard normal truck is not much different from that of the superload trucks, the degree of damage in the sense of rapid shear failure caused to the pavement may not be of the same order of magnitude. For example, the load on the steer axle of Truck-5 (8,250 lb) is 1.53 times the allowed wheel load (5,395 lb) whereas the factor for the load on the steer axle of the standard normal truck (6,000 lb) is just 1.11. In pavement engineering a power law relation is commonly adopted when transferring the load/stress into damage. If the previous two factors are raised to the power of 4, the damage due to steer axle of Truck-5 can be 3.6 times as much as that from the steer axle of the standard normal truck. In addition, to arrive at this observation only rapid shear failure is considered here. Other types of failure for the steer axle, and the impacts of the remaining wheels of the superload trucks to the pavement are not included yet. Therefore, caution is urged when permitting a superload truck to operate on a road that has successfully supported a standard truck in the past (even if only the rapid shear failure is concerned).

4.10 Case Study

A case study on the effects of superloads on pavement condition for a route through Wayne County was completed. The 12.5-mile route from Dudley, NC to Goldsboro, NC was permitted for superloads 132 times in 2011. The average gross vehicle weight of the 132 permits was

414,973 pounds. The highest load exceeded one million pounds. The multiple runs of superload trucks caused no visible damage to the pavement surface of the route according to a telephone interview with the District Engineer. The entire case study is in APPENDIX C section C.3.

4.11 Future Research Recommendations

As noted previously, the NCDOT PMU has no documented procedure for assessing superload permit applications. It is recommended that a procedure for permit approval be documented and followed. Research is needed to determine an adequate procedure for the PMU to follow given labor, resources, budgetary, and time constraints.

The pavement analysis of this study focused on a single pavement structure with a set of assumed material properties for modeling. Further research is needed to assess the impacts of superloads on several different pavement structures and to determine the sensitivity of pavement impact predictions to material properties. Furthermore, outside of the scope of this project, field-testing is needed to measure pavement responses under a superload truck to verify modeling predictions.

During this study, the feasibility of converting a superload truck to ESALs using computer modeling was demonstrated. Future research should be conducted to create ESAL equivalency factor tables for various pavement structures and axle configurations, thus creating a set of tables similar to the AASHTO equivalency tables for superload trucks. This would provide a quick and simple method for the PMU to assess the damage potential of superload trucks during the permit application process.

4.12 Summary and Conclusions

In this report a four part pavement impact analysis was used, (1) The AASHTO ESAL conversion factors were used to convert the superloads into number of equivalent 18-kip single axles as an initial simple analysis. (2) LVECD was selected for the pavement response modeling and analysis. Developed at NCSU, this program was initially written for analyzing pavement response and performance (including thermal cracking, fatigue cracking, and rutting) under traffic loading of normal trucks. It was then modified to accommodate the special geometric configurations of the overload trucks while keeping the algorithms and assumptions the same as for normal trucks. The goal of this portion of the analysis was to convert a superload truck to an equivalent number of the standard 18-kip single axles, based on the concept of equivalent damage (either fatigue or permanent deformation) caused to the pavement. (3) The wheel load charts developed by Jooste and Fernando with the PALS software were used to determine the risk of immediate damage from a superload due to rapid shear failure. (4) A case study was performed for a route that a one-million pound configuration 4, doublewide modular, superload. This vehicle was unable to be weighed during the study, as noted in chapter 2, and no other weight data was found for this configuration. Therefore, to compensate for this lack of weight data for analysis an interview was conducted with the NCDOT inspector, Gary Darden, who inspected the route before and after the superload move and a case study written.

The pavement analysis tool LVECD, developed in-house, was utilized to obtain the strain response of pavement to the overload trucks. In the framework of LVECD, asphalt concrete is treated as a linear viscoelastic material, while base and subgrade are considered as linear elastic. Given the length of the overload trucks and the resulting computational issues, all axle lines were grouped into several axle groups and then one axle group was used at a time in the strain response analysis. When the strain response was obtained, the strain profile at a depth of interest caused by each axle line in an axle group corresponding to the moment of the strain peak was extracted and then used to calculate the damage. For fatigue analysis, the transverse tensile strain at the bottom of asphalt layer was used to generate the damage profile across the pavement width. For rutting analysis, first, the vertical compressive strain was computed at the mid-depth of each sublayer of asphalt materials and then the rut depth coefficient (proportional to rut depth) profile across the pavement width was produced by summing up all the contributions from each sublayer. Finally, by comparing the fatigue damage and rut depth coefficient due to trucks to those caused by the standard 18-kip axle through both maximum and area-based methods, the fatigue/rut ESALs for each truck was found.

With the analysis by LVECD, it was determined that the AASHTO equivalency factors for converting axle loads to ESALs were inadequate for use with superloads. The AASHTO factors consistently underestimated ESALs when compared to ESALs calculated using LVECD modeling. The AASHTO ESAL method cannot manage the nonstandard axle configurations of superloads and therefore cannot account for the complex stress interactions within the pavement structure. As a result, the AASHTO ESAL method cannot be recommended for use by the PMU for analysis of superload permit applications.

In the LVECD analysis, it was shown that ESALs for both damage types increased when based on area of damage rather than the point of maximum damage. Superload trucks, to accommodate extra axles and wheels, are commonly wider than normal trucks and therefore cause damage to a wider portion of the pavement structure, indicated by the ESALs based on area. Although, damage to the pavement structure at a point would be more indicative to damage within the normal wheel paths, indicated by ESALs based on maximum, are of more concern since wheel paths are subject to a greater frequency and level of stresses caused by traffic loading. ESALs based on fatigue are higher than ESALs based on permanent deformation for every truck when based on point of maximum damage. This indicates that NC roads are at a higher risk over the long term for fatigue cracking damage from superload passes.

There seems not to be a direct correlation between the truck gross weight and the ESAL. This is reasonably due to the arrangement of increased number of tires in most axle lines, which helps better distribute the truck weight and thus reduce the damage caused to the pavement. Thus, tire load is of greater concern for pavement damage than gross weight. Although, as seen by the ESAL estimates based on areas, superloads with higher gross weights generally cause more damage to the pavement structure as a whole because they have more contact points over a larger area than lesser weight trucks. Number of equivalent standard normal trucks based on the point of maximum damage for fatigue and permanent deformation are lower than those based on gross weight. This suggests that every superload vehicle type analyzed causes less damage per pound of gross weight than a standard normal truck does when based on point of maximum damage.

The ESALs calculated using LVECD show that for truck-1, truck-2, and truck-3, the ESALs based on measured weights are close to or less than ESALs based on estimated weights. Therefore, for superload permit approval, it seems that using carrier estimates would provide a reasonable basis for analysis for the PMU.

The charts developed by Jooste and Fernando for TxDOT were used to determine maximum wheel loads for superload trucks to reduce the risk of rapid shear failure of pavements. It was determined that with a weak pavement structure, steer axles pose a higher risk of pavement damage since these axles generally carry higher wheel loads due to only having two tires. Although, ignoring steer axles, it was determined that only truck-3, the singlewide modular, posed a significant risk for damaging the pavement due to uneven weight distribution. It is recommended that the PMU use these chart in the superload permit approval process.

The case study showed that over 100 runs of various superload trucks along a single route caused no visible damage to the pavement surface. This indicates that the route had sufficient strength to support the superloads without damage.

Also noted in the literature review was the finding that superloads pose a significant risk to new seal coats. It is recommended that the PMU adopt the TxDOT policy of not allowing superloads to use roads that have seal coats younger than 5 weeks if other routing is possible. If other routing is not possible then the carrier should be required to mat the road to protect the seal coat from damage.

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APPENDIX A. CHAPTER 2

This appendix for Chapter 2 will contain the weight data and superload permits for the trucks included in this study. The organization of this appendix will follow the organization of chapter 2 and supporting materials will appear in the order that they appeared in chapter 2. Permit and citation data will include only relevant excerpts.

A.1 Configuration 1

A.1.1 Progress Energy Mobile Transformers

North Carolina DOT Division of Highways
Single Trip Permit #008184K0031

Valid From: 8/23/2010 to 9/ 1/2010

Issued to:
CAROLINA POWER & LIGHT CO
410 S WILMINGTON ST
RALEIGH, NC 27601-1849

Phone: 919.632.2899 State Fee: $ 324.00
Sent by: Fax - 919.691.4340

Load Description: MOBILE SUBSTATION Escorts: 2
Power Unit: TRUCK-TRACTOR License: LZ7509(NC) Registered weight: 80,000 VIN: E1006 Axles: 13
Vehicle 2: SEMI-TRAILER License: AA44665(NC)

Dimensions - Length: 119'0" Width: 10'0" Height: 13'6" Trailer: 65'0" Overhang - Front: NONE Rear: NONE

VEHICLE(S) MUST BE PROPERLY LICENSED FOR MAXIMUM WEIGHT ALLOWED BY LAW

GrossWeight: 228,700

Axle:	1	2	3	4	5	6	7	8	9	10	11	12	13
Weight:	11400	19000	19000	19000	19834	19833	19833	15975	15975	15975	15975	18450	18450
Spacing:	17'6"	3'8"	4'7"	16'10"	4'2"	4'2"	32'6"	4'8"	4'8"	4'8"	11'0"	4'8"	

From: GARNER NC To: HAMLET NC

Permit does not authorize travel on routes beyond "From", point of origin or "To", destination specified.

Via Routes: FROM A POINT ON WAKE CO SR2538/MECHICIAL BLVD TO SR2026/HAMMOND RD TO I40/440 TO US1 SOUTH TO NC177 TO RICHMOND SR1627/EARLIE FRANKLIN DR TO SR1628/ACS/HORSESHOE RD TO A POINT ON SR1628/ACS/HORSESHOE RD.

BRIDGE RESTRICTIONS

RICHMOND CO BRIDGE # 42 ON US1 - 2.3 MI. N. JCT. SR1600
USE AS ONE LANE OTHER VEHICLES SHOULD BE KEPT OFF BFRIDGE WHILE PERMIT TRUCK IS CROSSING

**LEE CO BRIDGE # 94 ON SR1329 - 0.2 MI. E. JCT. SR1329
ONLY PERMIT TRUCK ON BRIDGE AND NO IMPACT TRAVEL AT CRAWL SPEED 5 MPH OR LESS

Figure 156 Excerpt from Progress Energy Superload Permit.[42]

[42] Source: Progress Energy

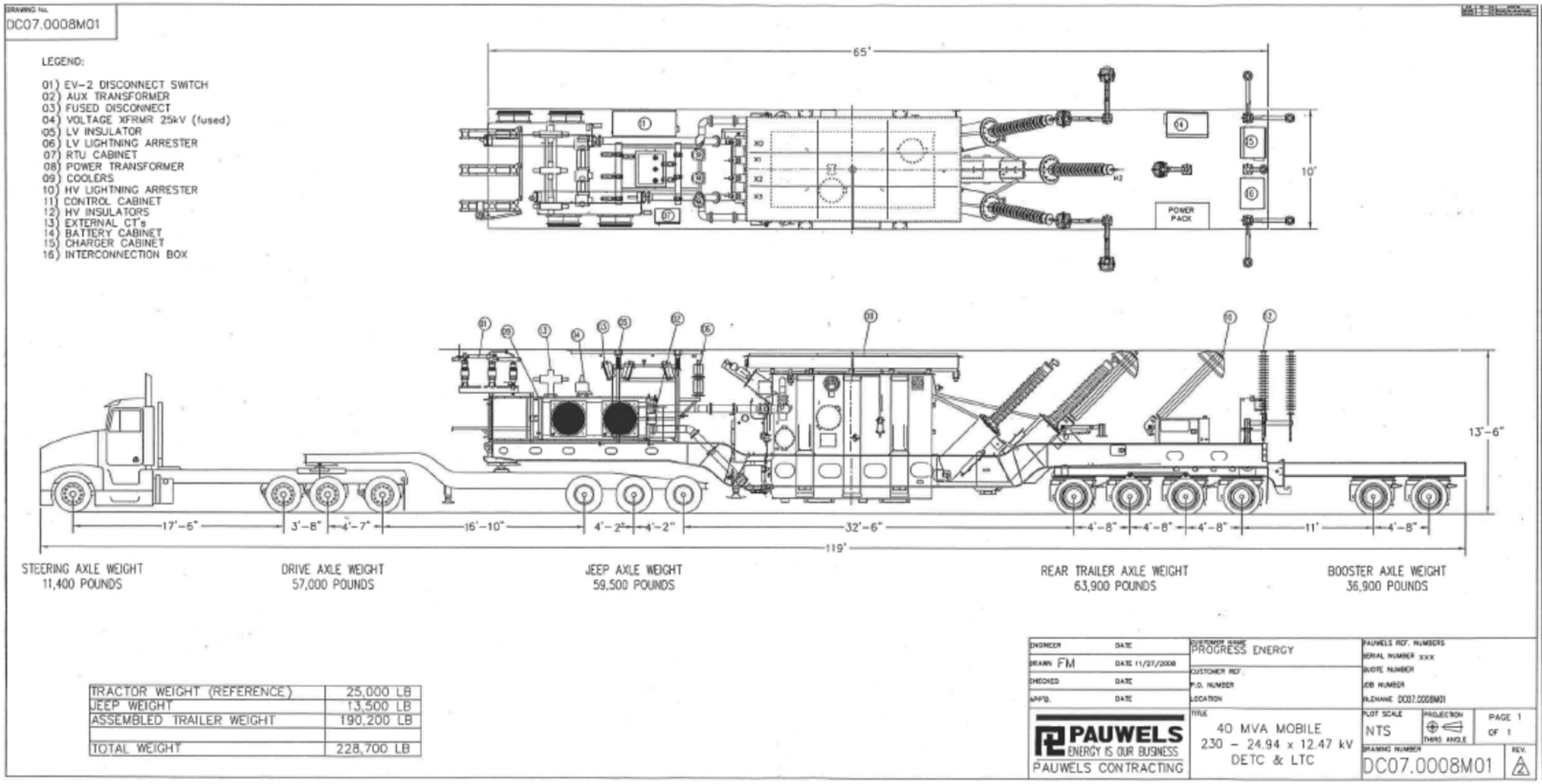


Figure 157 Progress Energy 13 Axle Mobile Transformer Truck Schematic.[43]

[43] Source: Progress Energy

Table 47 Weight Data for Progress Energy Mobile Transformers as Received from NC SHP

PROGRESS ENERGY WEIGHT FOR 3/7/2012

1ST TRUCK WEIGHED*

LEFT SIDE	RIGHT SIDE	TOTAL
5160	5000	10160
4020	3940	7960
6100	6500	12600
6100	6800	12900
7560	8720	16280
7260	7900	15160
7940	7380	15320
10840	9540	20380
10600	8580	19180
10580	9220	19800

TOTAL WEIGHT IS 149,740

1ST TRUCK WEIGHED ROCKING LEFT TO RIGHT*

LEFT SIDE	RIGHT SIDE	TOTAL
5160	5000	10160
3320	3520	6840
7540	6620	14160
7100	6580	13680
7980	9320	17300
7520	8220	15740
8220	7680	15900
10920	9060	19980
10640	8940	19580
10440	9320	19760

TOTAL WEIGHT IS 153,100

2ND TRUCK WEIGHED (LARGE LOAD)+

LEFT SIDE	RIGHTSIDE	TOTAL
6880	7000	13880
6200	5980	12180
10600	10420	21020
9700	10840	20540
9960	10200	20160
9340	9300	18640
8920	9060	17980
8720	8200	16920
7540	8620	16160
6960	8820	15780
7840	9200	17040
9440	9100	18540
8920	8760	17680

TOTAL WEIGHT IS 226,520

2ND TRUCK WEIGHED ROCKING LEFT TO RIGHT+

LEFT SIDE	RIGHT SIDE	TOTAL
6880	7000	13880
5800	6000	11800
10880	10660	21540
10180	10540	20720
10440	10860	21300
9520	9500	19020
8720	8800	17520
8720	8200	16920
7540	8620	16160
6900	8820	15720
7840	9200	17040
9440	9100	18540
8920	8760	17680

TOTAL WEIGHT IS 227,840

*Note: 1st Truck is Progress Energy 10-Axle Mobile Transformer

+Note: 2nd Truck is Progress Energy 13-Axle Mobile Transformer

A.1.2 NC Citation Data

Below are included The NC citation data as presented by the NC SHP, with permit numbers removed, with corresponding permit excerpts.

Vehicle #1 was not used in this study because a permit was not available for this truck.

Table 48 NC Citation Data: Vehicle #1

Vehicle #1	
Actual Weight	Permitted Weight
Axle 1: 13,500	12,000
Axle Group 2-4: 52,399	60,000
Axle Group 5-7: 73,601	60,000
Gross Vehicle Weight: 139,500	132,000

Vehicle #2 was not used in this study because of a transcription error in the data, axle weights do not sum to Gross vehicle weight.

Table 49 NC Citation Data: Vehicle #2

Vehicle #2	
Actual Weight	Permitted Weight
Axle 1: 6,700	16,000
Axle 2: 8,900	20,000
Axle 3: 13,000	20,000
Axle 4: 12,900	20,000
Axle 5: 5,200	20,000
Axle 6: 6,200	20,000
Axle 7: 6,400	20,000
Axle 8: 13,300	20,000
Axle 9: 13,000	20,000
Axle 10: 12,300	20,000
Gross Vehicle Weight: 194,100	196,000

Vehicle #3 was not used in this study because a permit was not available for this truck.

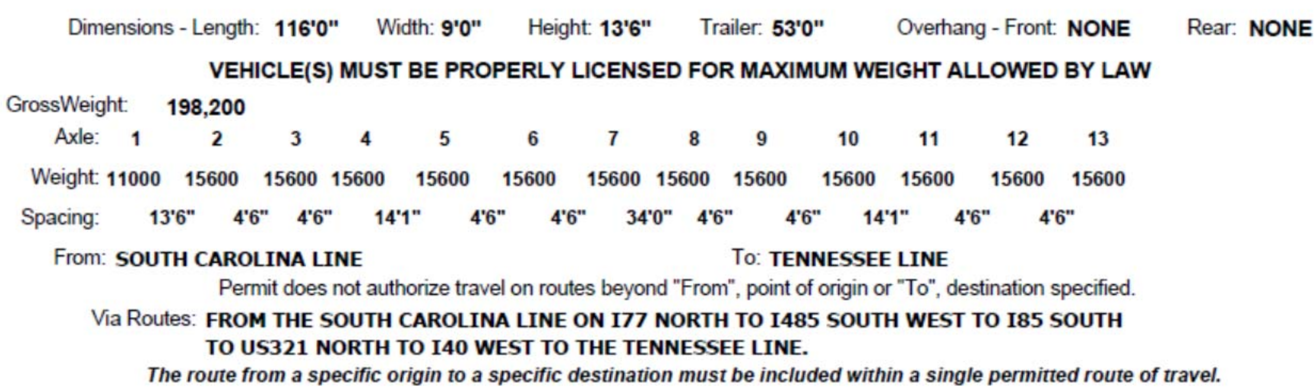
Table 50 NC Citation Data: Vehicle #3

Vehicle #3	
Actual Weight	Permitted Weight
Axle 1: 12,400	12,000
Axle Group 2-4: 62,300	60,000
Axle Group 5-7: 57,000	60,000
Axle Group 8-10: 61,400	60,000
Axle Group 11-13: 59,000	60,000
Gross Vehicle Weight: 252,100	252,000

Vehicle # 4 was used in this study and is the truck identified as NC Citation 13-Axle Truck-Jeep-Trailer-Stinger 7/2008 in the report.

Table 51 NC Citation Data: Vehicle #4

Vehicle #4	
Actual Weight	Permitted Weight
Axle 1: 11,480	11,000
Axle Group 2-4: 44,620	46,800
Axle Group 5-8: 44,300	46,800
Axle Group 8-10: 41,140	46,800
Axle Group 11-13: 40,600	46,800
Gross Vehicle Weight: 182140	198,200


Dimensions - Length: **116'0"** Width: **9'0"** Height: **13'6"** Trailer: **53'0"** Overhang - Front: **NONE** Rear: **NONE**

VEHICLE(S) MUST BE PROPERLY LICENSED FOR MAXIMUM WEIGHT ALLOWED BY LAW

GrossWeight: **198,200**

Axle:	1	2	3	4	5	6	7	8	9	10	11	12	13
Weight:	11000	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600	15600
Spacing:	13'6"	4'6"	4'6"	14'1"	4'6"	4'6"	34'0"	4'6"	4'6"	14'1"	4'6"	4'6"	

From: **SOUTH CAROLINA LINE** To: **TENNESSEE LINE**

Permit does not authorize travel on routes beyond "From", point of origin or "To", destination specified.

Via Routes: **FROM THE SOUTH CAROLINA LINE ON I77 NORTH TO I485 SOUTH WEST TO I85 SOUTH TO US321 NORTH TO I40 WEST TO THE TENNESSEE LINE.**

The route from a specific origin to a specific destination must be included within a single permitted route of travel.

Figure 158 Permit Excerpt Corresponding to NC Citation Data Vehicle #4.[44]

[44] Source: NCDOT

Vehicle #5 was used in this study and is the truck identified as NC Citation 8-Axle Truck-Trailer-Stinger 6/2008 in the report.

Table 52 NC Citation Data: Vehicle #5

Vehicle #5	
Actual Weight	Permitted Weight
Axle 1: 12,200	12,000
Axle Group 2-4: 62,080	58,000
Axle Group 5-7: 60,020	60,000
Axle 8: 18,200	19,000
Gross Vehicle Weight: 152,500	149,000

Dimensions - Length: **90'0"** Width: **12'0"** Height: **13'6"** Trailer: **67'0"** Overhang - Front: **NONE** Rear: **NONE**

VEHICLE(S) MUST BE PROPERLY LICENSED FOR MAXIMUM WEIGHT ALLOWED BY LAW

GrossWeight: **149,000**

Axle:	1	2	3	4	5	6	7	8
Weight:	12000	18000	20000	20000	20000	20000	20000	19000
Spacing:	15'0"	4'6"	4'6"	36'10"	4'6"	4'6"	14'1"	

From: **CHARLOTTE** To: **SOUTH CAROLINA LINE**

Permit does not authorize travel on routes beyond "From", point of origin or "To", destination specified.

Via Routes: **FROM A POINT ON MECKLENBURG CO SR2483 TO NC24 TO I77 SOUTH TO I85 SOUTH TO THE SOUTH CAROLINA LINE.**

The route from a specific origin to a specific destination must be included within a single permitted route of travel.

Figure 159 Permit Excerpt Corresponding to NC Citation Data Vehicle #5.[45]

Vehicle #6 was used in this study and is the truck identified as NC Citation 9-Axle Truck-Jeep-Trailer-Stinger 7/2007 in the report.

Table 53 NC Citation Data: Vehicle #6

Vehicle #6	
Actual Weight	Permitted Weight
Axle 1: 15,040	13,000
Tandem Axles 2-3: 32,340	44,000
Tandem Axles 4-5: 33,100	44,000
Tandem Axles 6-7: 37,760	44,000
Tandem Axles 8-9: 39,700	44,000
Gross Vehicle Weight: 157,940	189,000

[45] Source: NCDOT

Dimensions - Length: **115'0"** Width: **12'0"** Height: **14'6"** Trailer: **48'0"** Overhang - Front: **NONE** Rear: **NONE**

VEHICLE(S) MUST BE PROPERLY LICENSED FOR MAXIMUM WEIGHT ALLOWED BY LAW

GrossWeight: **189,000**

Axle:	1	2	3	4	5	6	7	8	9
Weight:	13000	22000	22000	22000	22000	22000	22000	22000	22000
Spacing:	20'6"	4'6"	13'4"	5'0"	36'4"	5'0"	14'6"	5'0"	

From: **VA LINE** To: **SC LINE**

Permit does not authorize travel on routes beyond "From", point of origin or "To", destination specified.

Via Routes: **FROM THE VIRGINIA LINE ON I95 SOUTH TO EXIT 107 TO US301 SOUTH TO HARNET CO SR1712/HOBSON RD TO SR1802/LANE RD TO SR1808/CAROLINA DR TO US301 SOUTH TO WADE TO CUMBERLAND CO SR1815/WADE RD TO US13 SOUTH TO I295 TO I95 SOUTH TO EXIT 41 TO NC59 TO SR2285/SHIPMAN RD TO US301 SOUTH TO EXIT 22 TO I95 SOUTH TO THE SOUTH CAROLINA LINE.**

The route from a specific origin to a specific destination must be included within a single permitted route of travel.

Figure 160 Permit Excerpt Corresponding to NC Citation Data Vehicle #6.[46]

Vehicle #7 was not used in this study because a permit was not available for this truck.

Table 54 NC Citation Data: Vehicle #7

Vehicle #7	
Actual Weight	Permitted Weight
Axle 1: 15,600	12,000
Axle Group 2-4: 71,100	60,000
Axle Group 5-7: 57,400	60,000
Axle 8: 20,100	24,000
Gross Vehicle Weight: 164,200	156,000

Vehicle #8 was used in this study and is the truck identified as NC Citation 13-Axle Truck-Jeep-Trailer-Stinger 12/2008 in the report.

Table 55 NC Citation Data: Vehicle #8

Vehicle #8	
Actual Weight	Permitted Weight
Axle 1: 14,800	18,000
Axle Group 2-4: 60,200	60,000
Axle Group 5-7: 58,400	60,000
Axle Group 8-10: 62,600	60,000
Axle Group 11-13: 62,300	60,000
Gross Vehicle Weight: 258,300	258,000

[46] Source: NCDOT

Dimensions - Length: **140'0"** Width: **12'6"** Height: **14'2"** Trailer: **115'0"** Overhang - Front: **NONE** Rear: **NONE**

VEHICLE(S) MUST BE PROPERLY LICENSED FOR MAXIMUM WEIGHT ALLOWED BY LAW

GrossWeight: **258,000**

Axle:	1	2	3	4	5	6	7	8	9	10	11	12	13
Weight:	18000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000

Spacing: 19'8" 4'6" 4'6" 15'6" 4'6" 4'6" 42'8" 4'6" 4'6" 15'6" 4'6" 4'6"

From: **VIRGINIA LINE** To: **AURORA NC**

Permit does not authorize travel on routes beyond "From", point of origin or "To", destination specified.

Via Routes: **FROM THE VIRGINIA LINE ON I95 SOUTH TO US264 EAST TO US264 BYP AT WILSON TO US264 EAST TO US264 BYP NORTH EAST AROUND GREENVILLE TO US264 EAST TO WASHINGTON TO US17 SOUTH TO CHOCOWINITY TO NC33 SOUTH EAST TO NC306 NORTH TO DESTINATION AT A POINT ON NC306 AT NEAR AURORA**

BRIDGE RESTRICTIONS:
MOVER IS TO REDUCE SPEED TO 30MPH OR LESS WHILE CROSSING BRIDGE STR#25 ON US17 OVER PAMLICO RIVER 3.1 MI.N.JCT.NC33.

The route from a specific origin to a specific destination must be included within a single permitted route of travel.

Figure 161 Permit Excerpt Corresponding to NC Citation Data Vehicle #8.[47]

Vehicle #9 was not used in this study because a permit was not available for this truck.

Table 56 NC Citation Data: Vehicle #9

Vehicle #9	
Actual Weight	Permitted Weight
Axle 1: 10,660	12,000
Axle Group 2-4: 44,980	60,000
Tandem Axle 5-6: 45,280	60,000
Axle Group 7-9: 70,400	60,000
Axle Group 10-12: 51,000	60,000
Gross Vehicle Weight: 258,300	242,000

[47] Source: NCDOT

Vehicle #10 was used in this study and is the truck identified as NC Citation 13-Axle Truck-Jeep-Trailer-Stinger 3/2011 in the report.

Table 57 NC Citation Data: Vehicle #9

Vehicle #10	
Actual Weight	Permitted Weight
Axle 1: 14,000	12,000
Axle Group 2-4: 55,300	60,000
Axle Group 5-7: 53,100	60,000
Axle Group 8-10: 55,800	60,000
Axle Group 11-13: 50,200	60,000
Gross Vehicle Weight: 228,400	252,000

Dimensions - Length: **137'0"** Width: **14'9"** Height: **15'9"** Trailer: **112'0"** Overhang - Front: **NONE** Rear: **NONE**

VEHICLE(S) MUST BE PROPERLY LICENSED FOR MAXIMUM WEIGHT ALLOWED BY LAW

GrossWeight: **252,000**

Axle:	1	2	3	4	5	6	7	8	9	10	11	12	13
Weight:	12000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000

Spacing: 16'2" 4'6" 4'6" 15'6" 4'6" 4'6" 48'0" 4'6" 4'6" 14'6" 4'6" 4'6"

From: **VIRGINIA LINE** To: **SOUTH CAROLINA LINE**

Permit does not authorize travel on routes beyond "From", point of origin or "To", destination specified.

Via Routes: **FROM THE VIRGINIA LINE ON US258 S TO MURFREESBORO TO US158 W TO US158 BYP W TO US158 W TO ROANOKE RAPIDS TO NC125 S TO NC48 S TO NC4/NC48 S TO NASH CO SR1500 SOUTH WEST TO SR1003 S TO RED OAK TO NC43 E TO I-95 SOUTH TO EXIT-107 AT KENLY TO US301 S TO HARNETT CO SR1712/HOBSON RD TO SR1802/LANE RD TO SR1808/CAROLINA DR TO US301 S TO CUMBERLAND CO SR1933/PEMBROKE RD NORTH EAST TO US13 S TO I-295 TO I-95 S TO EXIT 22 *RAMP BRIDGE AT THE JCT OF I-95 AND US301/SR1997 TO I-95 SOUTH TO EXIT 2 TO NC130 TO NC904 TO NC41 TO THE SOUTH CAROLINA LINE.**

***BRIDGE RESTRICTION: DRIVE AT CENTERLINE OF ROADWAY AND REDUCE SPEEDTO 30 MPH OR LESS ON JOHNSTON COUNTY BRIDGE #90 ON US301 OVER LITTLE RIVER LOCATED 0.7 MI N JCT SR2339, BRIDGE #70 ON US301 OVER NEUSE RIVER LOCATED 0.25 MI N JCT SR1343, BRIDGE #56 ON US301 OVER HOLTS LAKE(BLACK CREEK) LOCATED 0.7 MI N JCT US701, AND CUMBERLAND COUNTY BRIDGE #303 ON SR1933 OVER I-95 LOCATED .3 MI. S. JCT. US13.**

The route from a specific origin to a specific destination must be included within a single permitted route of travel.

Figure 162 Permit Excerpt Corresponding to NC Citation Data Vehicle #8.[48]

A.1.3 GDOT Data

On the following pages are the sample truck schematic and data table as provided by GDOT for the seven configuration 1 trucks used in this study.

[48] Source: NCDOT

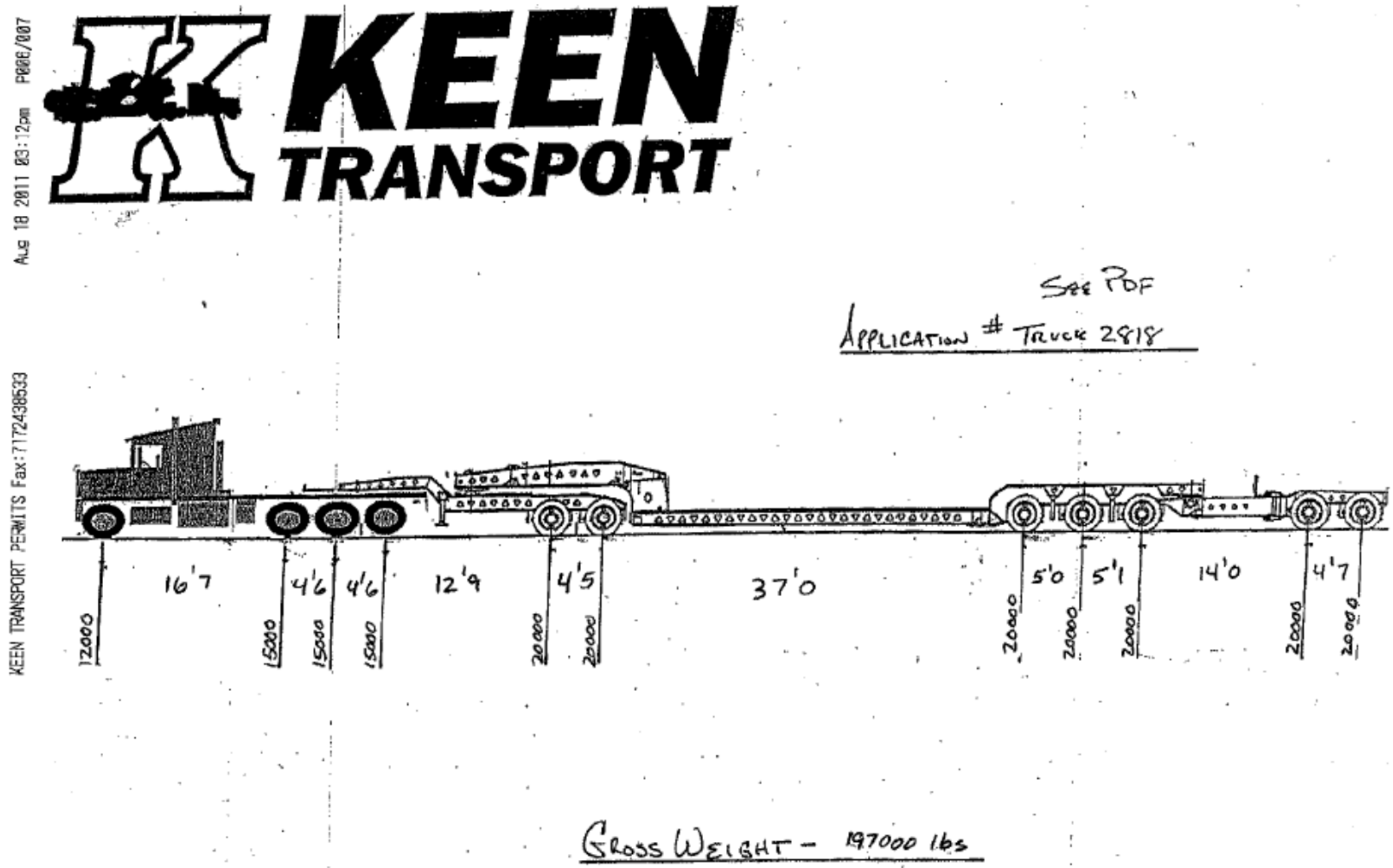


Figure 163 Sample Truck Schematic.[49]

[49] Source: GDOT

Table 58 Georgia DOT Permit and Measured Data for Superload Trucks

	Truck 1			Truck 2			Truck 3		
Axle	Permit	Measured	Spacing	Permit	Measured	Spacing	Permit	Measured	Spacing
1	18,000	15,580	17.00	17,000	16,260	17.00	18,000	15,780	14.00
2	20,000	19,700	4.50	20,000	19,580	4.50	20,000	15,760	4.50
3	20,000	19,040	16.33	20,000	19,360	16.33	20,000	13,100	4.50
4	20,000	17,460	4.58	19,000	18,300	4.58	20,000	12,880	16.33
5	20,000	17,960	4.58	19,000	18,380	4.58	20,000	21,400	4.50
6	20,000	17,860	39.00	19,000	18,460	39.00	20,000	21,500	38.58
7	20,000	19,720	4.58	20,000	19,480	4.58	20,000	16,260	4.50
8	20,000	19,320	4.58	20,000	18,900	4.58	20,000	18,260	4.50
9	20,000	19,480	14.17	20,000	19,780	14.17	20,000	16,180	14.00
10	20,000	21,220	4.50	20,500	20,840	4.50	20,000	17,000	4.50
11	20,000	19,320	-	20,500	19,600	-	20,000	17,980	-
12	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-
Total	218,000	206,660	-	215,000	208,940	-	218,000	186,100	-

Table 59 Georgia DOT Permit and Measured Data for Superload Trucks (Cont.)

	Truck 4			Truck 5			Truck 6			Truck 7		
Axle	Permit	Measured	Spacing	Permit	Measured	Spacing	Permit	Measured	Spacing	Permit	Measured	Spacing
1	18,000	14,720	14.17	17,000	15,600	14.50	18,000	14,540	14.42	12,000	12,220	16.67
2	19,000	12,160	4.58	19,333	12,160	4.58	20,000	14,820	4.58	17,000	13,380	4.50
3	19,000	17,340	4.58	19,333	15,460	4.50	20,000	18,580	4.85	17,000	14,360	4.50
4	19,000	17,200	15.33	19,334	14,780	15.50	20,000	18,680	15.34	17,000	14,200	13.17
5	19,000	14,520	5.00	19,333	19,760	4.50	20,000	16,520	5.00	21,000	19,780	4.50
6	19,000	14,520	5.00	19,333	19,080	4.50	20,000	16,540	5.00	21,000	19,880	37.17
7	19,000	14,980	39.67	19,334	18,100	39.00	20,000	16,400	39.34	18,000	17,380	5.00
8	19,000	16,560	5.00	19,333	19,060	4.50	20,000	19,840	5.00	18,000	17,400	5.00
9	19,000	16,260	5.00	19,333	19,260	4.50	20,000	19,720	5.00	18,000	18,580	14.17
10	19,000	16,180	14.50	19,334	18,800	14.33	20,000	19,880	14.08	20,000	17,500	4.50
11	19,000	16,300	5.00	19,500	19,340	4.50	20,000	20,500	5.00	20,000	16,740	-
12	19,000	16,620	5.00	19,500	19,440	-	20,000	20,920	5.00	-	-	-
13	19,000	15,660	-	-	-	-	20,000	17,920	-	-	-	-
Total	246,000	203,020	-	230,000	210,840	-	258,000	234,860	-	199,000	181,420	-

A.2 Configuration 2

A.2.1 NC Citation

Included on the following pages are excerpts from the NC citation for the configuration 2 tr
supplied by the NC SHP, along with excerpts from the permit supplied by the NCDOT.

Over Axle Weight					
Begin Axle	End Axle	Shifted	Scale Weight	Less Permissible Weight	Total Overweight
1	1		12100	20000	0
2	4		47000		0
5	5		41100	19000	22100
6	6		41100	19000	22100
7	7		37800	19000	18800
8	8		37800	19000	18800
9	9		37150	19000	18150
10	10		37150	19000	18150
11	16		226000		0
17	17		12700	20000	0
18	19		28300		0

Over Axle Group Weight						
Begin Axle	End Axle	Feet	Scale Weight	Less Permissible Weight	Total Over Weight	Penalty for Axle Group
1	19	231	558200	80000	478200	$2,516.16
2	19	215	546100	80000	466100	$2,452.04
5	19	184	499100	80000	419100	$2,202.96
2	16	175	505100	80000	425100	$2,234.78

Comment

on today?s date around 0735 I met with the driver of the truck at the i-26 welcome center in Polk county to escort them to the Tennessee line. I checked the permit and verified it with the truck hooked to the trailer. the vin # did not match. I asked the driver why the vin didn?t match and he stated that the truck on the permit broke down yesterday in sc near hwy 11. they towed the truck and sent another truck to pick up the load to move it to nc. he stated that the repair shop said it would be 10 to 12 hours to fix the truck. he called his boss and he said to hook up with the other truck and get it to nc. he pulled it into the welcome center and waited to til a.m. to meet with me. When I arrived no one said anything about the trucks. It wasn?t until I compared the truck with the permit and asked them what happened was it mentioned. The driver stated that he tried to tell his boss and that he was just doing what he was told. He stated that the boss man told him to stay hooked up and be ready for this morning. The driver stated that had he unhooked and lied about how he had gotten there that no one would have known that he traveled into NC with the wrong truck. I spoke to Fsgt Fairchild and he advised that we would move it from the rest area to allow better access to the public and escort it to the weigh station for safety and it would remain there until the company could obtain a new permit. Due to the size of the load we moved it to the Asheville West Bound weigh station off the highway for safety and because it was currently down for repairs, the load could stay there without affecting any other operations. Myself and trp Franklin (g950) weighed the super load with portable scales in the Asheville wb weigh station. The front axle on the truck were weighed simultaneously, the tri axle on the truck was weighed right side first then left side. The trailer had tandem axles that were spaced from 13'10" to 21'3" apart. They were weighed both sides at a time. At the rear was another tractor attached to the trailer to assist in pushing the trailer. The front axle on it ,#17, was weighed alone. The truck had a tri axle on the rear but the #2 axle was raised so axles #18 and 19 were weighed simultaneously. I began entering the information on the ENF-001 and was not able to add all the axle weights past axle #10. I have included the axle weights for the remaining axles in the notes. axle #11= 37900, axle #12= 37900, axle #13= 37700, axle #14=37700, axle #15=37400, #16=37400.

Figure 164 Excerpts from NC Citation for Configuration 2 Truck.[50]

[50] Source: NC SHP

Dimensions - Length: **236'0"** Width: **18'0"** Height: **15'2"** Trailer: **199'0"** Overhang - Front: **NONE** Rear: **NONE**

VEHICLE(S) MUST BE PROPERLY LICENSED FOR MAXIMUM WEIGHT ALLOWED BY LAW

GrossWeight: **607,000**

Axle: **1 2 3 4 5 6 7 8 9 10 11 12 13 14 15**

Weight: **15000 20000 20000 20000 40000 40000 40000 40000 40000 40000 40000 40000 40000 40000 40000**

Spacing: **16'2" 4'6" 4'6" 21'3" 5'9" 16'1" 5'9" 14'0" 5'9" 50'0" 5'9" 16'1" 5'9" 14'0" 5'9"**

Axle: **16 17 18 19**

Weight: **40000 12000 20000 20000**

Spacing: **13'10" 19'7" 4'6"**

From: **SOUTH CAROLINA LINE** To: **TENNESSEE LINE**

Permit does not authorize travel on routes beyond "From", point of origin or "To", destination specified.

Via Routes: **I-26 WEST FROM THE SC LINE TO I-40 WEST TO THE TN LINE.**

STATE HIGHWAY PATROL ESCORT IS REQUIRED THE ENTIRE ROUTE
MOVEMENT IS AURTHORIZED FROM SUNRISE TO 12(NOON) SATURDAY OR SUNDAY ONLY
TRUNNION AXLES MUST BE EXTENDED TO 18' WIDE DURING THE ENTIRE ROUTE OF TRAVEL
***BRIDGE RESTRICTIONS:**
ONLY VEHICLE ON BRIDGE WHILE CROSSING HENDERSON COUNTY BRIDGE #108 ON I-26 OVER GREEN RIVER LOCATED 1.7 MI. E. JCT. US25.
ONLY VEHICLE ON BRIDGE IN DIRECTION OF TRAVEL WHILE CROSSING WITH A SPEED LESS THAN 20 MPH.

The route from a specific origin to a specific destination must be included within a single permitted route of travel.

Figure 165 Excerpt from Permit Corresponding to NC Citation for Configuration 2 Truck.[51]

[51] Source: NCDOT

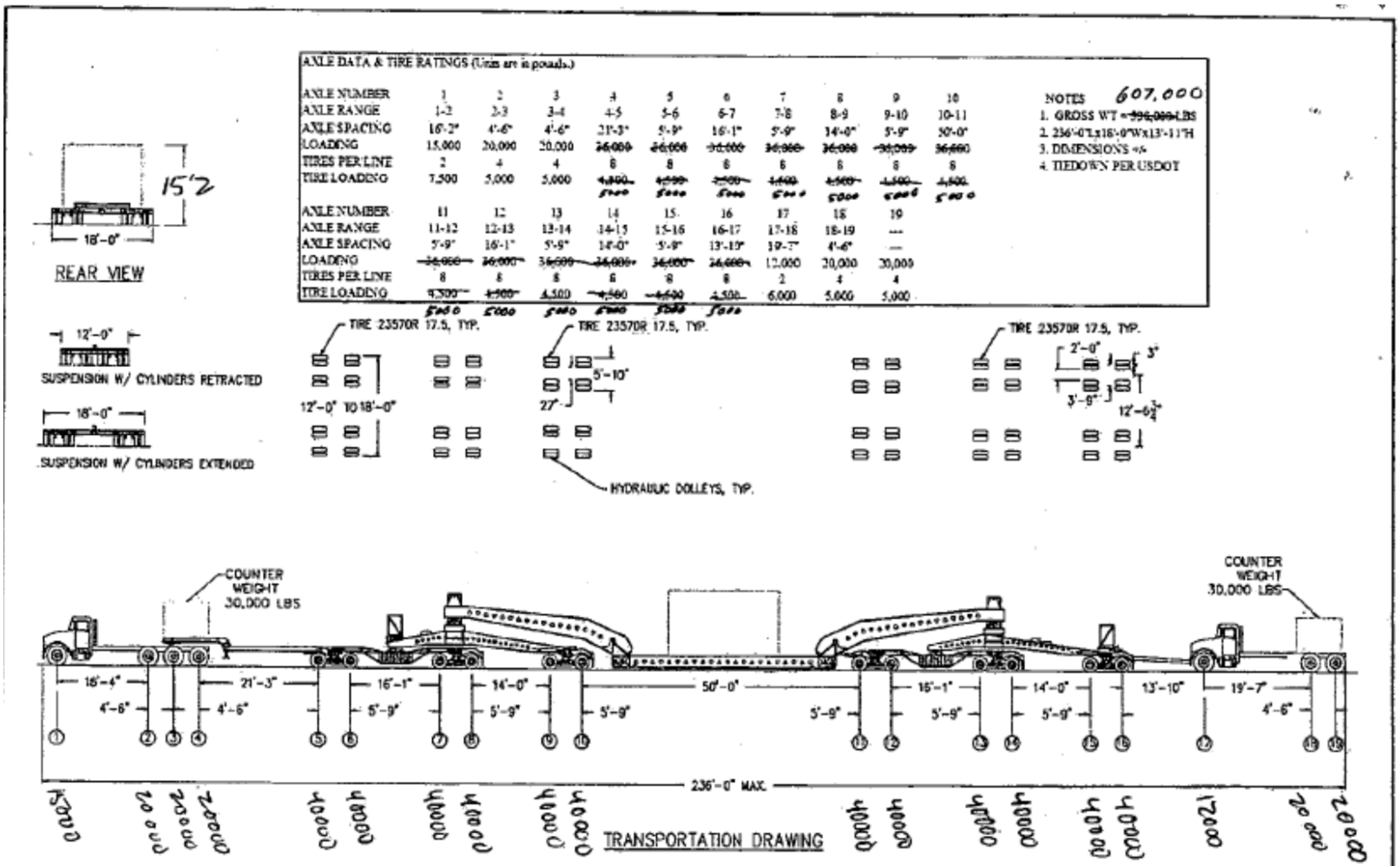


Figure 166 Excerpt from Truck Schematic Corresponding to NC Citation for Configuration 2 Truck.[52]

[52] Source: NCDOT

A.2.2 GDOT Port of Savannah Permits

Included on the following pages are excerpts from the GDOT permits for configuration 2 trucks originating at the Port of Savannah use in this study.

Oversize Permit Unit

GEORGIA SINGLE TRIP PERMIT # K0455281

The issuance of this permit authorizes the movement of the vehicle or load below pursuant to authority contained in the Georgia Code of Public Transportation, Chapter 32-6, as amended, and the Regulations set forth by the State Transportation Board.
For information, call 1 (888) 262-8306.

PERMIT INFORMATION

Issued to: **GUY M TURNER INC - DOT# 223397**
4514 South Holden Road
GREENSBORO, NC 27407

Account No: **10254**
Valid: **05/03/11 to 05/13/11**
DOT #: **223397**

Load Description: **OTHER - PRESS**

Tractor Make: **PETERBILT** License: **LY8495(NC)** Trailer License: **L819844(NC)**

Overall Dimensions: Width: **14'9"** Height: **14'3"** Length: **188'0"**

Gross Weight: **366,200** on **19** axles

Axles:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Weight:	11600	15600	22400	22100	20400	20300	19900	20000	20300	19800	18300	19800	19800	19300	19300
Spacing:	16'5"	4'5"	4'6"	15'1"	5'0"	5'0"	14'2"	5'0"	5'1"	48'8"	5'0"	5'0"	14'2"	4'11"	5'2"
Tape From Rear:	5'2"	10'2"	24'2"	29'4"	34'3"	48'5"	53'5"	58'5"	107'1"	112'2"	117'2"	131'4"	136'4"	141'4"	156'5"

Axles:	16	17	18	19
Weight:	18700	20000	19400	19200
Spacing:	14'0"	5'0"	5'2"	
Tape From Rear:	160'11"	165'4"	181'9"	

Origin: **SAVANNAH** Destination: **AL LINE**

Route of **RIVER ST, E LATHROP AVE, BAY ST, US-80 W, CHATHAM PKWY S, I-16 W, USE EXIT #111 RAMPS AT INT OF I-16 AND CR-49 TO BYP BRIDGE, I-16, GA-26 N (EX #39), US-80 W, GA-358 S, GA-96 S, GA-87 N/US-23/US-129 ALT, GA-19 W/US-80 W, I-16 W, I-75 N, USE EXIT #169 RAMPS AT THE INT OF I-75 AND CR-85 TO BYP LOAD RESTRICTED BRIDGE, I-75 N, I-285 W BYPASS, I-85 S, GA-154 S (EX #51), GA-34 W, I-85 S, USE EXIT #18 RAMPS AT THE INT OF I-85 AND GA-109 TO BYP LOAD RESTRICTED BRIDGE, I-85 S.**

BEG: OCEAN TERMINAL

Figure 167 Excerpt GA Permit #K0455281.[53]

[53] Source: GDOT

Turner Kia Superload

Total Width= 14' 09"
Total Length= 188' 02"
Height= 14'03"

Please Note: measurements start at the rear of the load (push Truck).

AXLE #	AXLE SPACING	WEIGHT RIGHT SIDE (EACH AXLE)	WEIGHT LEFT SIDE (EACH AXLE)
1 – 19	181'09"	11,600	Tractor-Single Axle
2 - 19	165'04"	15,600	Tractor-Single Axle
3 - 19	160'11"	22,400	Tractor-Single Axle
4 - 19	156'05"	22,100	Tractor-Single Axle
5- 19	141'04"	20,400	Trailer-Single Axle
6- 19	136'04"	20,300	Trailer-Single Axle
7- 19	131'04"	19,900	Trailer-Single Axle
8- 19	117'02"	20,000	Trailer-Single Axle
9- 19	112'02"	20,300	Trailer-Single Axle
10-19	107'01"	19,800	Trailer-Single Axle
11-19	58'05'	18,300	Trailer-Single Axle
12-19	53'05"	19,800	Trailer-Single Axle
13-19	48'05"	19,800	Trailer-Single Axle
14-19	34'03"	19,300	Trailer-Single Axle
15-19	29'04"	19,300	Trailer-Single Axle
16-19	24'02"	18,700	Trailer-Single Axle
17-19	10'02"	20,000	Trailer-Single Axle
18-19	05'02"	19,400	Trailer-Single Axle
19-19	00'00"	19,200	Trailer-Single Axle

Gross Weight = 366,200 lbs.

Figure 168 Excerpt GA Permit #K0455281 (Cont).[54]

[54] Source: GDOT

Oversize Permit Unit

GEORGIA SINGLE TRIP PERMIT # K0382781

The Issuance of this permit authorizes the movement of the vehicle or load below pursuant to authority contained in the Georgia Code of Public Transportation, Chapter 32-6, as amended, and the Regulations set forth by the State Transportation Board.
For information, call 1 (888) 262-8306.

PERMIT INFORMATION

Issued to: **GUY M TURNER INC - DOT# 223397**
4514 South Holden Road
GREENSBORO, NC 27407

Account No: **10166**
Valid: **04/14/11 to 04/25/11**
DOT #: **223397**

Load Description: **OTHER - PRESS**

Tractor Make: **PETERBILT** License: **LZ2536(NC)** Trailer License: **L820357(NC)**

Overall Dimensions: Width: **18'0"** Height: **14'3"** Length: **252'0"**

Gross Weight: **631,000** on **30** axles

Origin: **SAVANNAH** Destination: **WEST POINT**

Route of **RIVER ST, E LATHROP AVE, BAY ST, US-80 W, CHATHAM PKWY S, I-16 W, US-280 E (EX #143), US-80 W/GA-26, GA-119 S, I-16 W, USE EXIT #111 RAMPS AT INT OF I-16 AND CR-49 TO BYP BRIDGE, I-16, GA-26 N (EX #39), US-80 W, GA-358 S, GA-96 S, GA-87 N/US-23/US-129 ALT, GA-19 W/US-80 W, I-16 W, I-75 N, I-285 W BYPASS, I-85 S, GA-154 S (EX #51), GA-34 W, I-85 S, GA-14 W/US-29 (EX #35), LONE OAK RD S/FORREST RD, GA-54 W, I-85 S, AT MP 21.80 (WILDWOOD RD) TRAVEL IN THE FAR LEFT LANES ONLY, I-85 S, USE EXIT #18 RAMPS AT THE INT OF I-85 AND GA-109 TO BYP LOW VERT CL, I-85 S, KIA BLVD (EX #6).**

BEG: OCEAN TERMINAL **END: 5500 WEBB RD**

AXLE WEIGHTS: (1) 11,600 (2) 12,900 (3) 17,300 (4) 17,200 (5) 22,200-R 22,800-L (6) 22,600-R 22,800-L (7) 20,400-R 21,300-L (8) 20,700-R 21,600-L (9) 21,200-R 21,000-L (10) 21,000-R 21,300-L (11) 21,300-R 21,800-L (12) 21,300-R 21,500-L (13) 21,100-R 22,300-L (14) 21,100-R 21,900-L (15) 21,800-R 22,400-L (16) 22,200-R 22,100-L (17) 13,000 (18) 17,300 (19) 16,700

AXLE SPGS: 16'-4", 4'-6", 4'-5", 21-3", 5'-9", 16'-0", 5'-9", 14'-0", 5'-9", 66'-3", 5'-10", 16'-1", 5'-9", 13'-11", 5'-9", 13'-6", 21'-0", 4'-6"

GROSS VEHICLE WEIGHT: 631,000 ON 30 AXLES

Figure 169 Excerpt GA Permit #K0382781.[55]

[55] Source: GDOT

Turner Kia Superload

Total Width= 18'
Total Length= 252'02"
Height= 14'03"

Please Note: measurements start at the rear of the load (push Truck).

AXLE #	AXLE SPACING	WEIGHT RIGHT SIDE (EACH AXLE)		WEIGHT LEFT SIDE (EACH AXLE)	
1 – 19	246'04"	11,600		Tractor-Single Axle	
2 - 19	230'	12,900		Tractor-Single Axle	
3 - 19	225'06"	17,300		Tractor-Single Axle	
4 - 19	221'01"	17,200		Tractor-Single Axle	
5- 19	199'10"	22,200		22,800	
6- 19	194'01"	22,600		22,800	
7- 19	178'01"	20,400		21,300	
8- 19	172'04"	20,700		21,600	
9- 19	158'04"	21,200		21,000	
10-19	152'07"	21,000		21,300	
11-19	86'04"	21,300		21,800	
12-19	80'06"	21,300		21,500	
13-19	64'05"	21,100		22,300	
14-19	58'08"	21,100		21,900	
15-19	44'09"	21,800		22,400	
16-19	39'00"	22,200		22,100	
17-19	25'06"	13,000		Tractor-Single Axle	
18-19	04'06"	17,300		Tractor-Single Axle	
19-19	00'00"	16,700		Tractor-Single Axle	

Gross Weight = 625,700 lbs.

Figure 170 Excerpt GA Permit #K0382781 (Cont).[56]

[56] Source: GDOT

Oversize Permit Unit

GEORGIA SINGLE TRIP PERMIT # K0383872

The issuance of this permit authorizes the movement of the vehicle or load below pursuant to authority contained in the Georgia Code of Public Transportation, Chapter 32-6, as amended, and the Regulations set forth by the State Transportation Board.
For information, call 1 (888) 262-8306.

PERMIT INFORMATION

Issued to: **MCTYRE TRUCKING CO INC - DOT# 203926**
P O Box 590147
ORLANDO, FL 32859

Account No: **99000**
Valid: **04/15/11** to **04/26/11**
DOT #: **203926**

Load Description: **OTHER - PRESS CROWN**

Tractor Make: **KENWORTH** License: **Z4662J(FL)** Trailer License: **3882CF(FL)**

Overall Dimensions: Width: **20'6"** Height: **15'9"** Length: **283'0"**

Gross Weight: **736,300** on **38** axles

Origin: **SAVANNAH** Destination: **WEST POINT**

Route of **RIVER ST, E LATHROP AVE, BAY ST, US-80 W, CHATHAM PKWY S, I-16 W, US-280 E (EX #143), US-80 W/GA-26, GA-119 S, I-16 W, USE EXIT #111 RAMPS AT INT OF I-16 AND CR-49 TO BYP BRIDGE, I-16, GA-26 N (EX #39), US-80 W, GA-358 S, GA-96 S, GA-87 N/US-23/US-129 ALT, GA-19 W/US-80 W, I-16 W, I-75 N, I-285 W BYPASS, I-85 S, GA-154 S (EX #51), GA-34 W, I-85 S, GA-14 W/US-29 (EX #35), LONE OAK RD S/FORREST RD, GA-54 W, I-85 S, USE EXIT #18 RAMPS AT THE INT OF I-85 AND GA-109 TO BYP LOAD RESTRICTED BRIDGE, I-85 S, KIA BLVD (EX #6).**

BEG: OCEAN TERMINAL **END: 5500 WEBB RD**

AXLE WEIGHTS: (1) 15,800 (2) 19,800 (3) 19,600 (4) 20,300-R 21,200-L (5) 20,000-R 20,000-L (6) 18,300-R 20,000-L (7) 18,700-R 21,000-L (8) 18,500-R 21,000-L (9) 18,500-R 20,700-L (10) 19,000-R 19,900-L (11) 18,700-R 20,100-L (12) 19,200-R 20,000-L (13) 19,400-R 19,900-L (14) 19,800-R 19,300-L (15) 19,800-R 19,600-L (16) 19,100-R 20,700-L (17) 19,000-R 20,400-L (18) 19,700-R 19,600-L (19) 19,400-R 19,500-L (20) 15,900 (21) 17,300 (22) 17,600

AXLE SPGS: 20-0", 4'-6", 20-11" 5'-10", 16-1", 5'-9", 14'-0", 5'-9", 16'-2", 5'-10", 51'-9", 5'-8", 16'-3", 5'-9", 14'-4", 5'-8", 16'-2", 5'-10", 12'-7", 20'-0", 4-7"

GROSS VEHICLE WEIGHT: 736,300 ON 38 AXLES

Figure 171 Excerpt GA Permit #K0383872.[57]

[57] Source: GDOT

McTyre Kia Superload

Total Width= 20'06"
Total Length=282'08"
Height= 15'09"

Please Note: measurements start at the rear of the load (push Truck).

AXLE #	AXLE SPACING	WEIGHT RIGHT SIDE (EACH AXLE)		WEIGHT LEFT SIDE (EACH AXLE)	
1 – 22	273'05"	15,800		Tractor-Single Axle	
2 – 22	253'05"	19,800		Tractor-Single Axle	
3 – 22	248'11"	19,600		Tractor-Single Axle	
4 – 22	228'00"	20,300		21,200	
5- 22	222'02"	20,000		20,000	
6- 22	206'01"	18,300		20,000	
7- 22	200'04"	18,700		21,000	
8- 22	186'04"	18,500		21,000	
9- 22	180'07"	18,500		20,700	
10-22	164'05"	19,000		19,900	
11-22	158'07"	18,700		20,100	
12-22	106'10"	19,200		20,000	
13-22	101'02"	19,400		19,900	
14-22	84'11"	19,800		19,300	
15-22	79'02"	19,800		19,600	
16-22	64'10"	19,100		20,700	
17-22	59'02"	19,000		20,400	
18-22	43'00"	19,700		19,600	
19-22	37'02"	19,400		19,500	
20-22	24'07"	15,900		Tractor-Single Axle	
21-22	04'07"	17,300		Tractor-Single Axle	
22-22	00'00"	17,600		Tractor-Single Axle	

Gross Weight = 736,300 lbs.

Figure 172 Excerpt GA Permit #K0383872 (Cont).[58]

[58] Source: GDOT

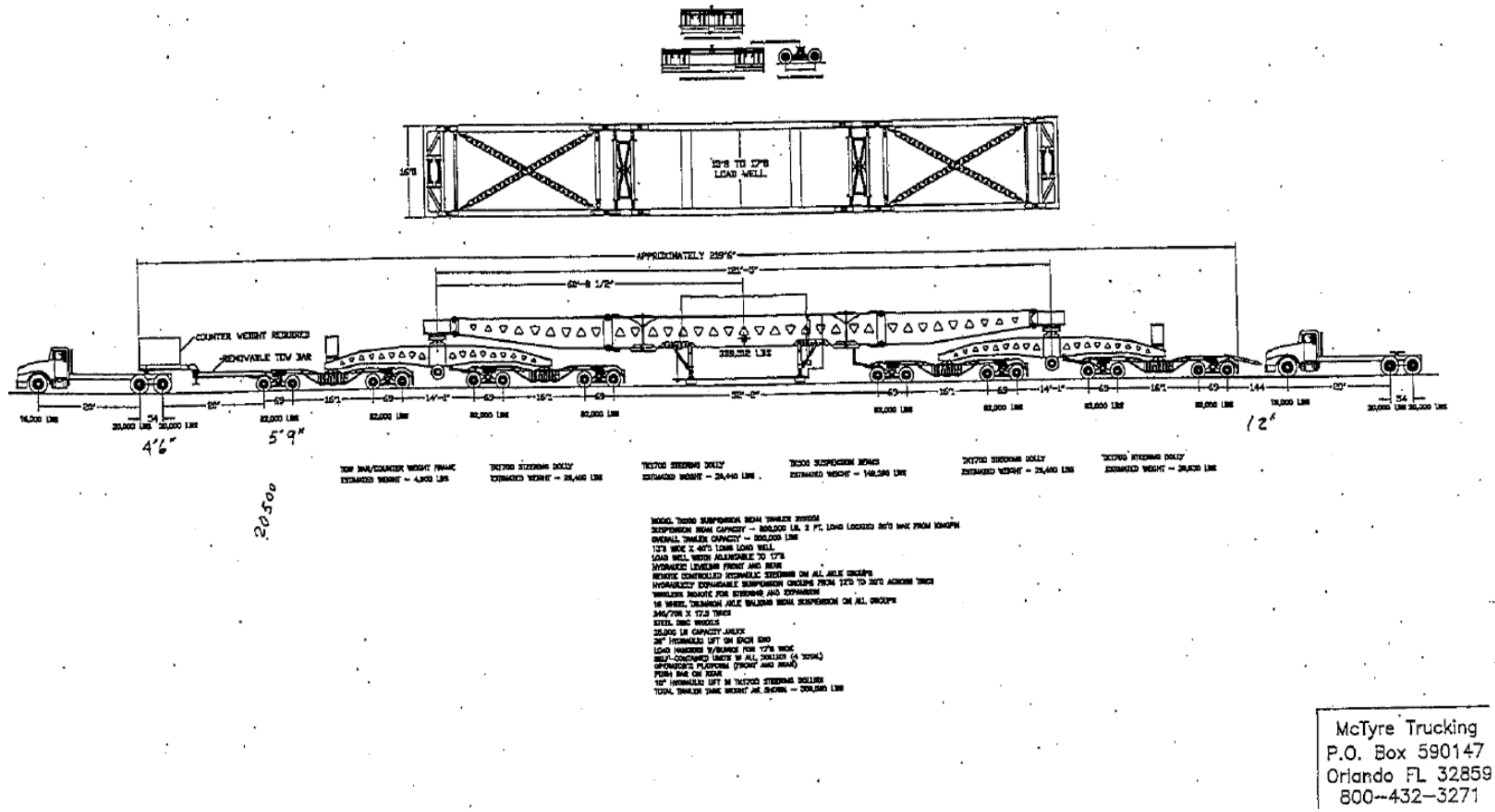


Figure 173 Truck Schematic Corresponding to GA Permit #K0383872.[59]

[59] Source: GDOT

APPENDIX B. CHAPTER 3

B.1 Maximum Moment Demand Graphs

B.1.1 <u>Results for One-Lane Simply Supported Bridges</u>

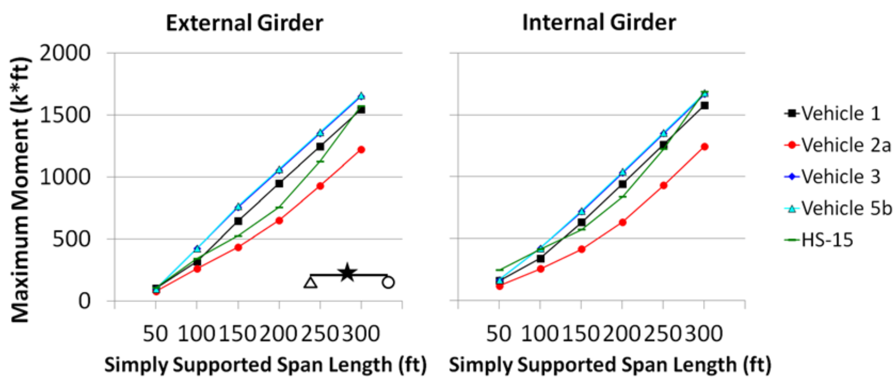


Figure 174 Moment Demands of One-Lane Bridges with Varying Span Lengths.

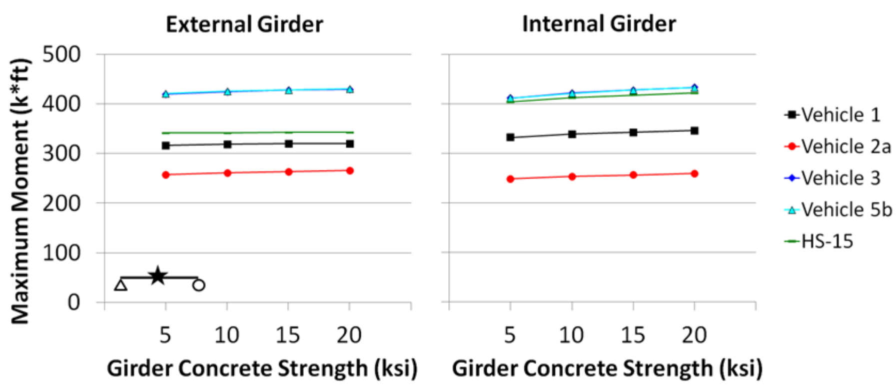


Figure 175 Moment Demands of One-Lane Bridges with Varying Girder Strengths.

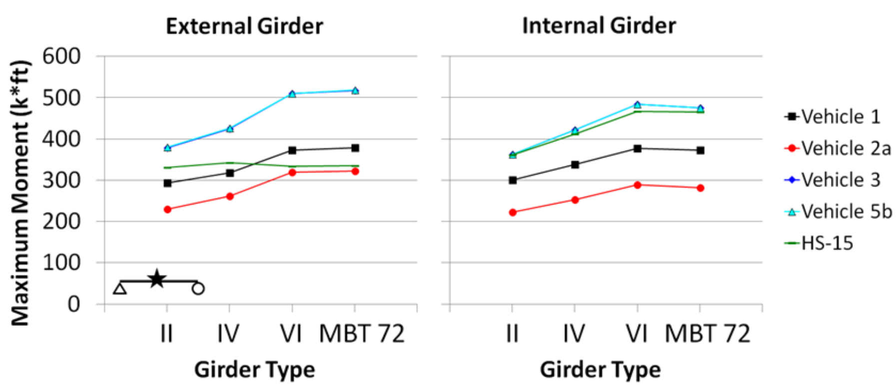


Figure 176 Moment Demands of One-Lane Bridges with Varying Girder Types.

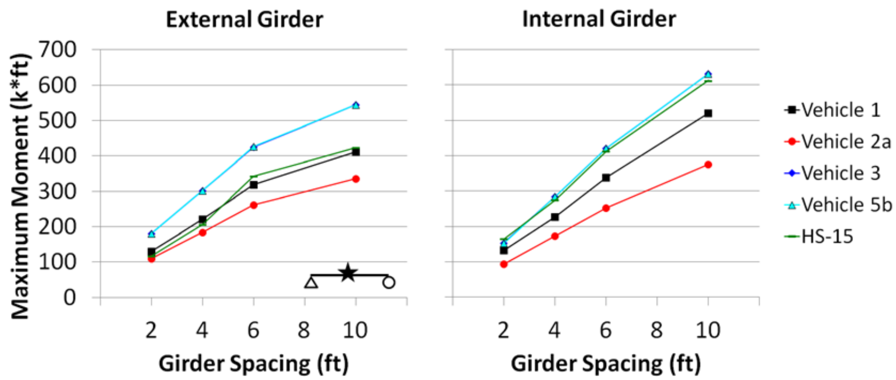


Figure 177 Moment Demands of One-Lane Bridges with Varying Girder Spacing.

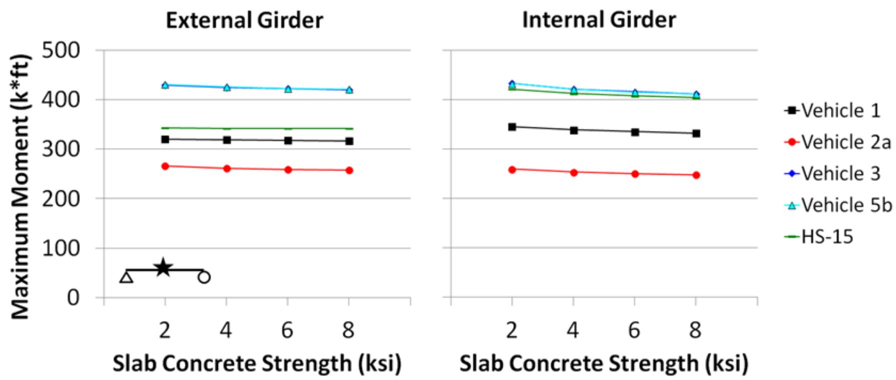


Figure 178 Moment Demands of One-Lane Bridges with Slab Concrete Strength.

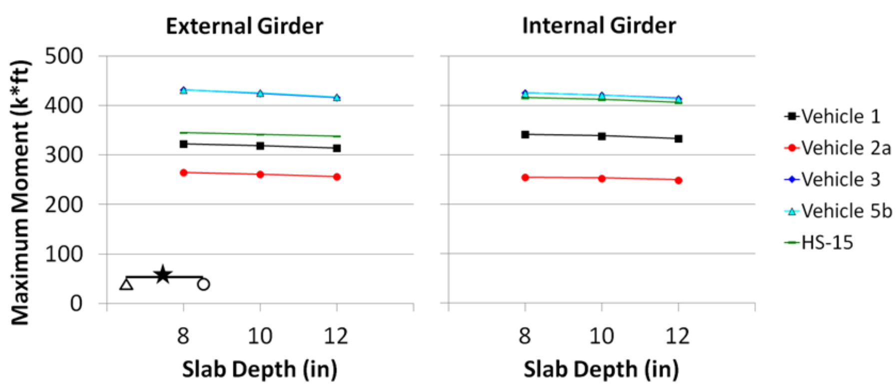


Figure 179 Moment Demands of One-Lane Bridges with Slab Depth.

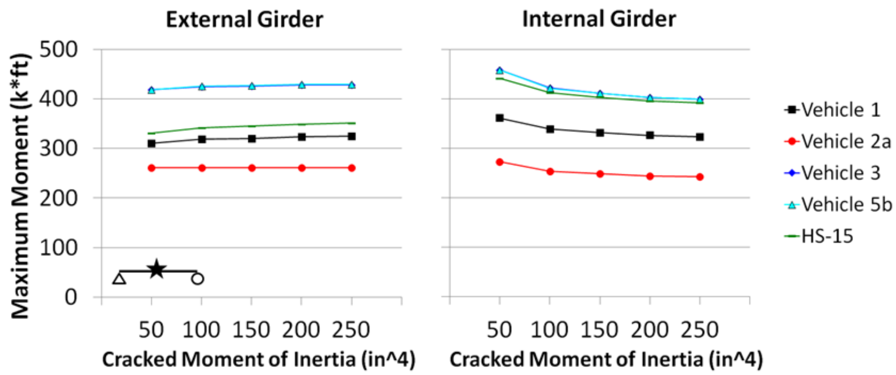


Figure 180 Moment Demands of One-Lane Bridges with Varying Cracked Moment of Inertia of Slab.

B.1.2 Results for Two-Lane Simply Supported Bridge

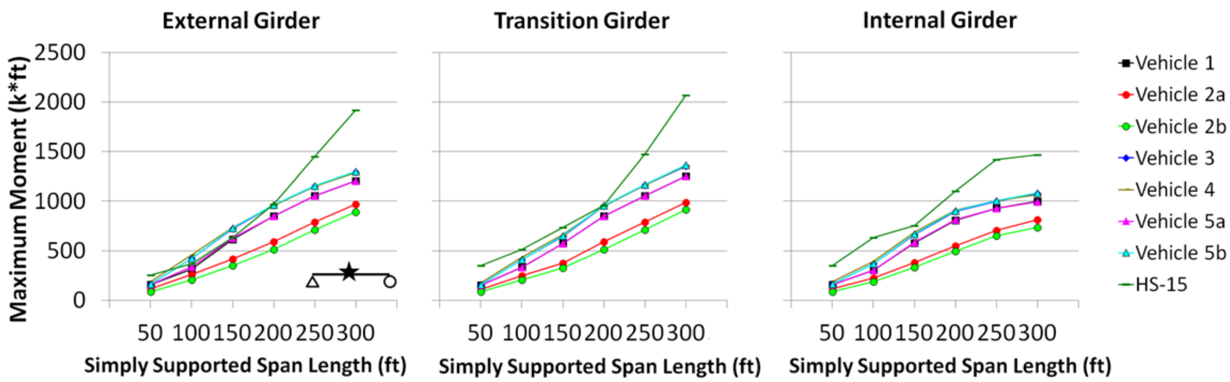


Figure 181 Moment Demands of Two-Lane Bridges with Varying Span Lengths.

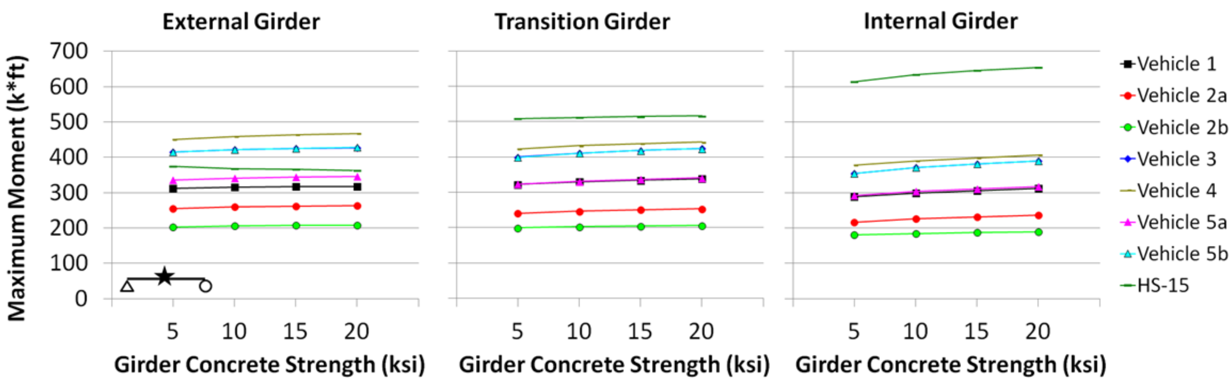


Figure 182 Moment Demands of Two-Lane Bridges with Varying Girder Strengths.

Figure 183 Moment Demands of Two-Lane Bridges with Varying Girder Types.

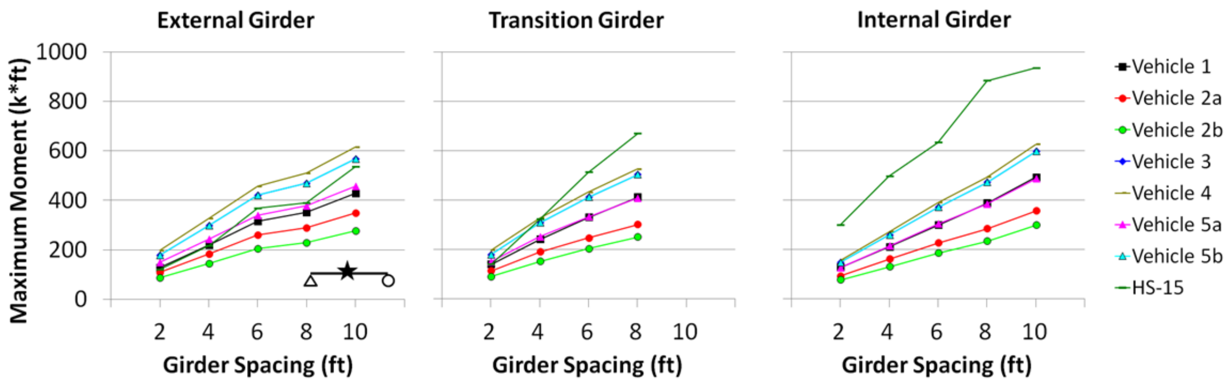


Figure 184 Moment Demands of Two-Lane Bridges with Varying Girder Spacing.

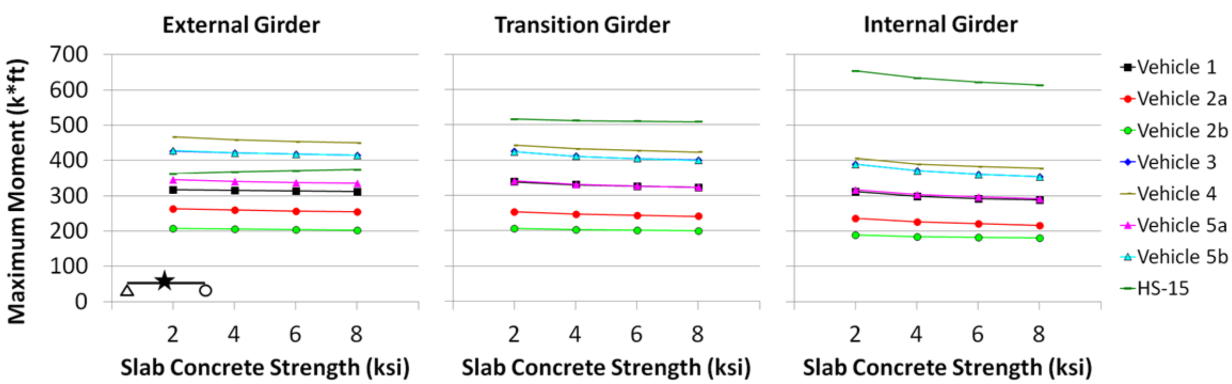


Figure 185 Moment Demands of Two-Lane Bridges with Varying Slab Strength.

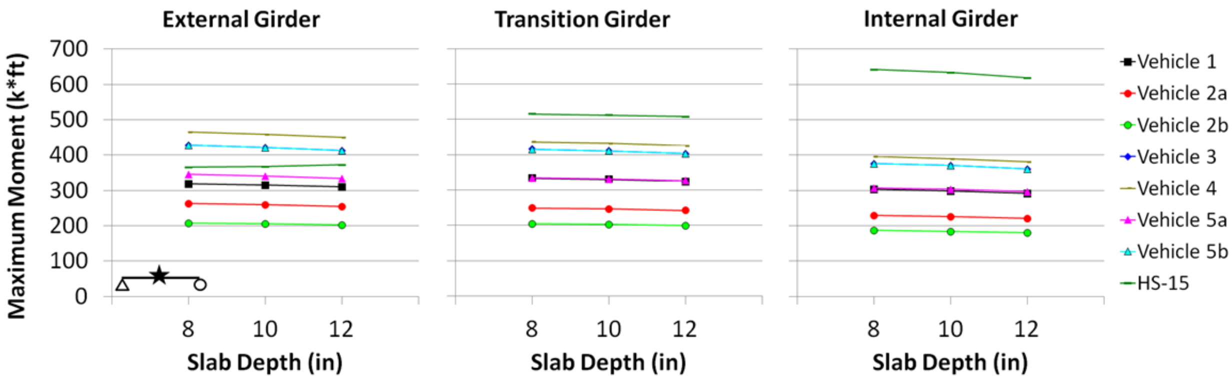


Figure 186 Moment Demands of Two-Lane Bridges with Varying Slab Depth.

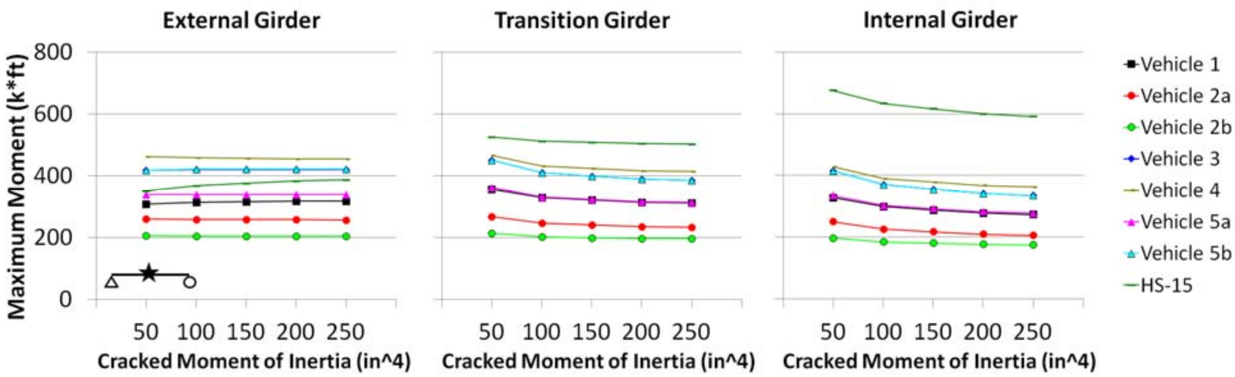


Figure 187 Moment Demands of Two-Lane Bridges with Varying Cracked Moment of Inertia of Slab.

B.1.3 Results for One-Lane Continuous Bridges

B.1.3.1 Four Span Bridges

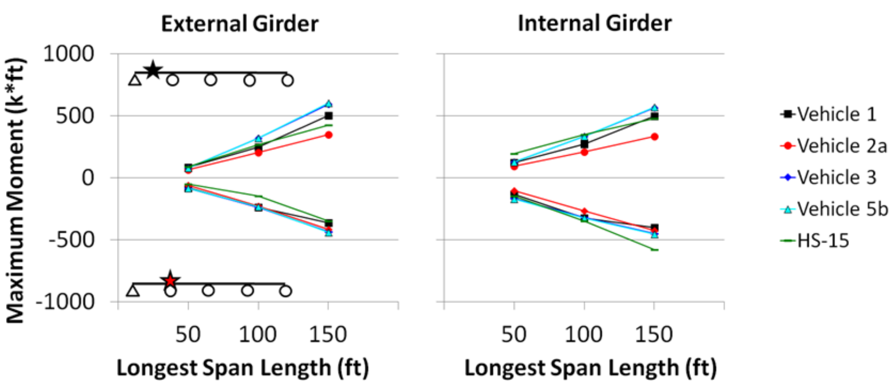


Figure 188 Moment Demands for One-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (1 of 2).

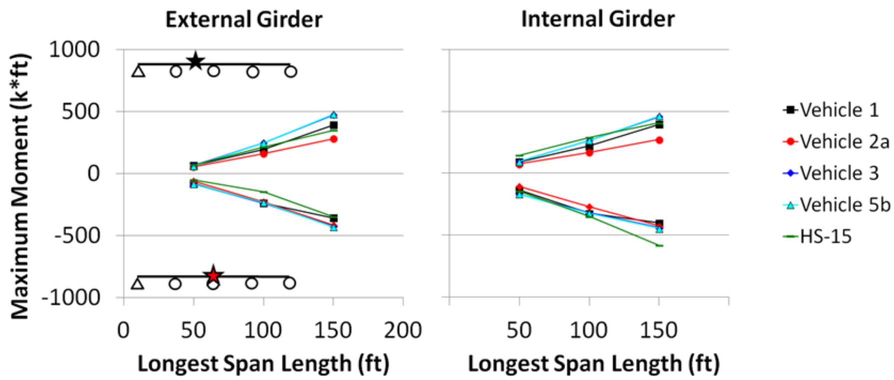


Figure 189 Moment Demands for One-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (2 of 2).

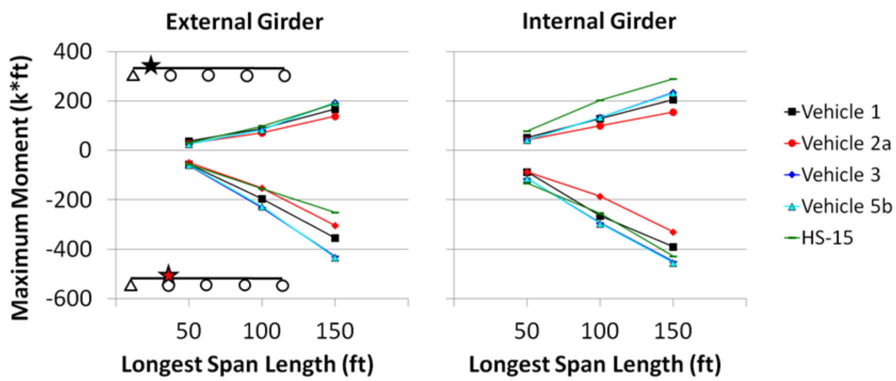


Figure 190 Moment Demands for One-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (1 of 2).

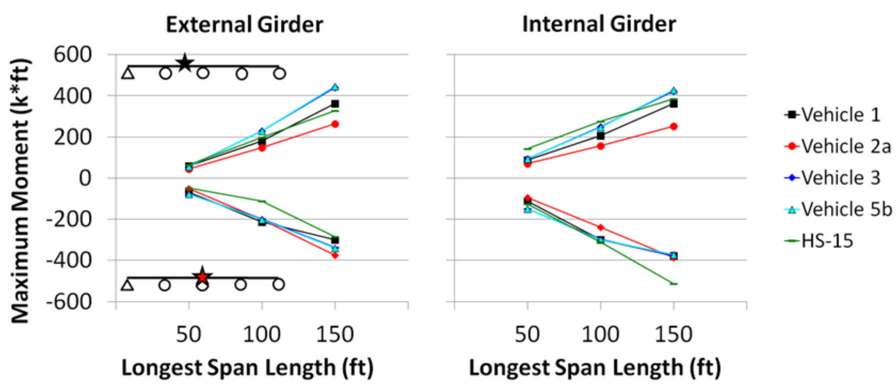


Figure 191 Moment Demands for One-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (2 of 2).

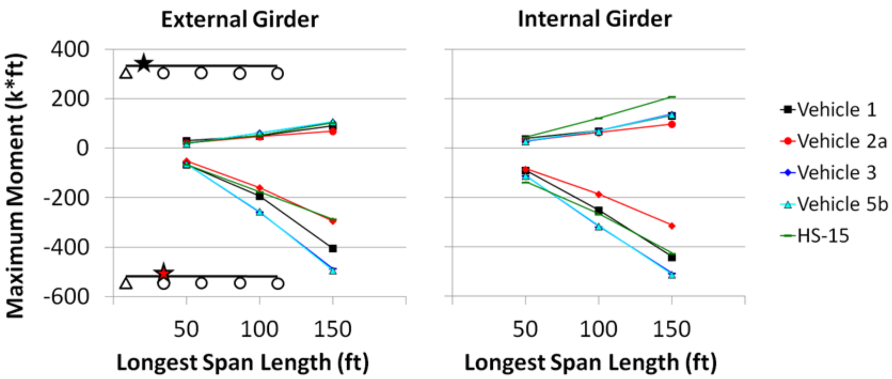


Figure 192 Moment Demands for One-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (1 of 2).

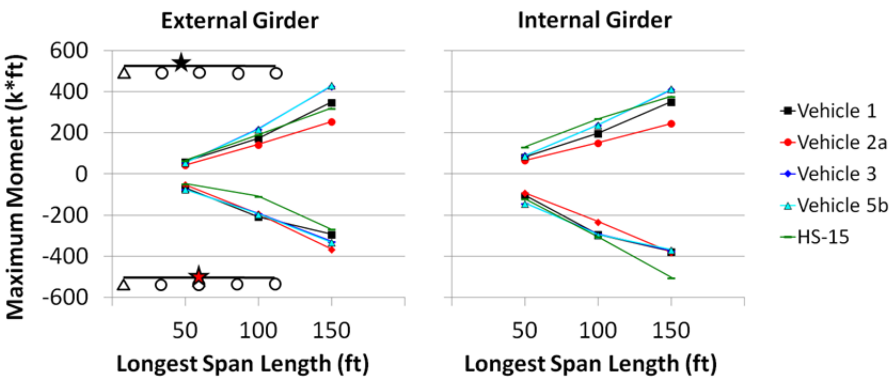


Figure 193 Moment Demands for One-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (2 of 2).

B.1.3.2 Three Span Bridges

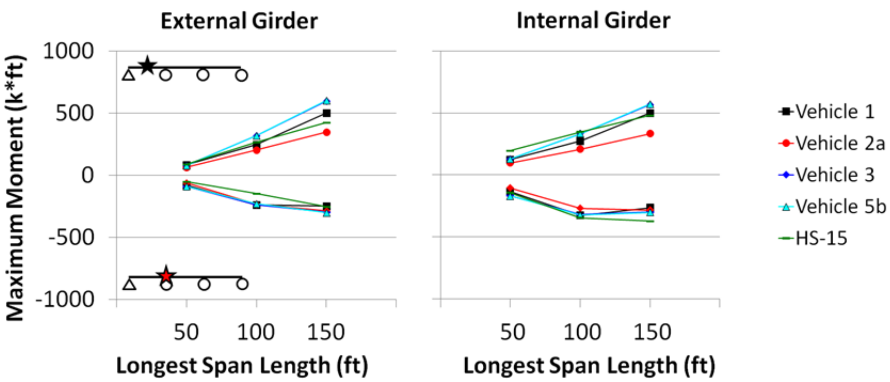


Figure 194 Moment Demands for One-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (1 of 2).

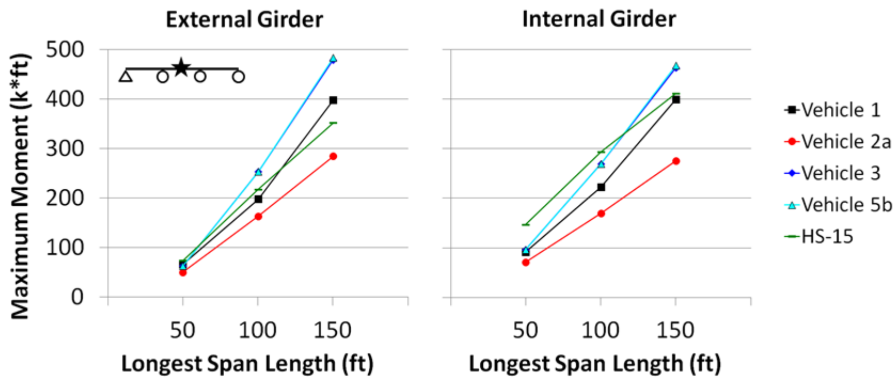


Figure 195 Moment Demands for One-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (2 of 2).

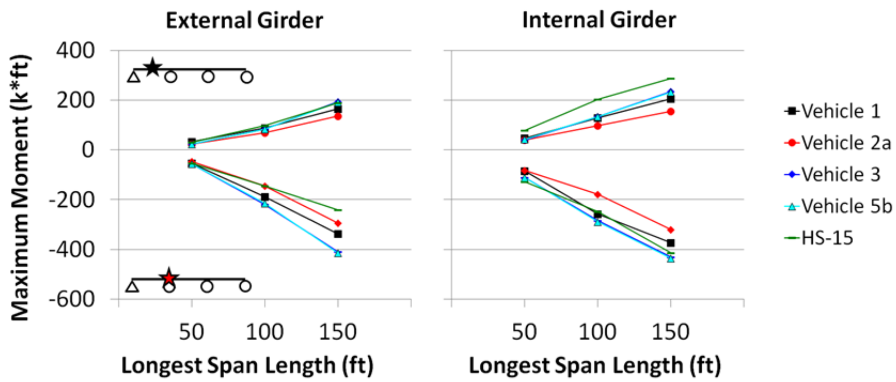


Figure 196 Moment Demands for One-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (1 of 2).

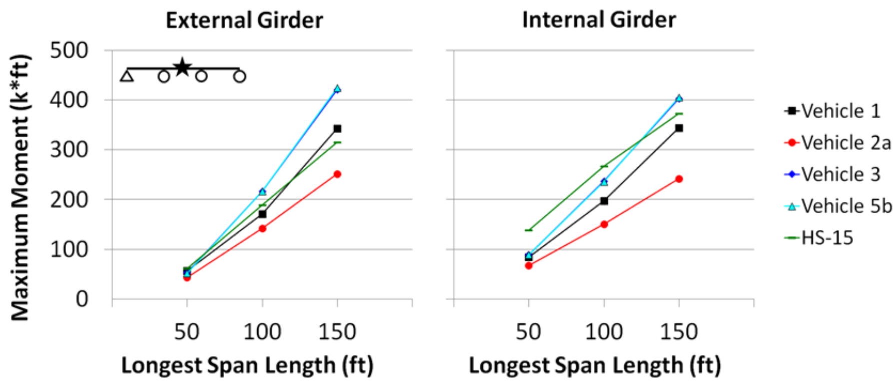


Figure 197 Moment Demands for One-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (2 of 2).

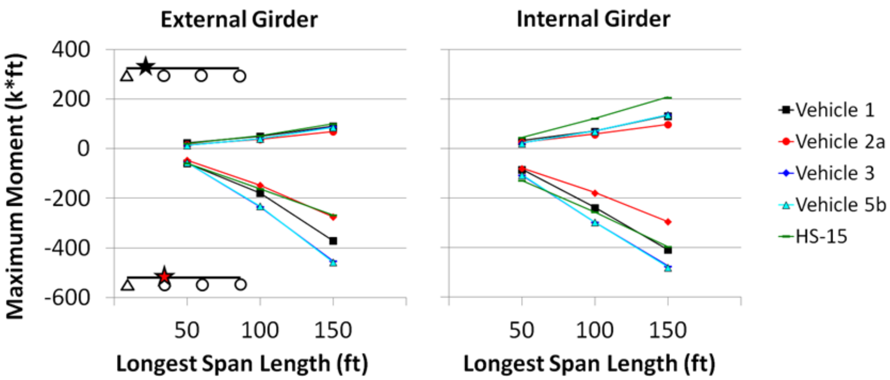


Figure 198 Moment Demands for One-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (1 of 2).

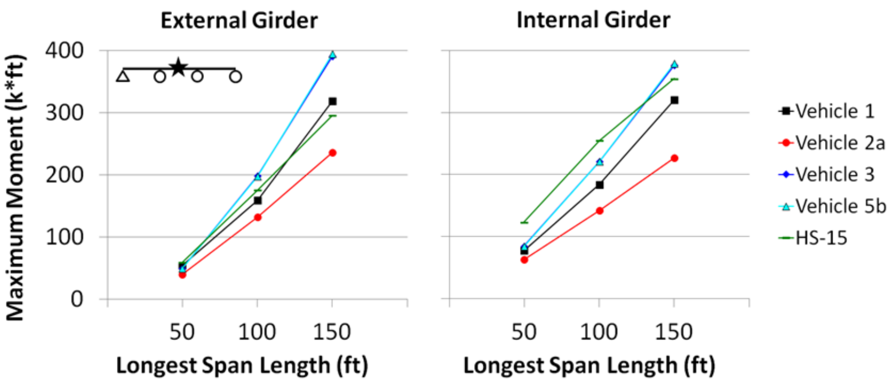


Figure 199 Moment Demands for One-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (2 of 2).

B.1.3.3 Two Span Bridges

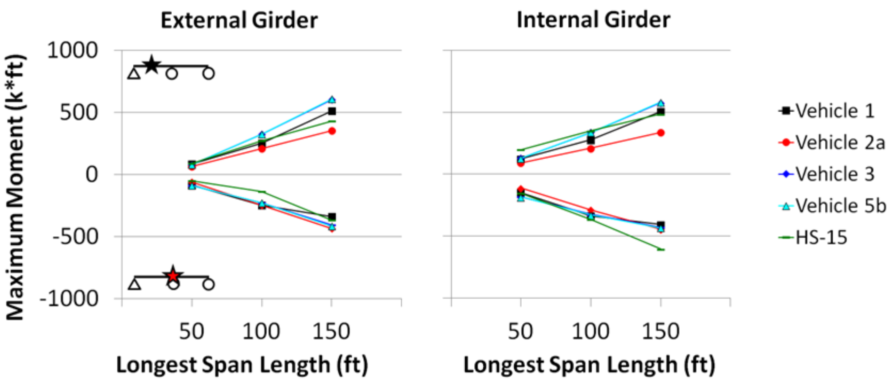


Figure 200 Moment Demands for One-Lane Bridges with an SLR of 1:1 and Varied Span Lengths.

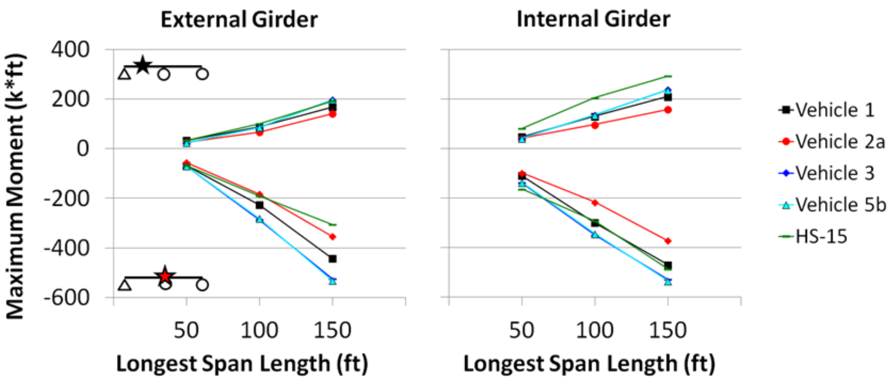


Figure 201 Moment Demands for One-Lane Bridges with an SLR of 1:2 and Varied Span Lengths.

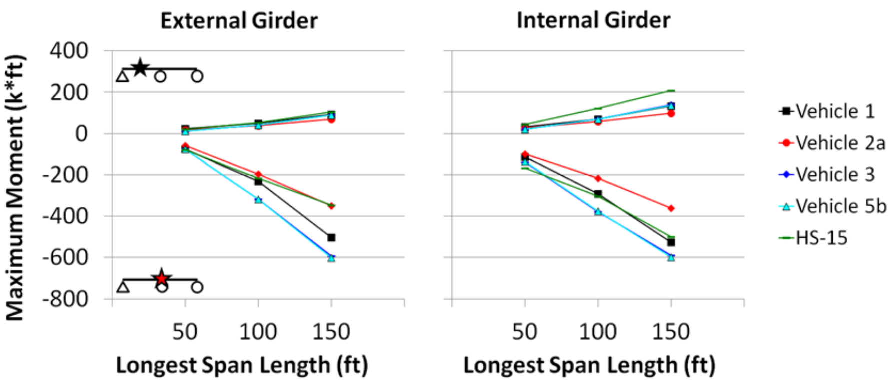


Figure 202 Moment Demands for One-Lane Bridges with an SLR of 1:3 and Varied Span Lengths.

B.1.4 <u>Results for Two-Lane Continuous Bridges</u>

B.1.4.1 Four Span Bridges

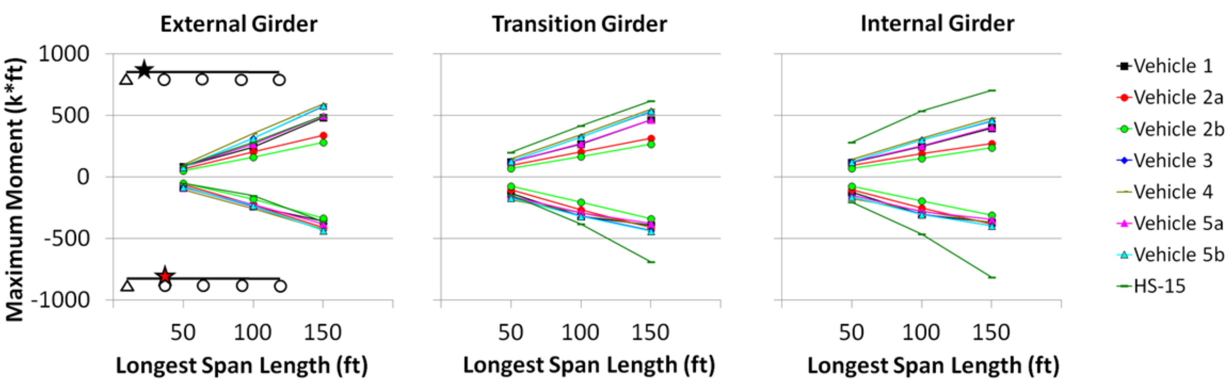


Figure 203 Moment Demands for Two-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (1 of 2).

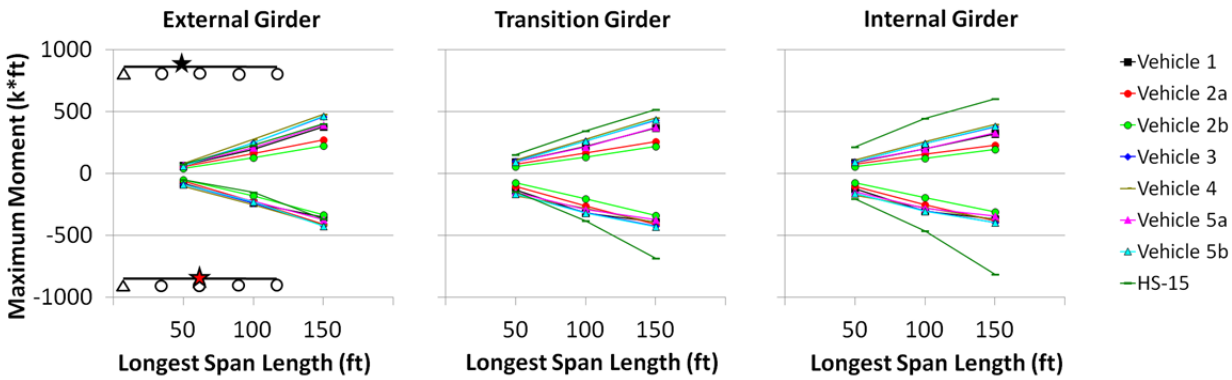


Figure 204 Moment Demands for Two-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (2 of 2).

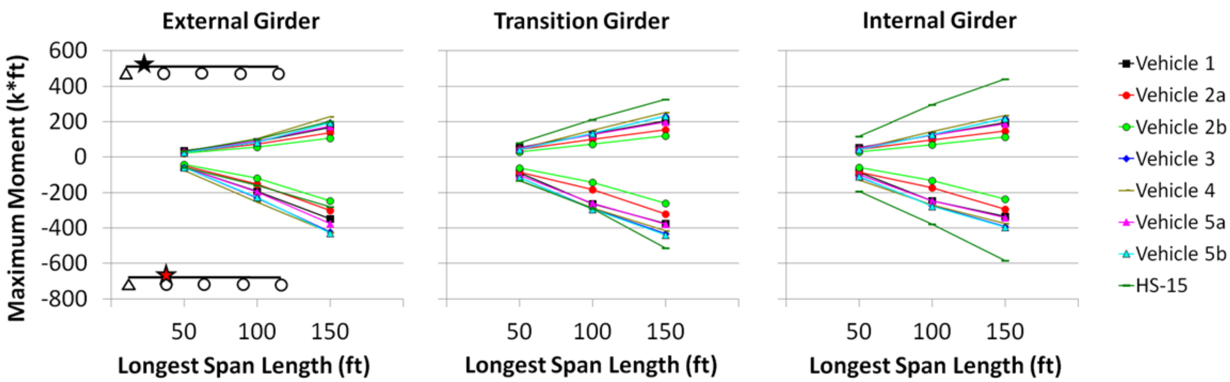


Figure 205 Moment Demands for Two-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (1 of 2).

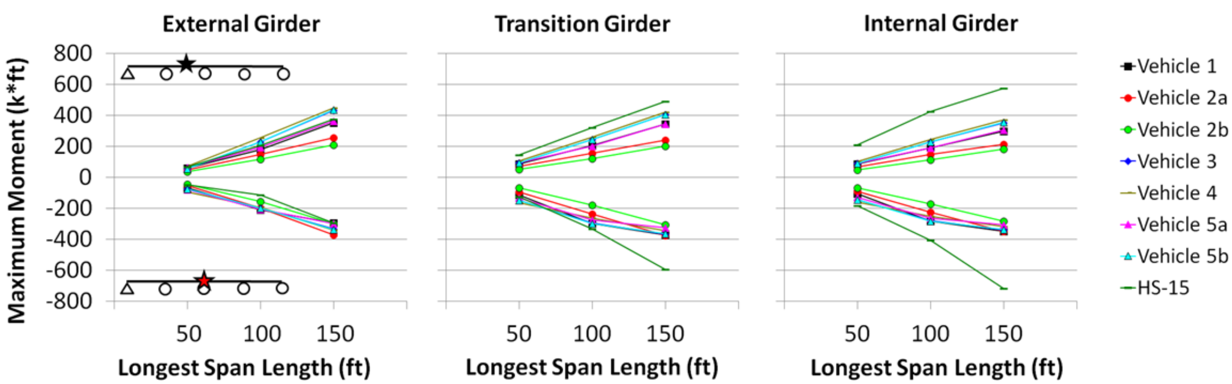


Figure 206 Moment Demands for Two-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (2 of 2).

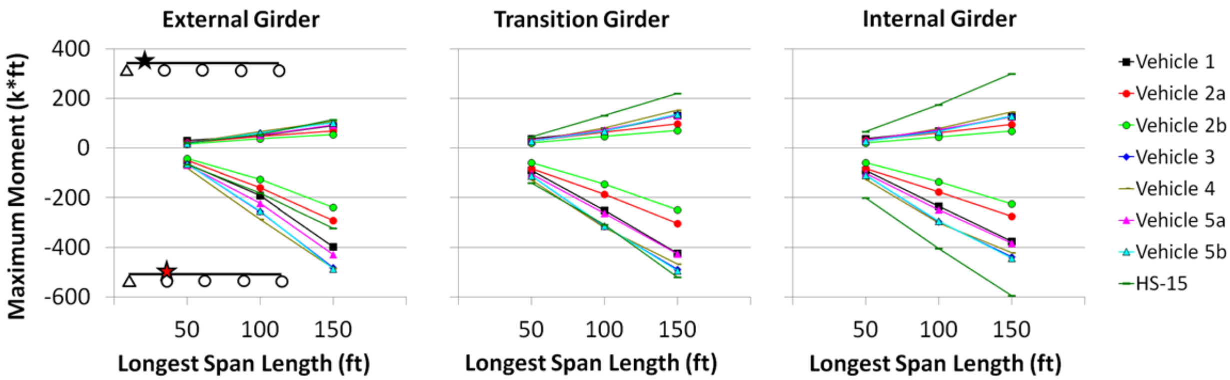


Figure 207 Moment Demands for Two-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (1 of 2).

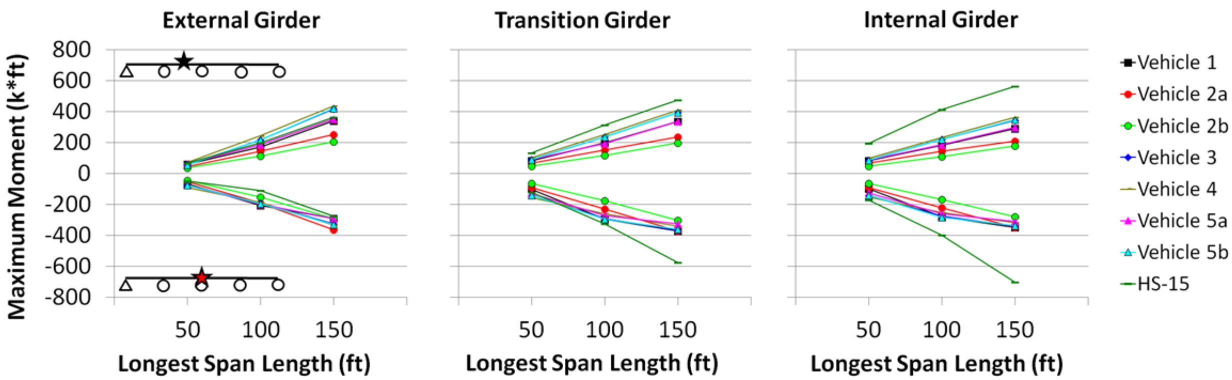


Figure 208 Moment Demands for Two-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (2 of 2).

B.1.4.2 Three Span Bridges

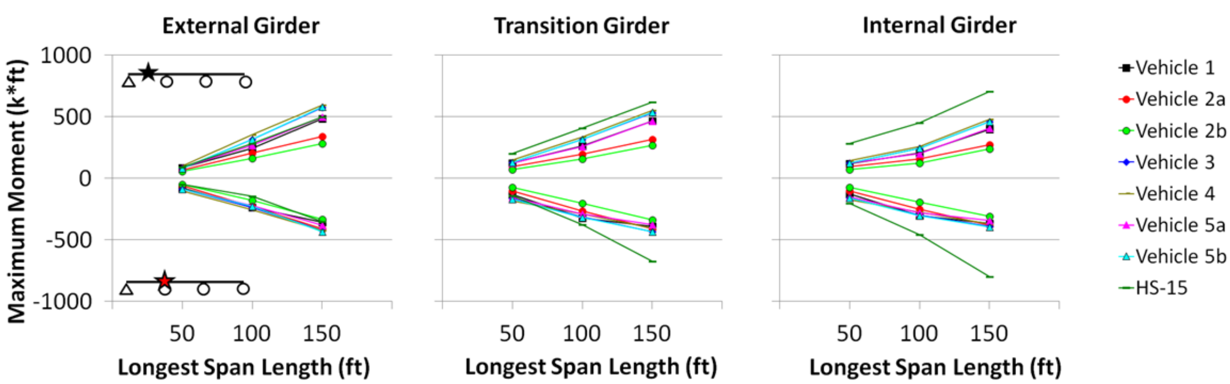


Figure 209 Moment Demands for Two-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (1 of 2).

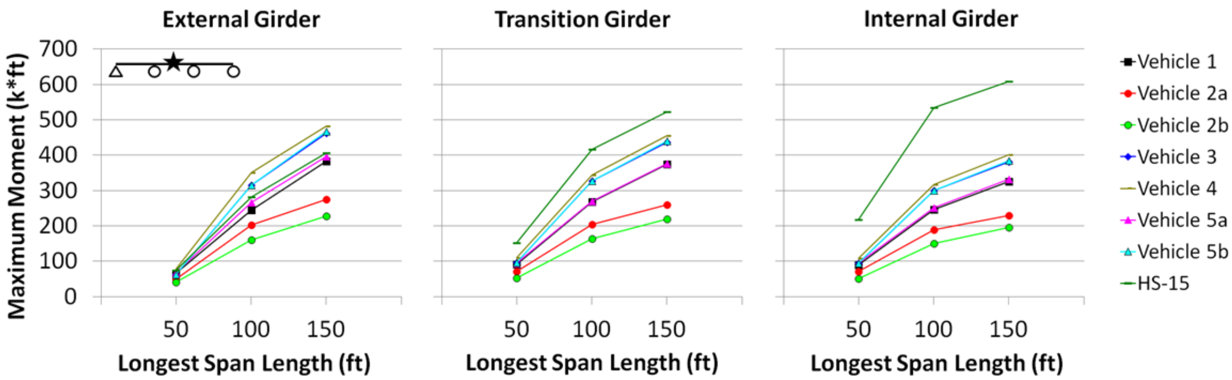


Figure 210 Moment Demands for Two-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (2 of 2).

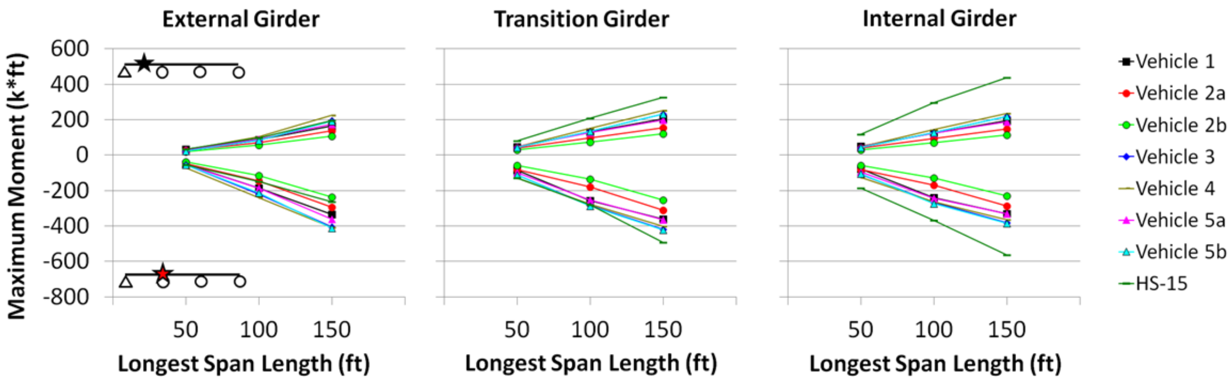


Figure 211 Moment Demands for Two-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (1 of 2).

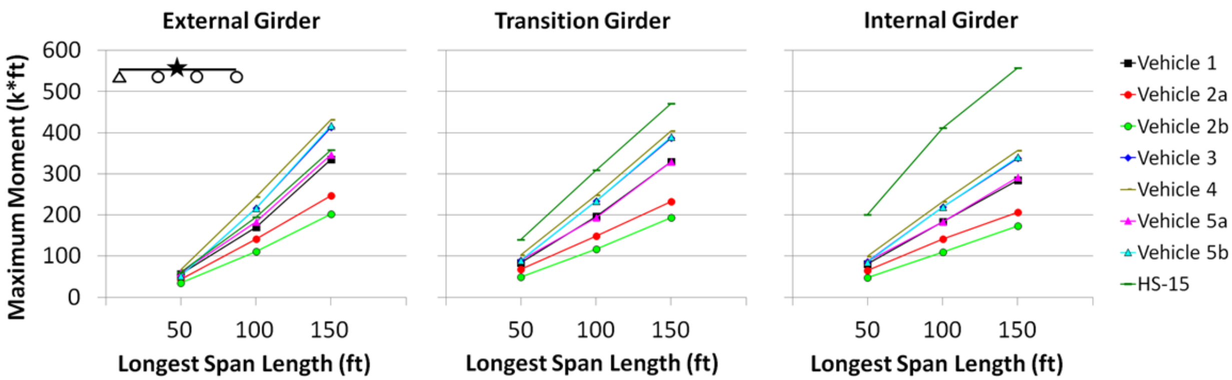


Figure 212 Moment Demands for Two-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (2 of 2).

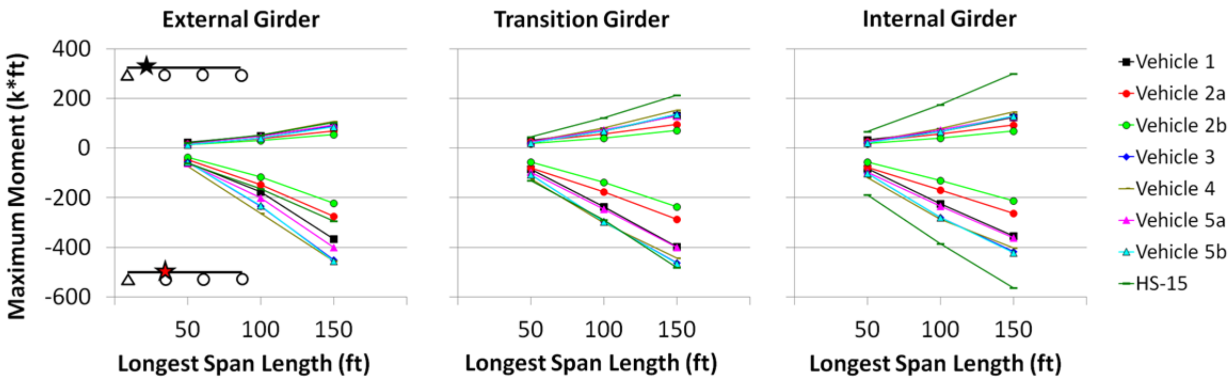


Figure 213 Moment Demands for Two-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (1 of 2).

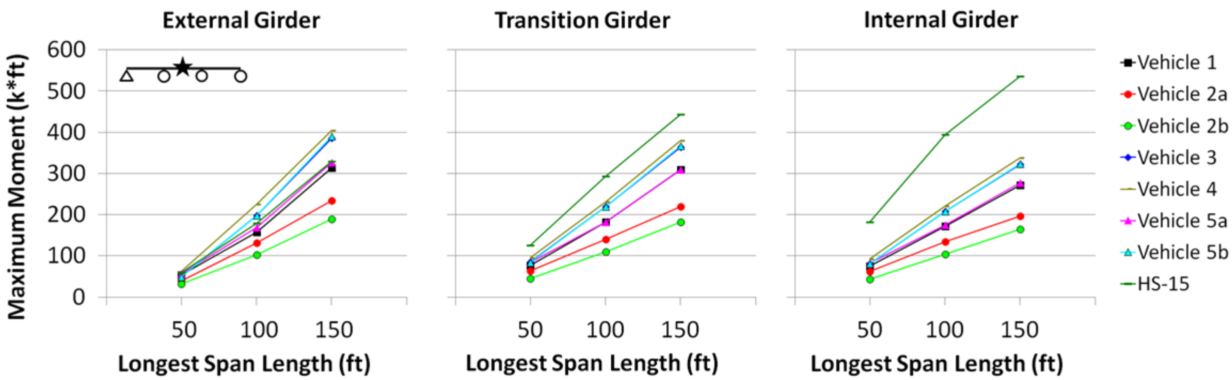
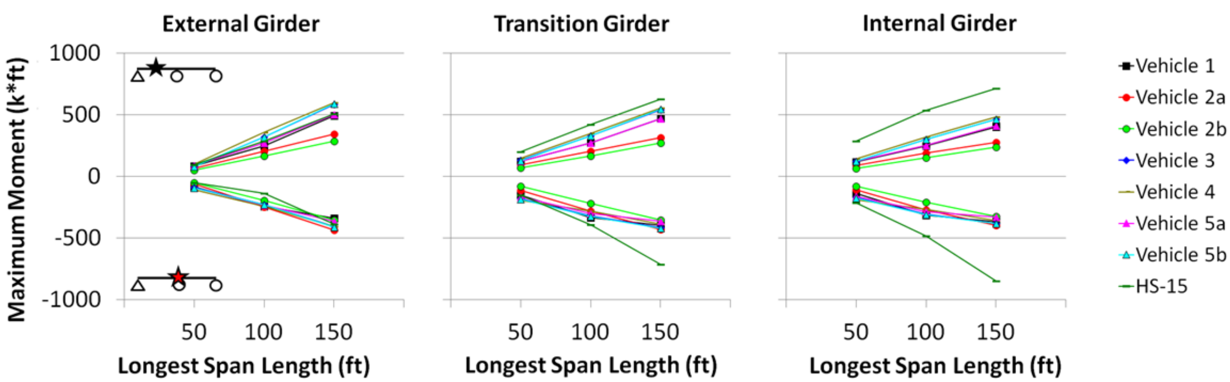


Figure 214 Moment Demands for Two-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (2 of 2).



B.1.4.3 Two Span Bridges

Figure 215 Moment Demands for Two-Lane Bridges with an SLR of 1:1 and Varied Span Lengths.

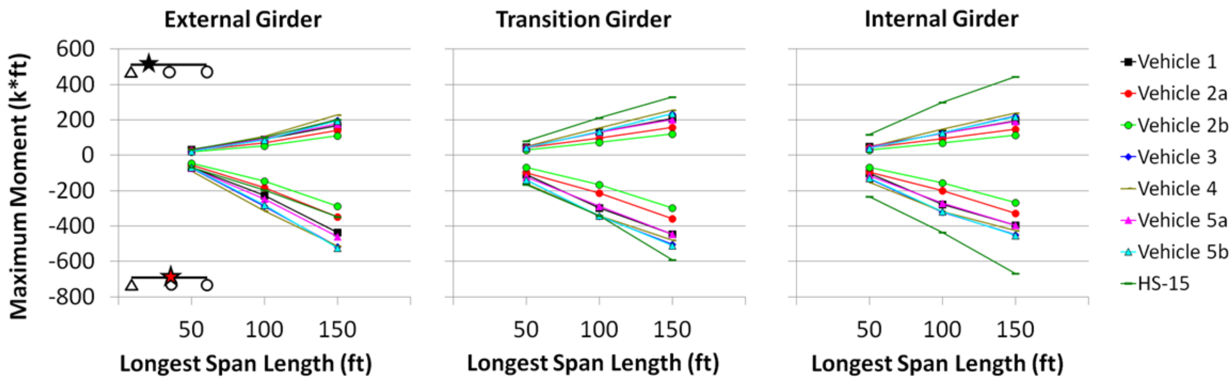


Figure 216 Moment Demands for Two-Lane Bridges with an SLR of 1:2 and Varied Span Lengths.

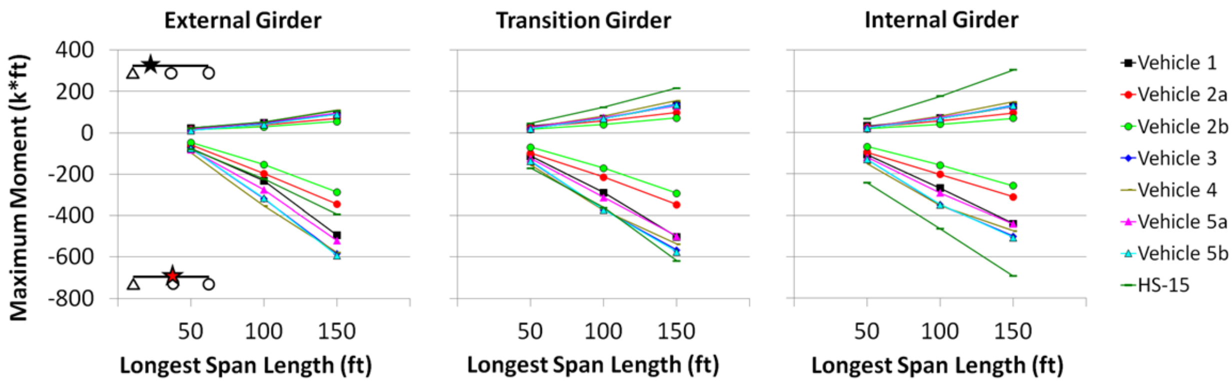


Figure 217 Moment Demands for Two-Lane Bridges with an SLR of 1:3 and Varied Span Length.

B.2 HS-Equivalent Vehicle Weight Graphs

B.2.1 Results for One-Lane Simply Supported Bridges

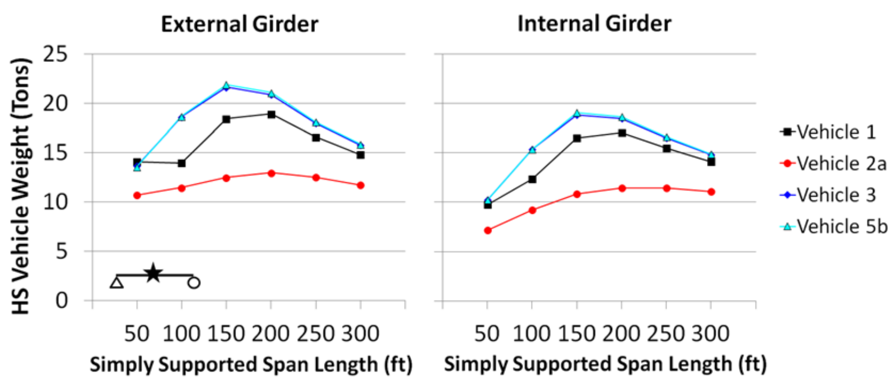


Figure 218 HS Vehicle Weights of One-Lane Bridges with Varying Span Lengths.

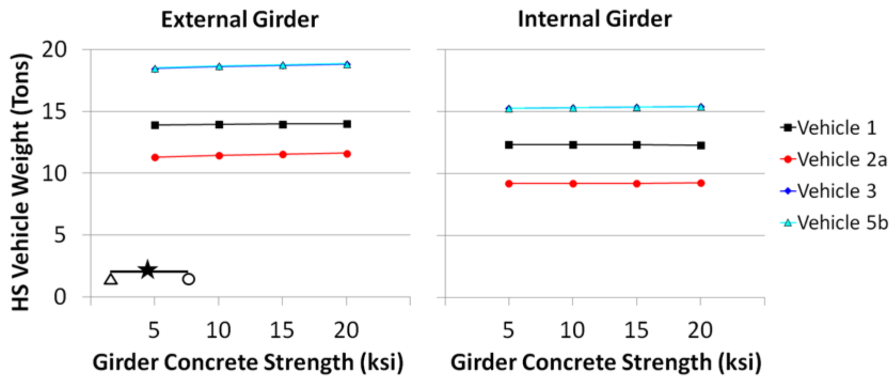


Figure 219 HS Vehicle Weights of One-Lane Bridges with Varying Girder Strengths.

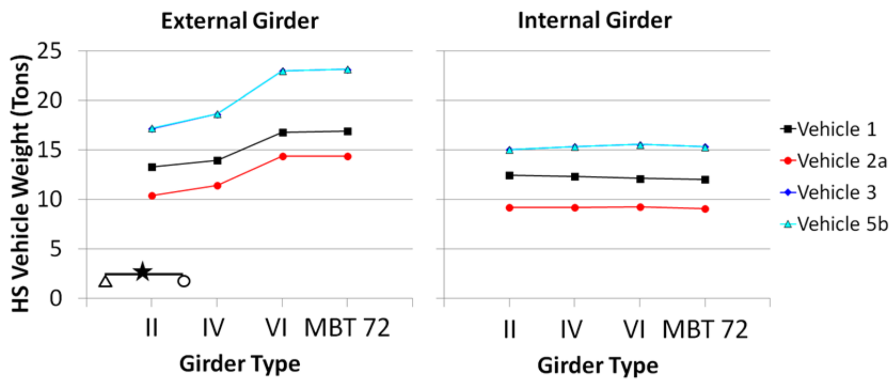


Figure 220 HS Vehicle Weights of One-Lane Bridges with Varying Girder Types.

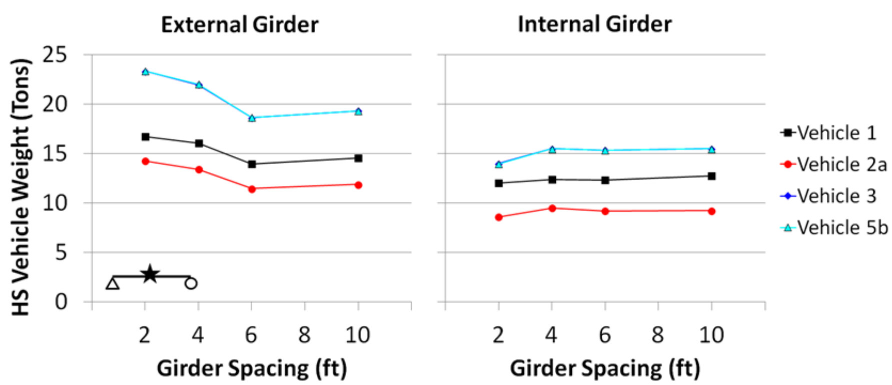


Figure 221 HS Vehicle Weights of One-Lane Bridges with Varying Girder Spacing.

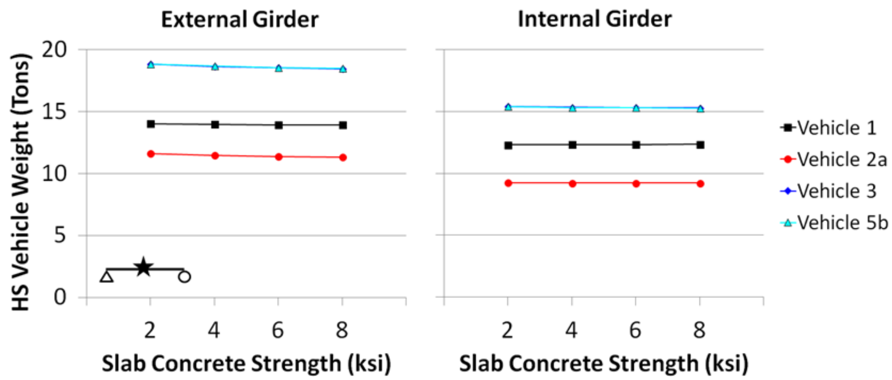


Figure 222 HS Vehicle Weights of One-Lane Bridges with Slab Concrete Strength.

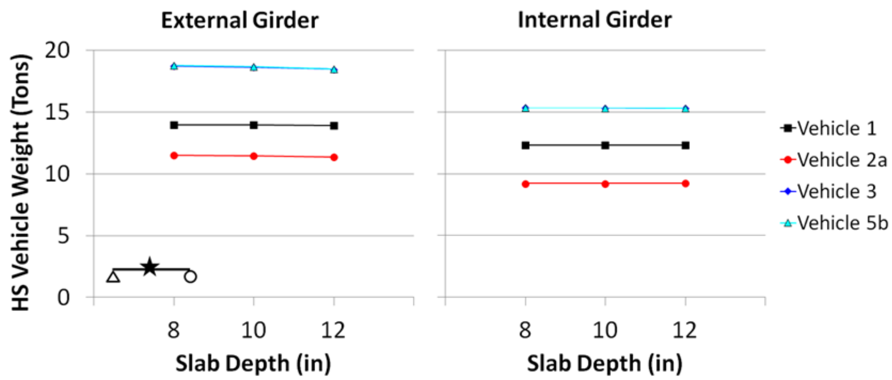


Figure 223 HS Vehicle Weights of One-Lane Bridges with Slab Depth.

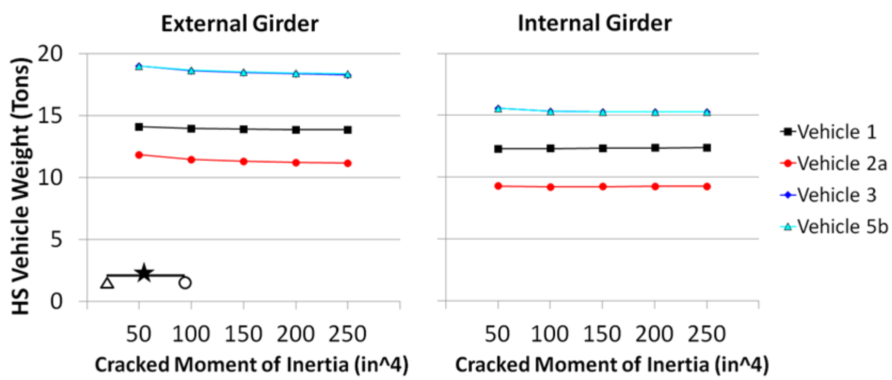


Figure 224 HS Vehicle Weights of One-Lane Bridges with Varying Cracked Moment of Inertia of Slab.

B.2.2 Results for Two-Lane Simply Supported Bridge

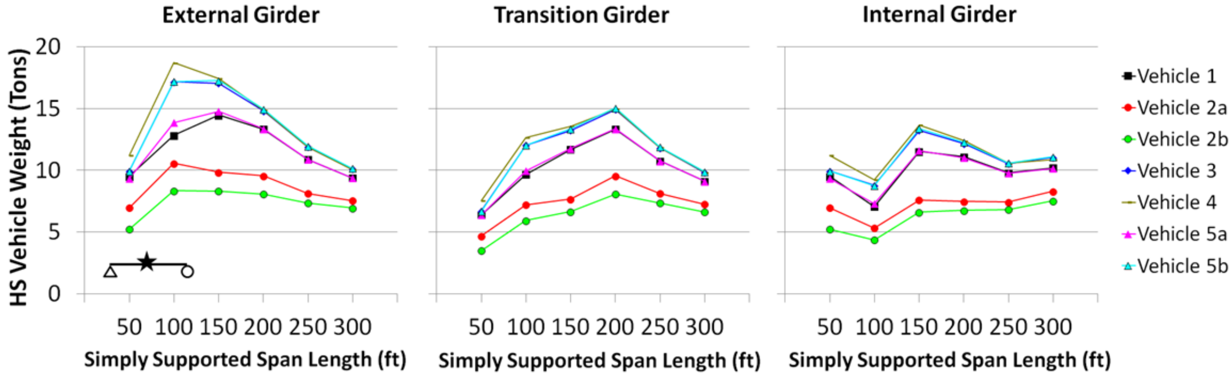


Figure 225 HS Vehicle Weights of Two-Lane Bridges with Varying Span Lengths.

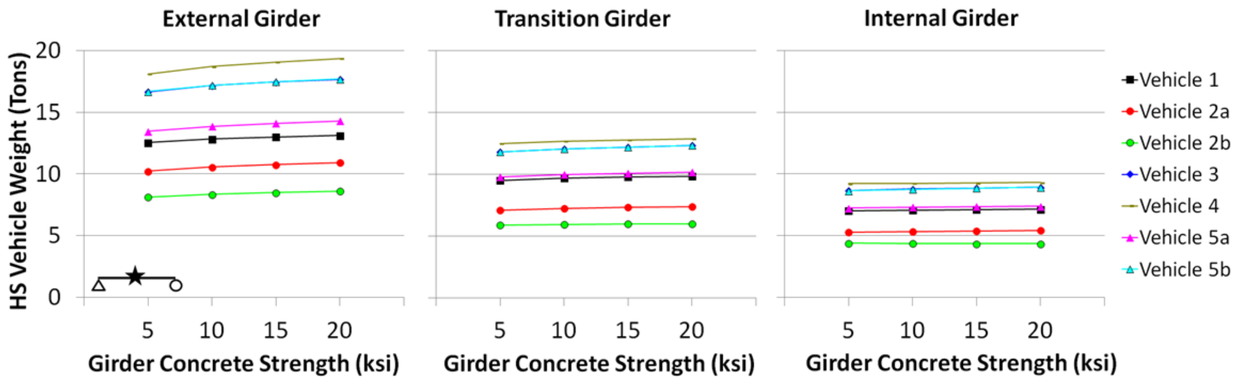


Figure 226 HS Vehicle Weights of Two-Lane Bridges with Varying Girder Strengths.

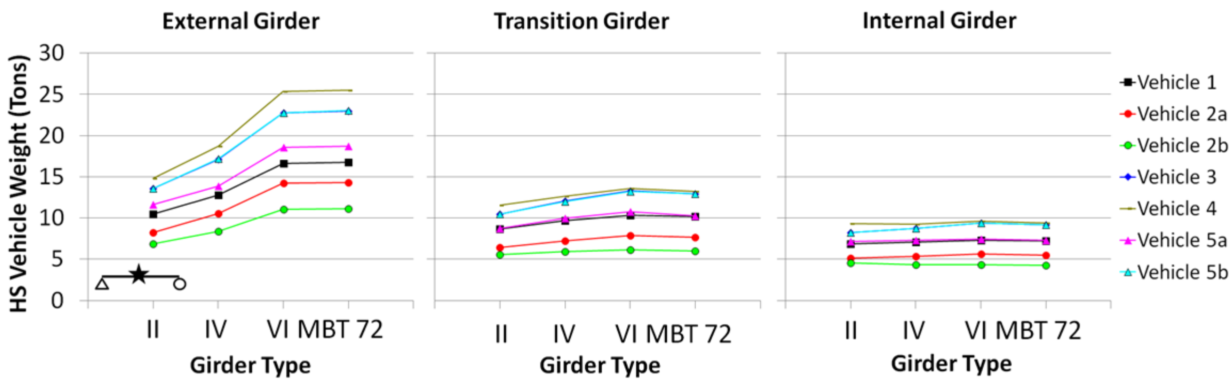


Figure 227 HS Vehicle Weights of Two-Lane Bridges with Varying Girder Types.

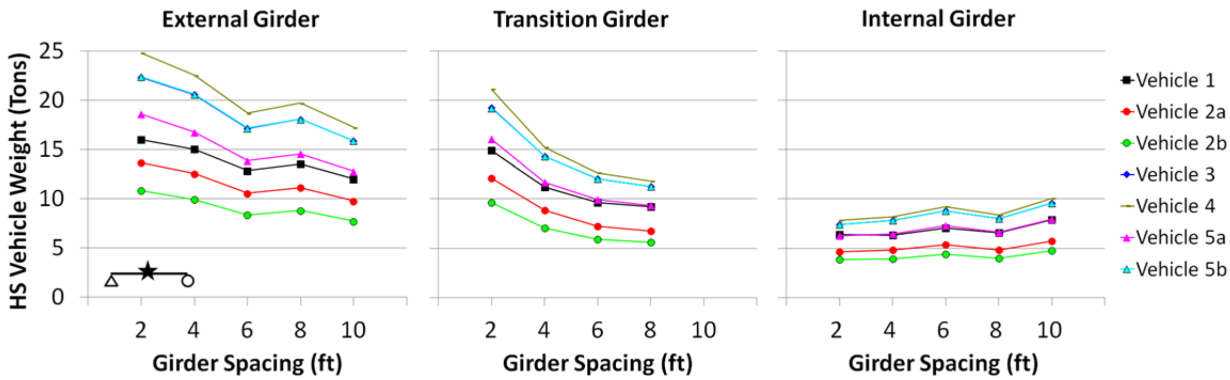


Figure 228 HS Vehicle Weights of Two-Lane Bridges with Varying Girder Spacing.

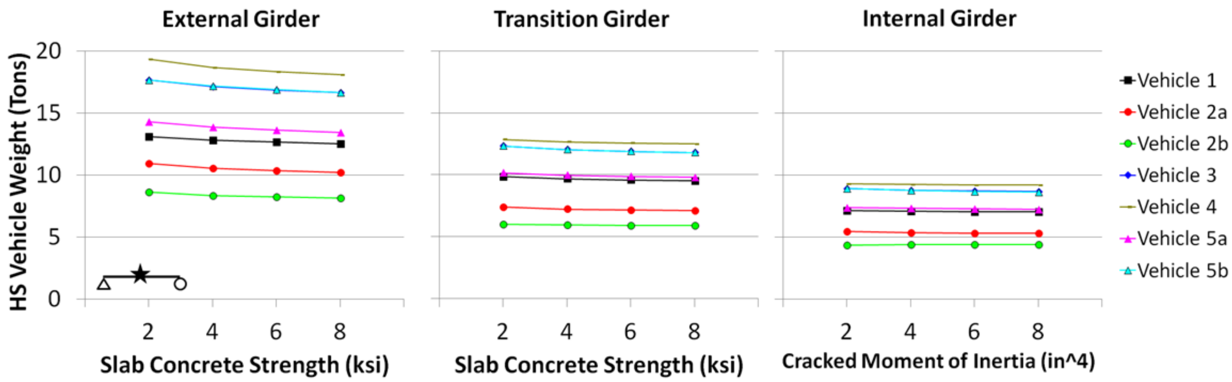


Figure 229 HS Vehicle Weights of Two-Lane Bridges with Varying Slab Strength.

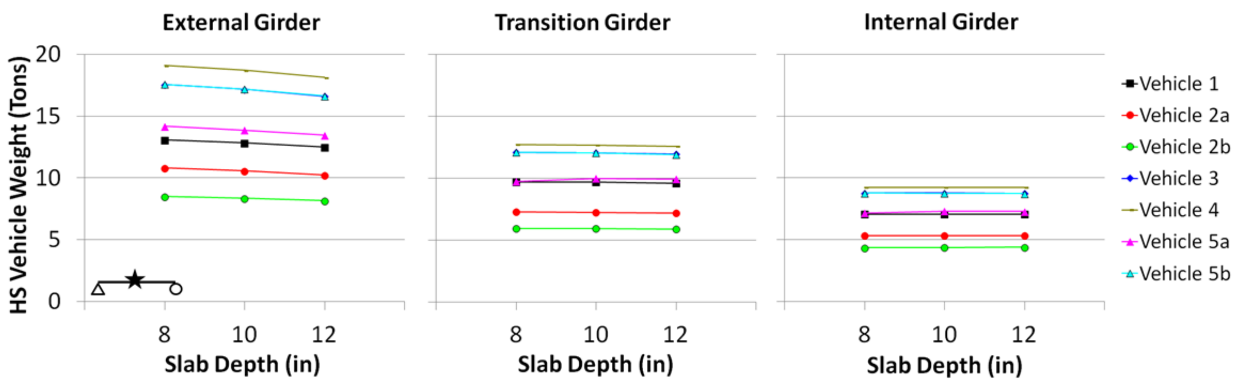


Figure 230 HS Vehicle Weights of Two-Lane Bridges with Varying Slab Depth.

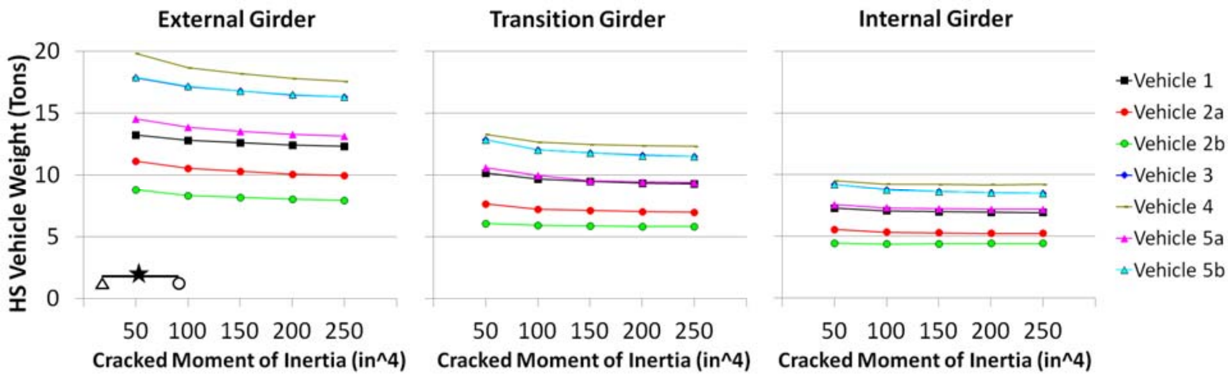


Figure 231 HS Vehicle Weights of Two-Lane Bridges with Varying Cracked Moment of Inertia of Slab.

B.2.3 Results for One-Lane Continuous Bridges

B.2.3.1 Four Span Bridges

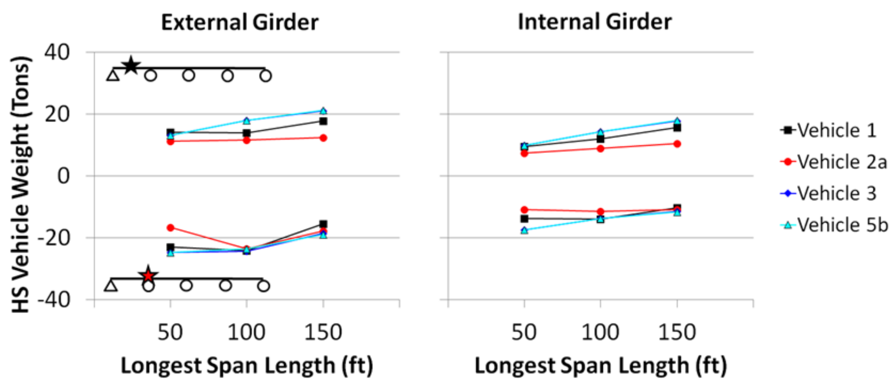


Figure 232 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (1 of 2).

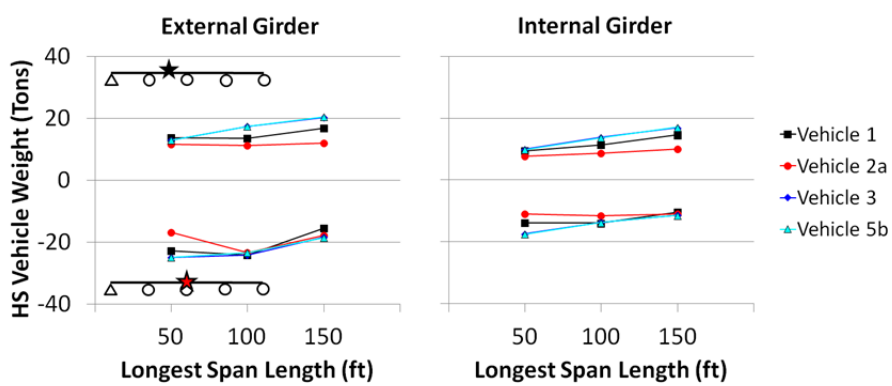


Figure 233 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (2 of 2).

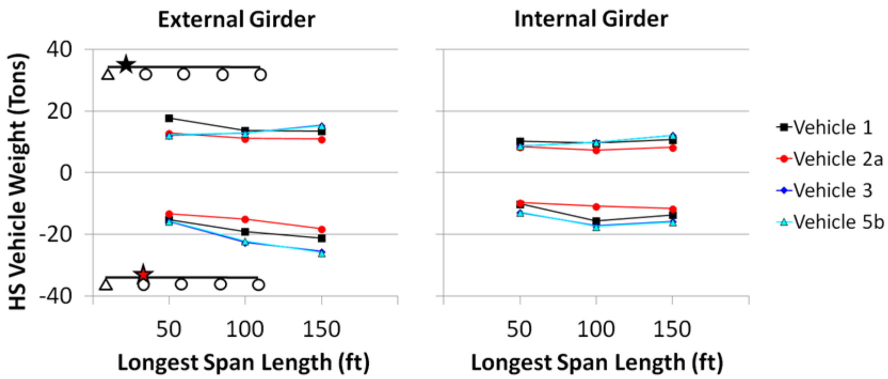


Figure 234 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (1 of 2).

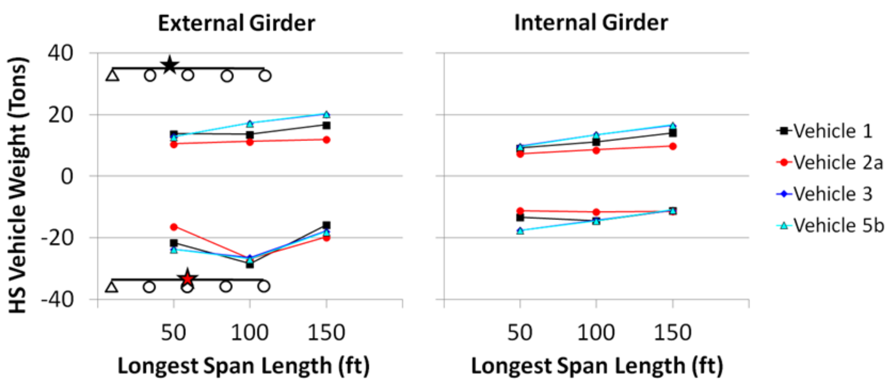


Figure 235 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (2 of 2).

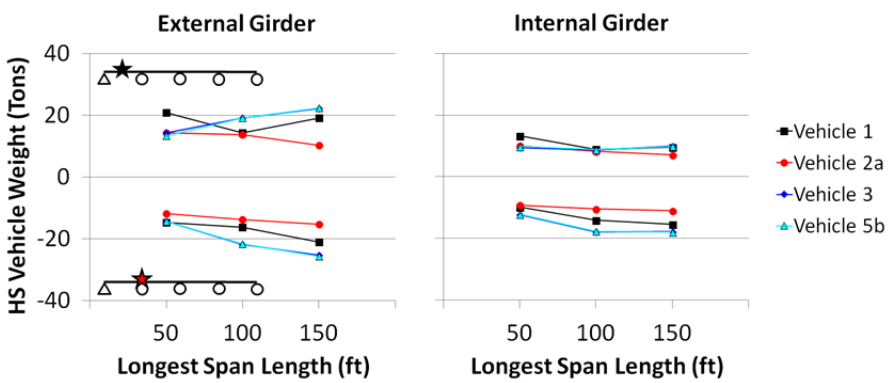


Figure 236 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (1 of 2).

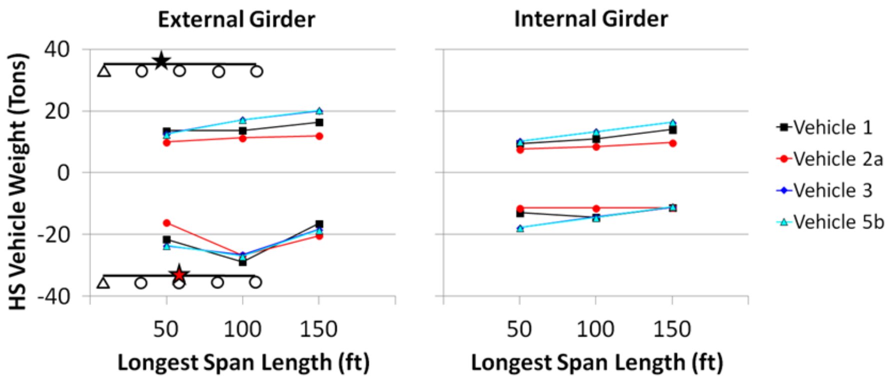


Figure 237 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (2 of 2).

B.2.3.2 Three Span Bridges

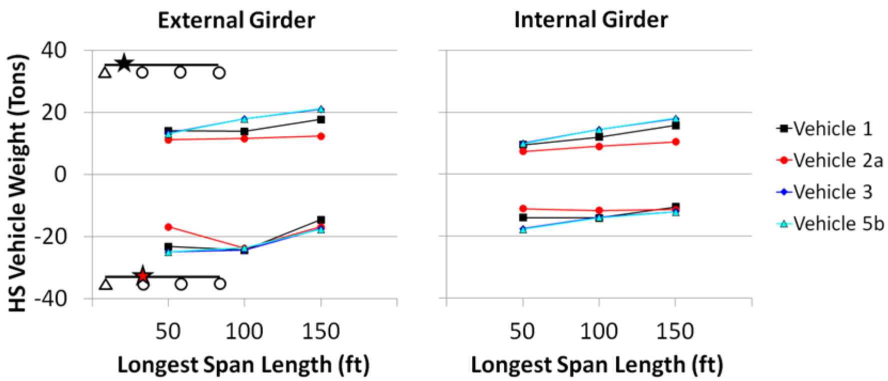


Figure 238 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (1 of 2).

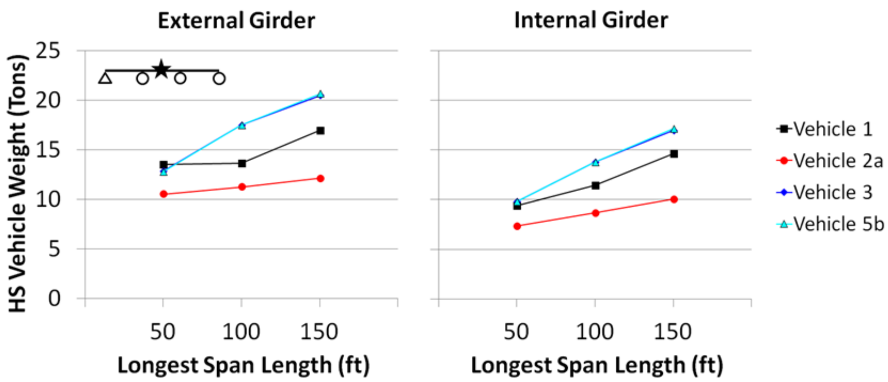


Figure 239 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (2 of 2).

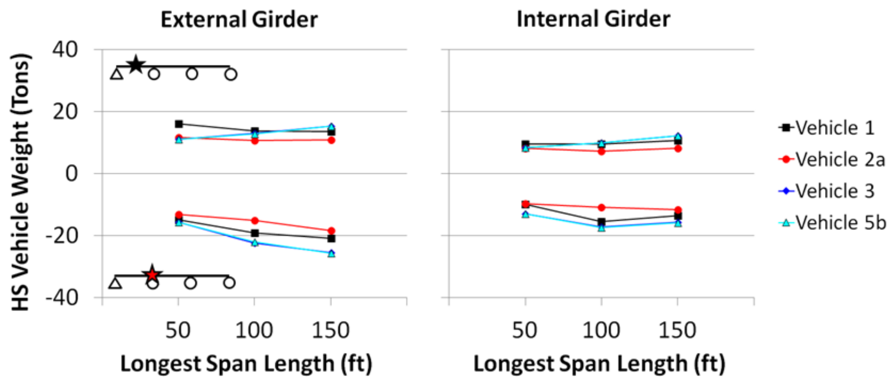


Figure 240 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (1 of 2).

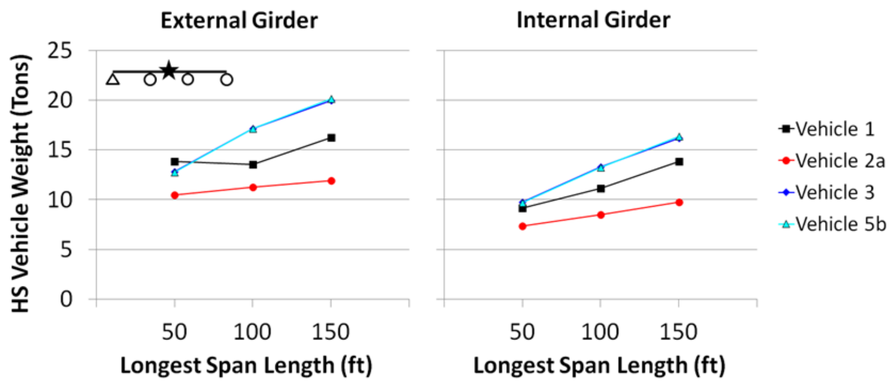


Figure 241 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (2 of 2).

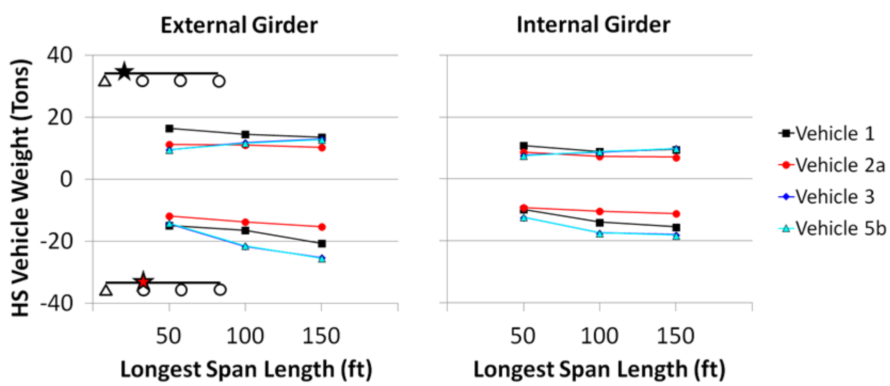


Figure 242 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (1 of 2).

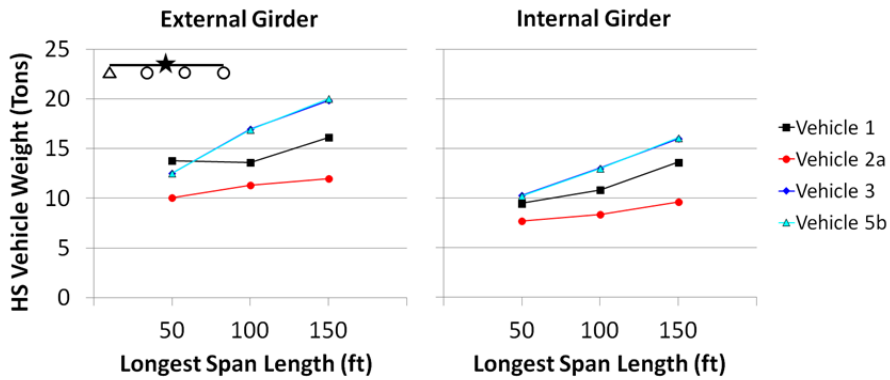


Figure 243 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (2 of 2).

B.2.3.3 Two Span Bridges

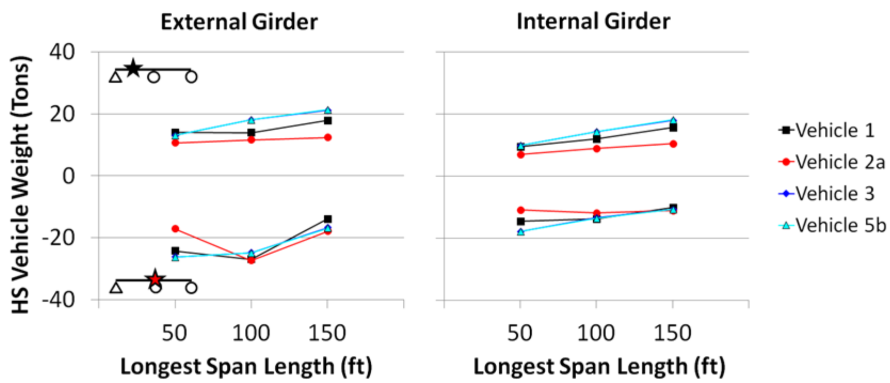


Figure 244 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:1 and Varied Span Lengths.

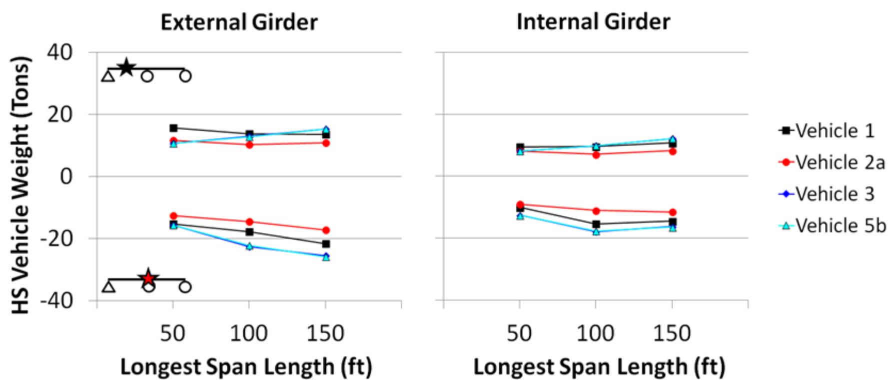


Figure 245 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:2 and Varied Span Lengths.

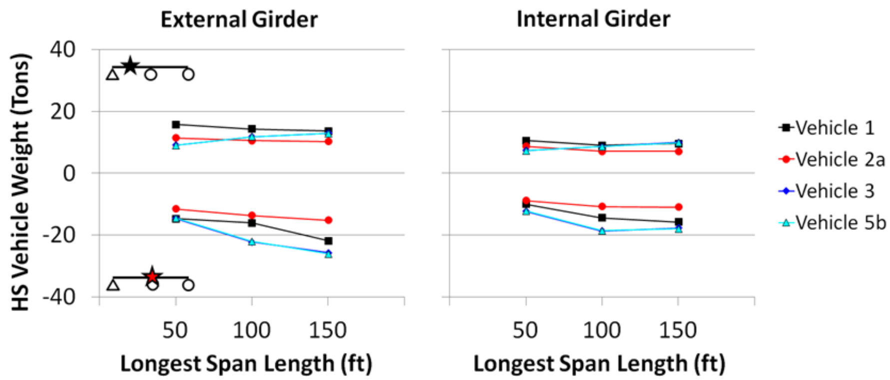


Figure 246 HS Vehicle Weights for One-Lane Bridges with an SLR of 1:3 and Varied Span Lengths.

B.2.4 Results for Two-Lane Continuous Bridges

B.2.4.1 Four Span Bridges

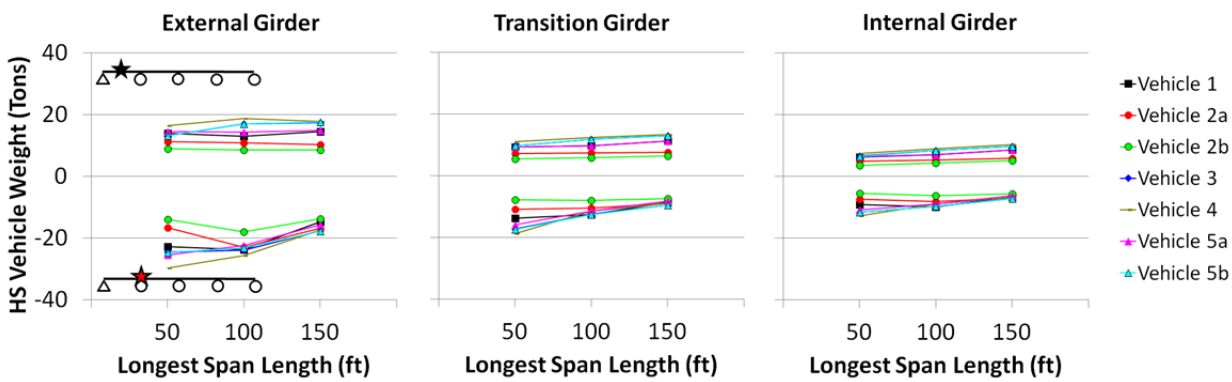


Figure 247 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (1 of 2).

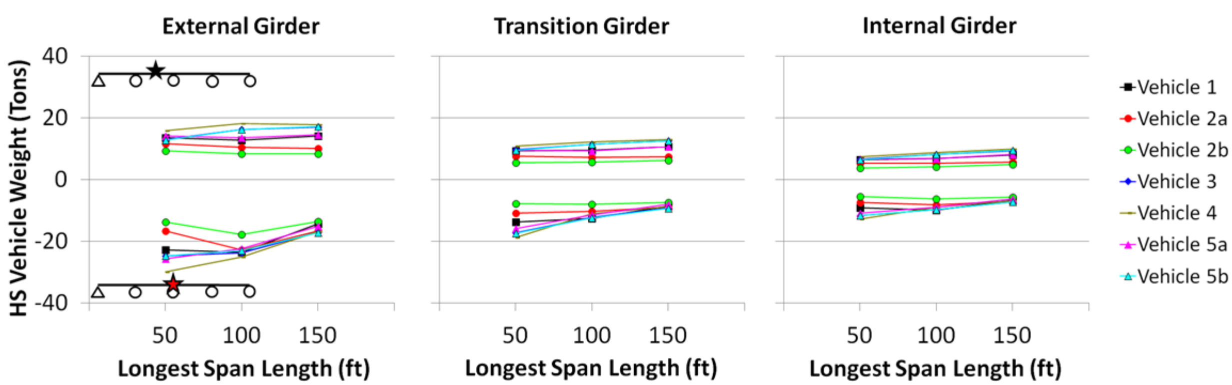


Figure 248 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:1:1:1 and Varied Span Lengths (2 of 2).

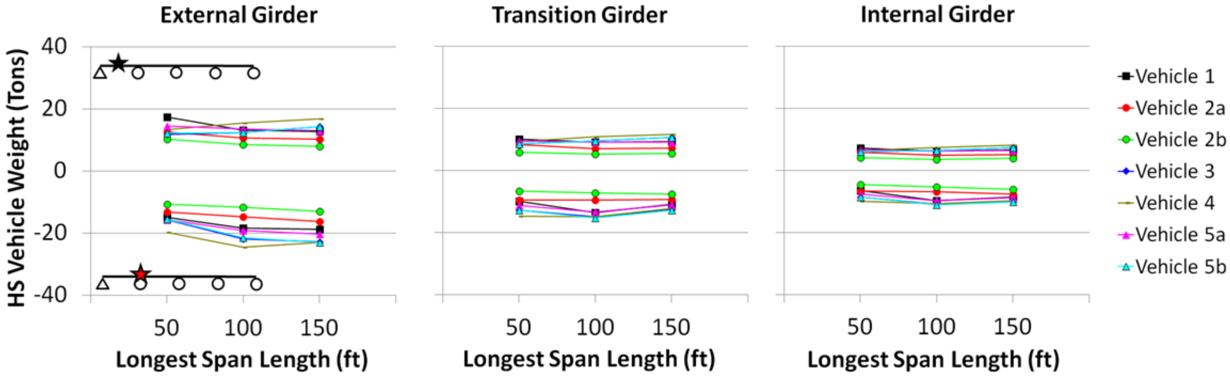


Figure 249 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (1 of 2).

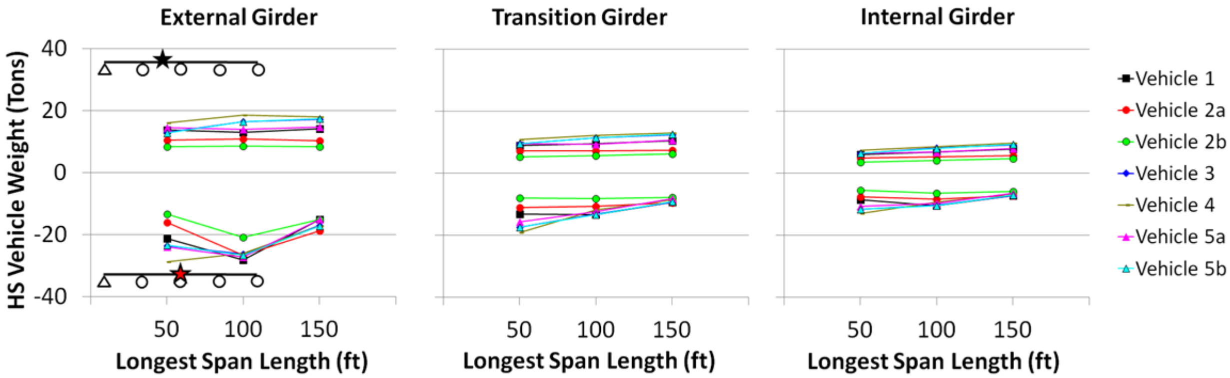


Figure 250 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:2:2:1 and Varied Span Lengths (2 of 2).

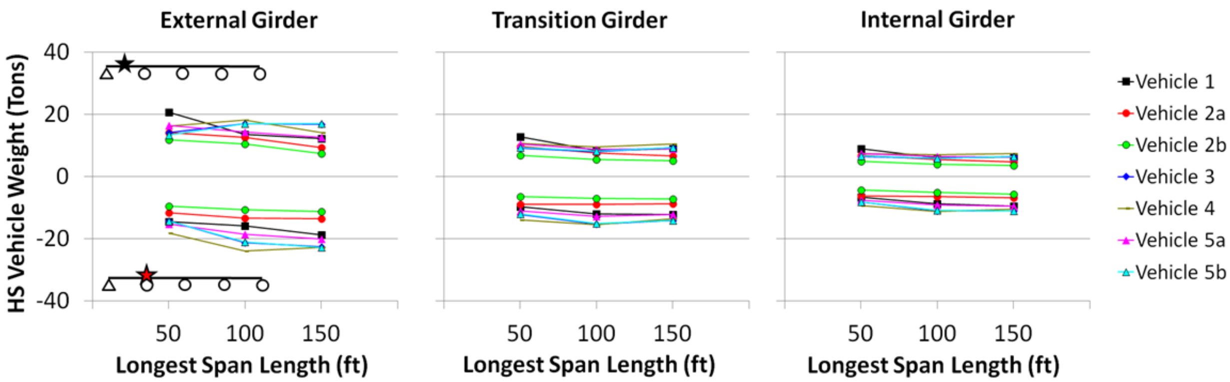


Figure 251 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (1 of 2).

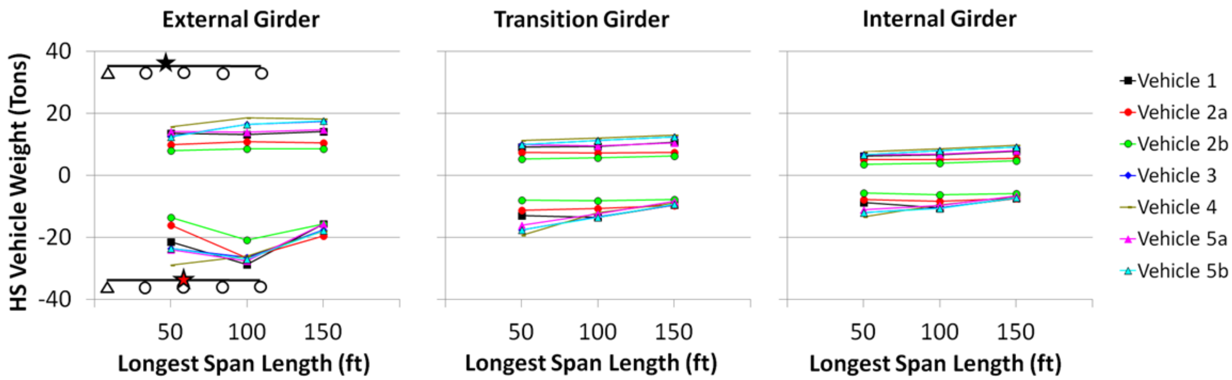
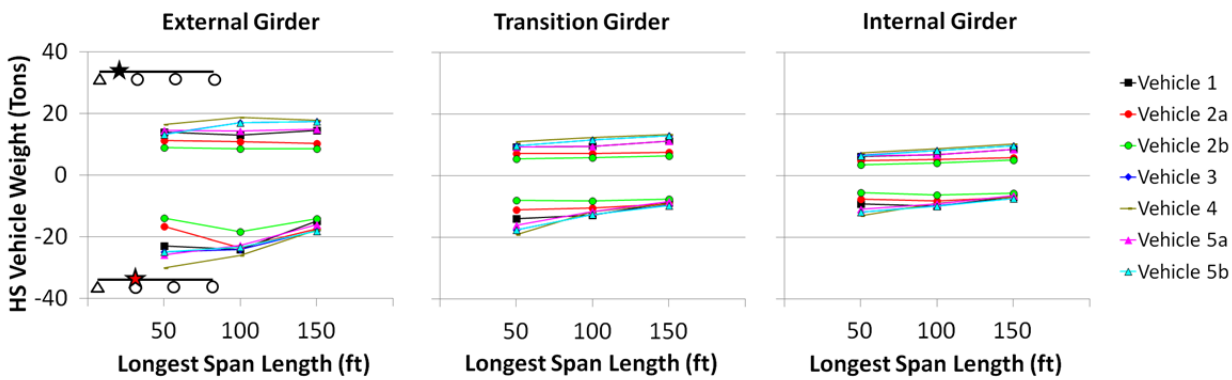


Figure 252 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:3:3:1 and Varied Span Lengths (2 of 2).



B.2.4.2 Three Span Bridges

Figure 253 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (1 of 2).

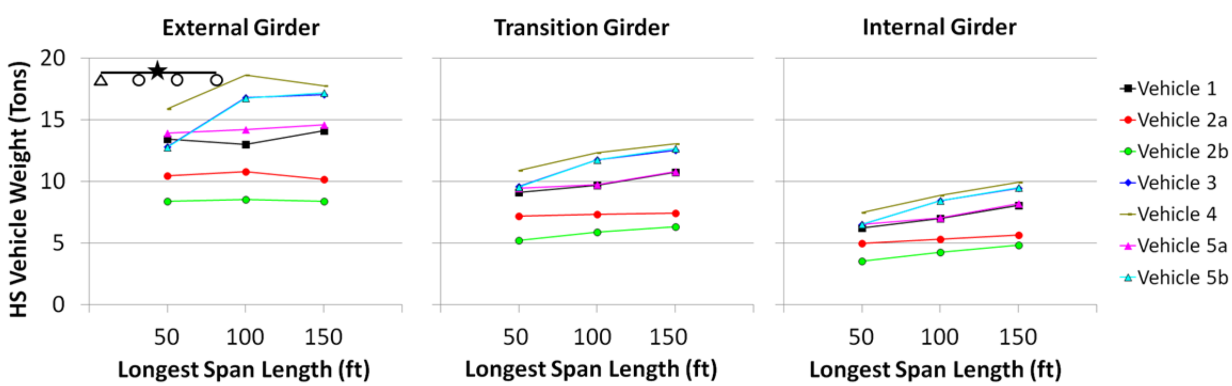


Figure 254 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:1:1 and Varied Span Lengths (2 of 2).

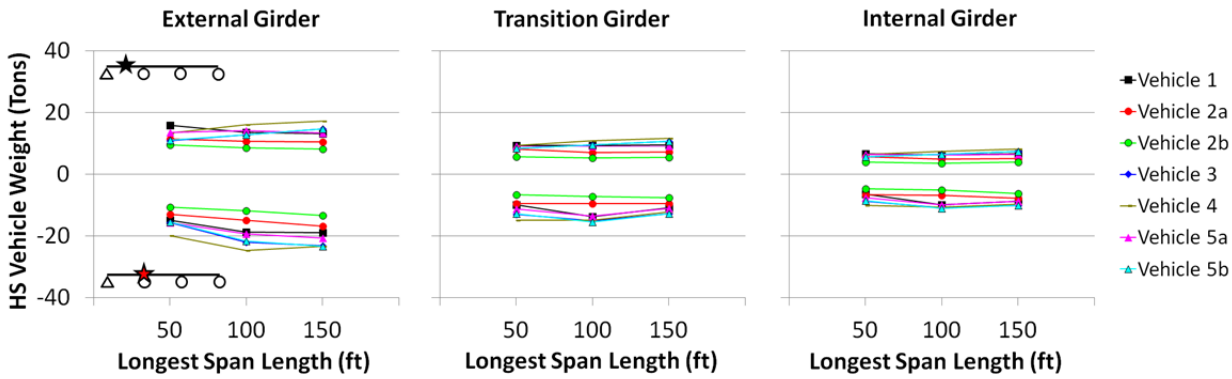


Figure 255 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (1 of 2).

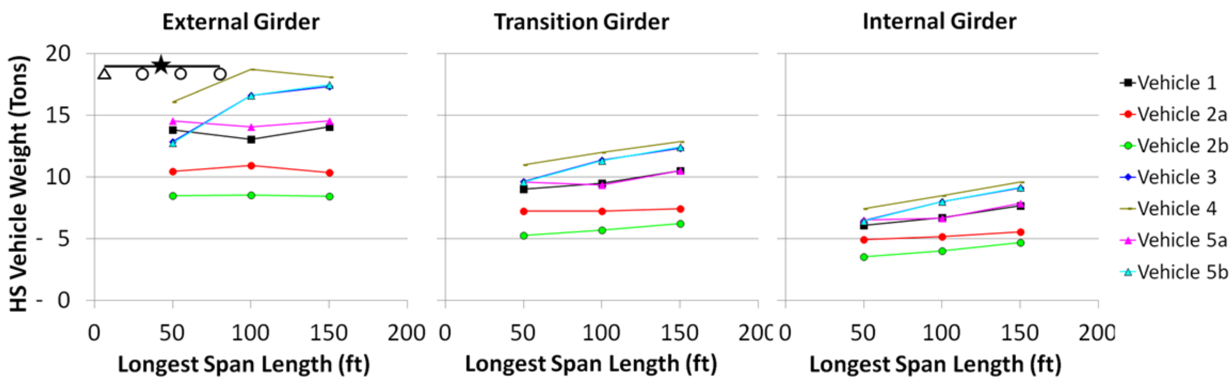


Figure 256 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:2:1 and Varied Span Lengths (2 of 2).

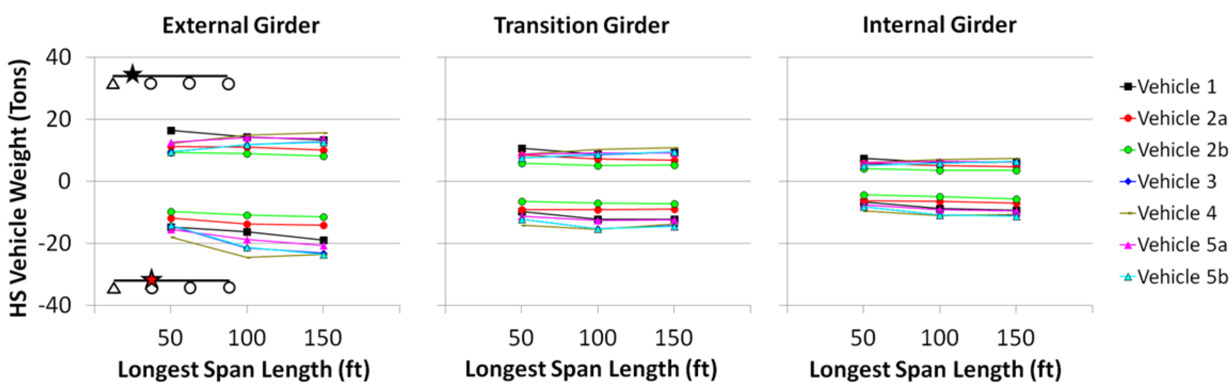


Figure 257 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (1 of 2).

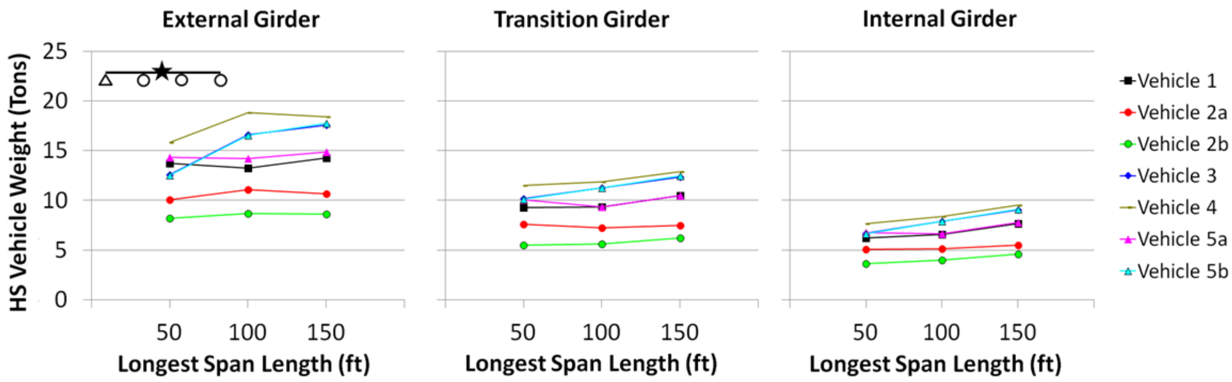


Figure 258 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:3:1 and Varied Span Lengths (2 of 2).

B.2.4.3 Two Span Bridges

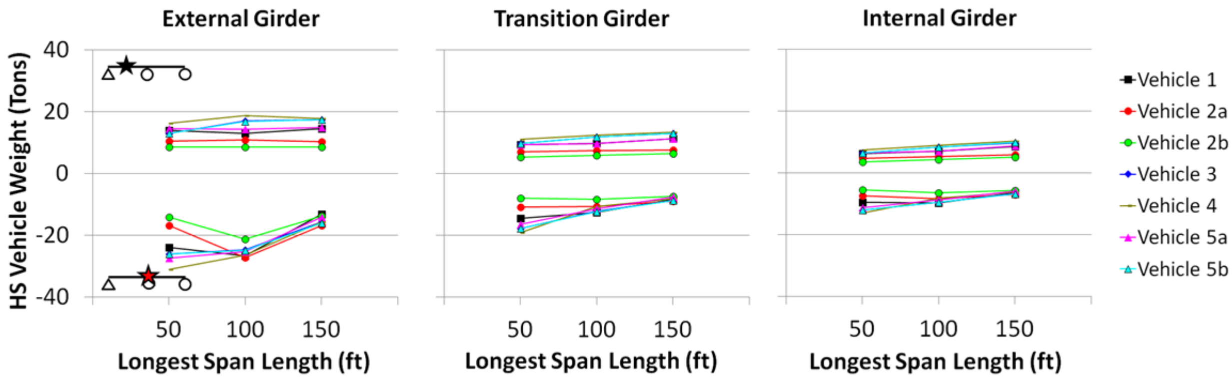


Figure 259 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:1 and Varied Span Lengths.

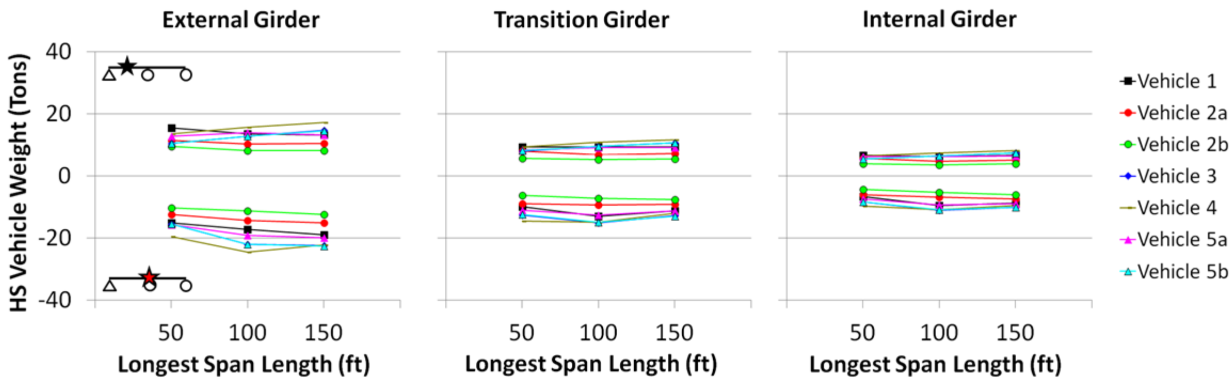


Figure 260 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:2 and Varied Span Lengths.

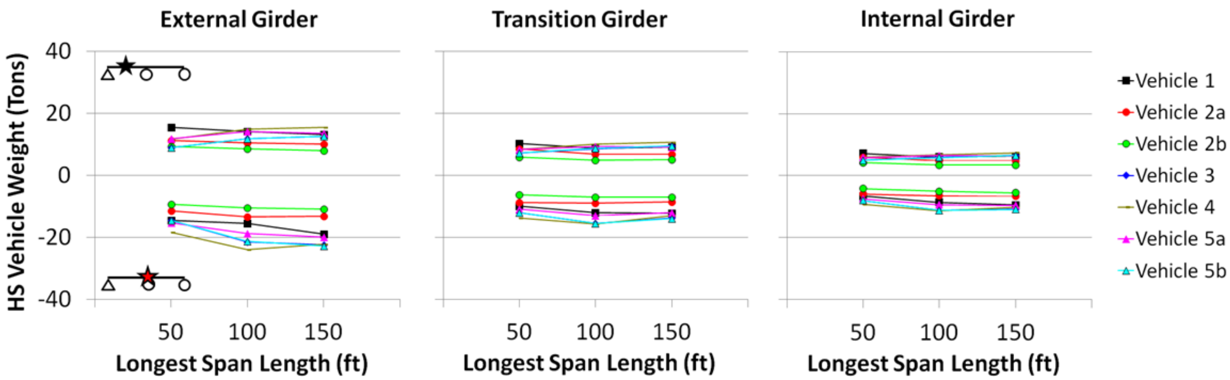


Figure 261 HS Vehicle Weights for Two-Lane Bridges with an SLR of 1:3 and Varied Span Lengths.

APPENDIX C. CHAPTER 4

C.1 Truck Schematics for Pavement Analysis

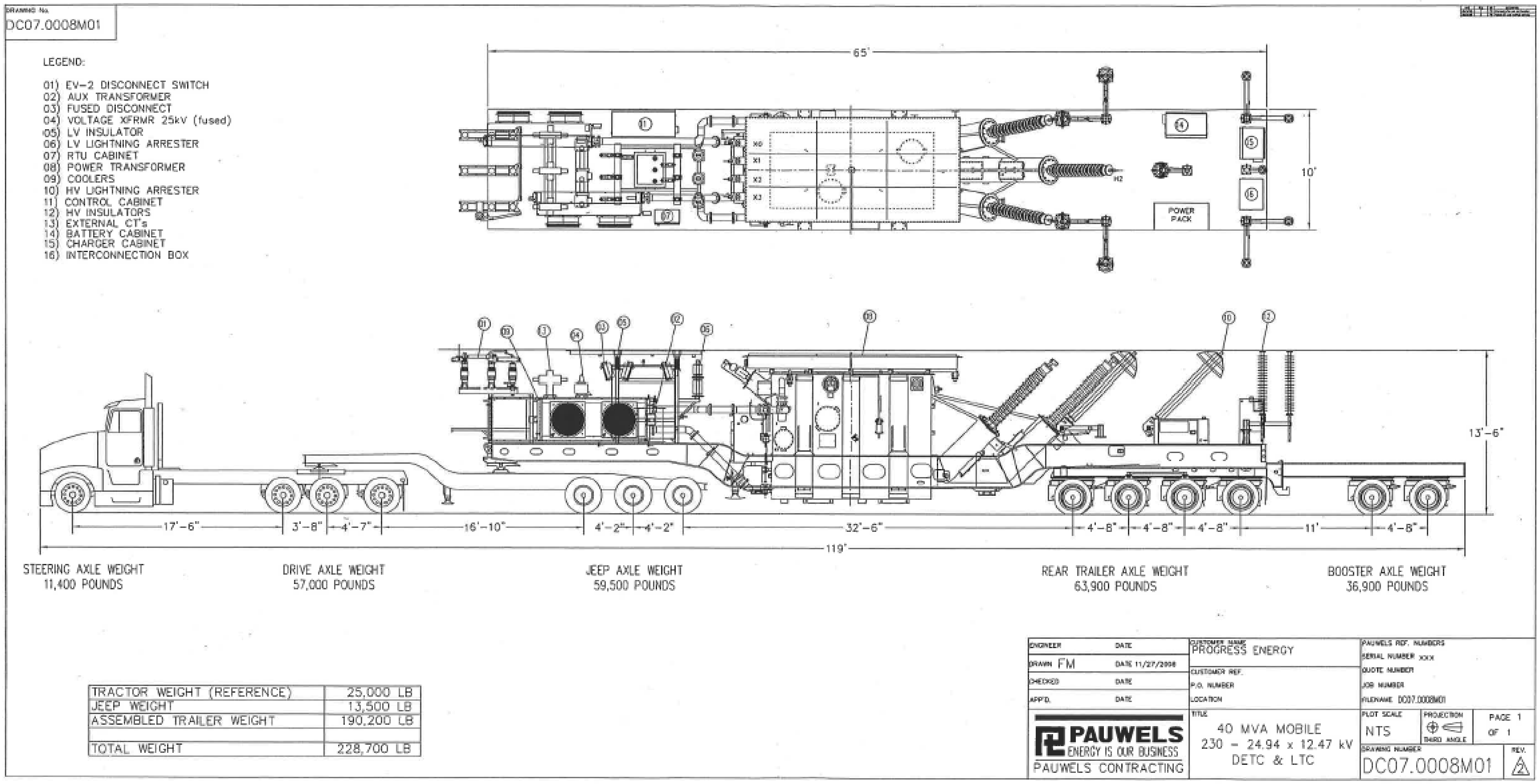
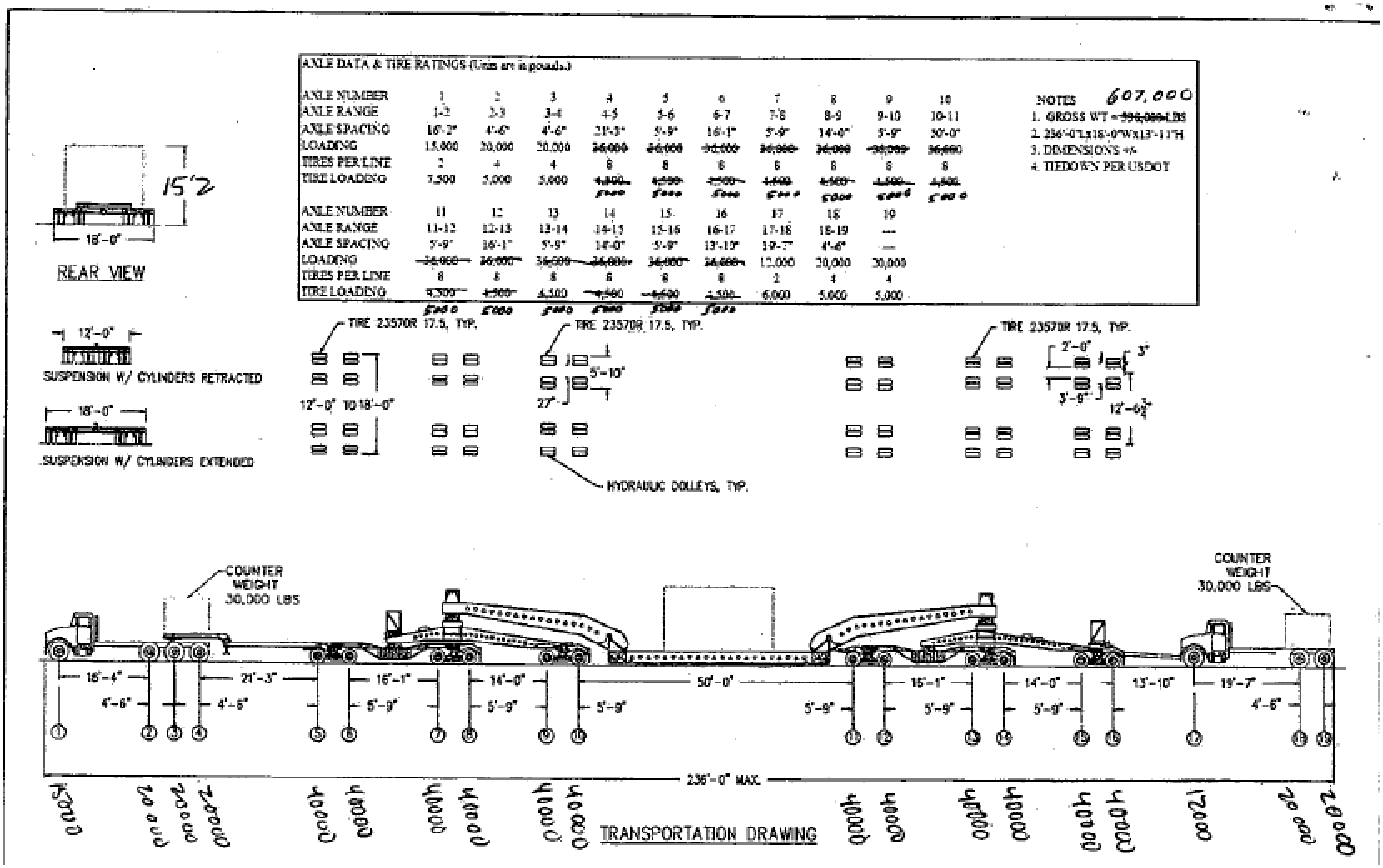


Figure 262 Truck-1: Progress Energy 13 Axle Mobile Transformer Truck Schematic.[60]

[60] Source: Progress Energy



AXLE DATA & TIRE RATINGS (Units are in pounds.)

AXLE NUMBER	1	2	3	4	5	6	7	8	9	10
AXLE RANGE	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11
AXLE SPACING	16'-2"	4'-6"	4'-6"	21'-3"	5'-9"	16'-1"	5'-9"	14'-0"	5'-9"	30'-0"
LOADING	15,000	20,000	20,000	~~36,000~~	~~46,000~~	~~31,000~~	~~36,000~~	~~36,000~~	~~30,000~~	~~36,000~~
TIRES PER LINE	2	4	4	8	8	8	8	8	8	8
TIRE LOADING	7,500	5,000	5,000	~~4,800~~ 5000	~~4,500~~ 5000	~~2,500~~ 5000	~~4,600~~ 5000	~~4,500~~ 5000	~~4,500~~ 5000	~~4,500~~ 5000

AXLE NUMBER	11	12	13	14	15	16	17	18	19
AXLE RANGE	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	---
AXLE SPACING	5'-9"	16'-1"	5'-9"	14'-0"	5'-9"	13'-10"	19'-7"	4'-6"	---
LOADING	~~36,000~~	~~36,000~~	~~36,000~~	~~36,000~~	~~36,000~~	~~36,000~~	12,000	20,000	20,000
TIRES PER LINE	8	8	8	8	8	8	2	4	4
TIRE LOADING	~~4,500~~ 5000	~~4,500~~ 5000	~~4,500~~ 5000	~~4,500~~ 5000	~~4,500~~ 5000	~~4,500~~ 5000	6,000	5,000	5,000

NOTES 607,000
1. GROSS WT = ~~596,000~~ LBS
2. 236'-0"Lx16'-0"Wx13'-11"H
3. DIMENSIONS +/-
4. TIEDOWN PER USDOT

Figure 263 Truck-2: NC Citation Polk, Co. 19-Axle-Line Dual-Lane Drop Deck Gooseneck Truck Schematic.[61]

[61] Source: NCDOT

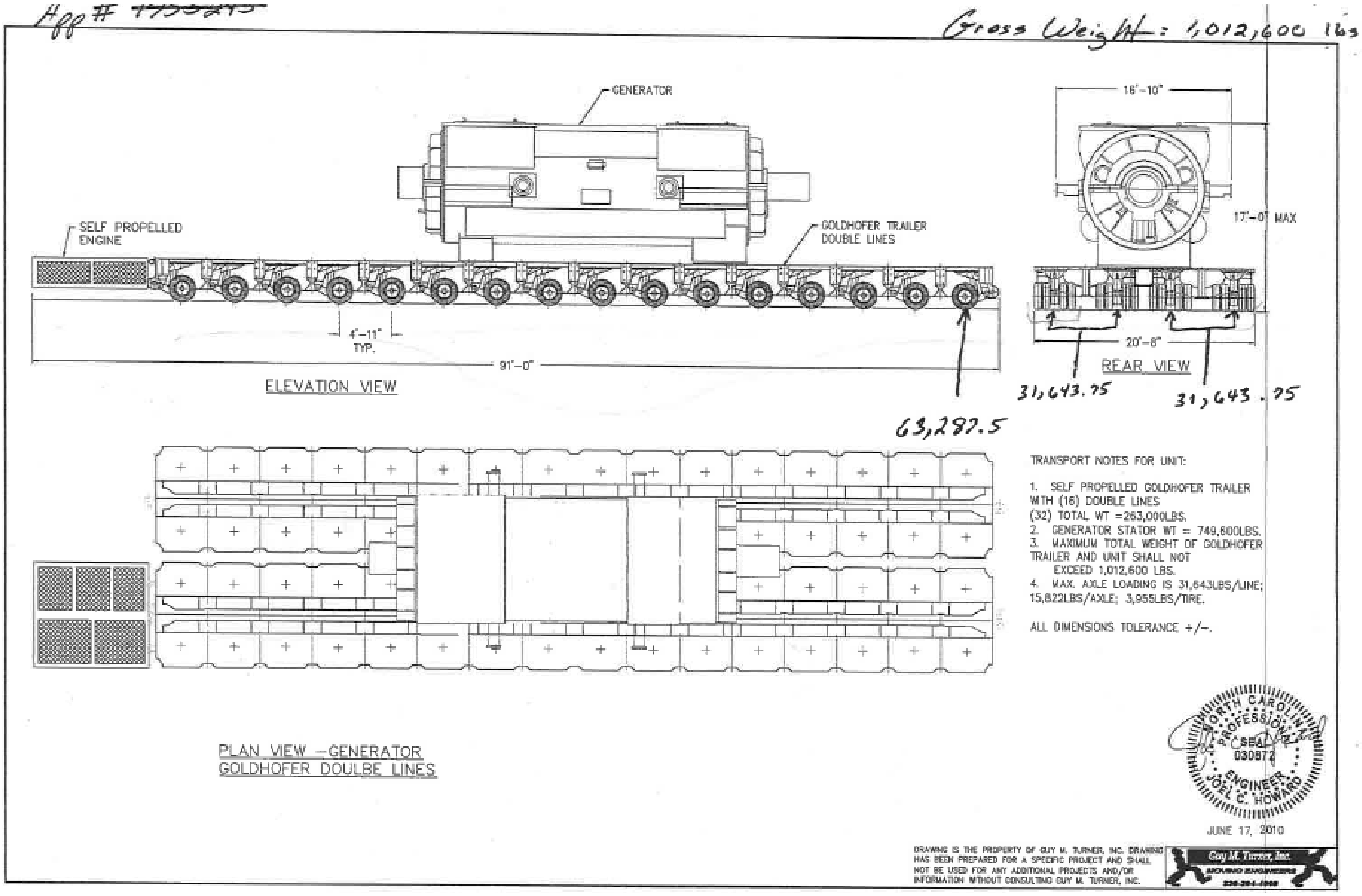
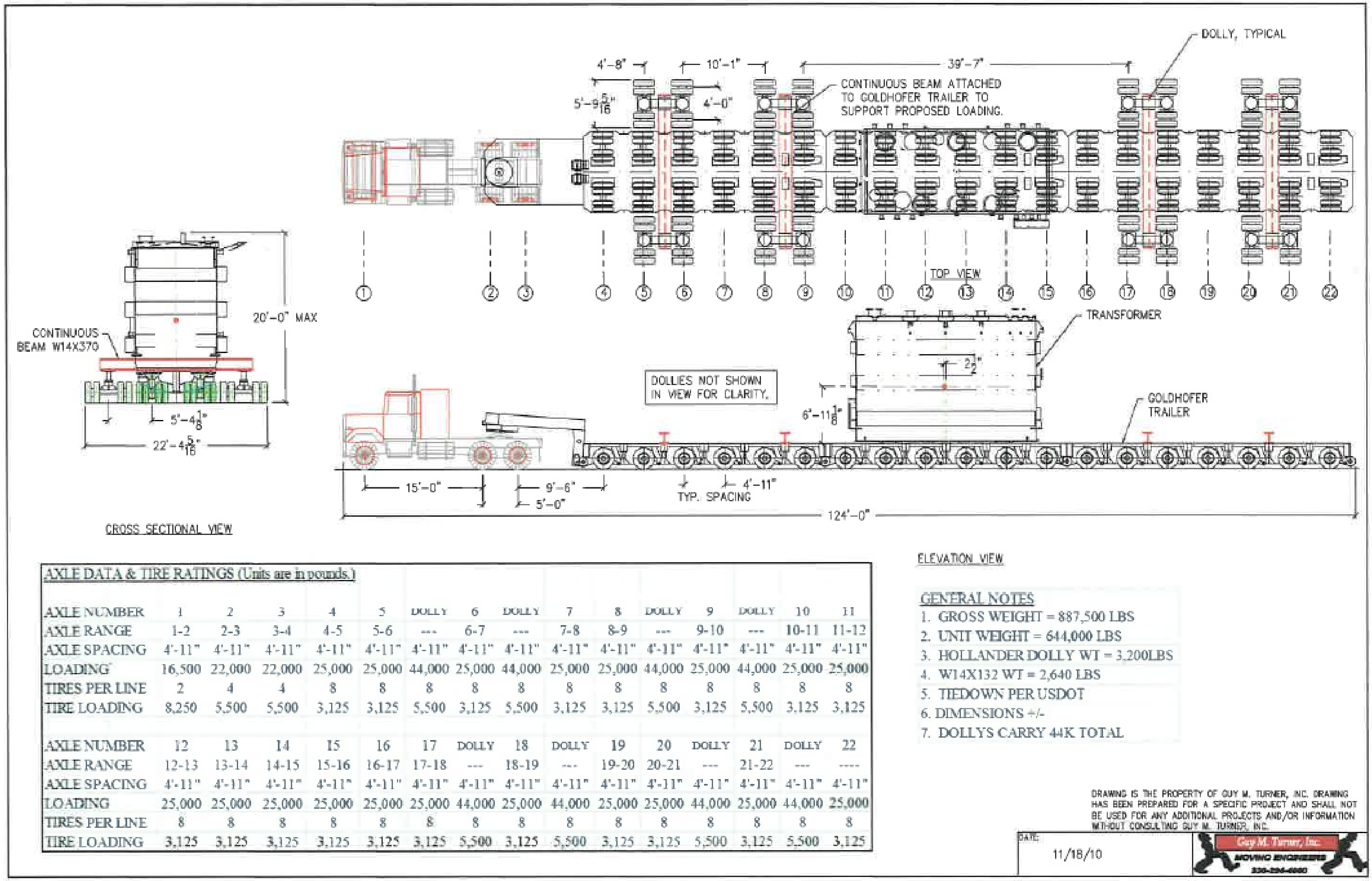


Figure 264 Truck-4: Guy M. Turner 16 Axle-Line Doublewide Modular Truck Schematic.[62]

[62] Source: NCDOT



AXLE DATA & TIRE RATINGS (Units are in pounds.)

AXLE NUMBER	1	2	3	4	5	DOLLY	6	DOLLY	7	8	DOLLY	9	DOLLY	10	11
AXLE RANGE	1-2	2-3	3-4	4-5	5-6	---	6-7	---	7-8	8-9	---	9-10	---	10-11	11-12
AXLE SPACING	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"
LOADING	16,500	22,000	22,000	25,000	25,000	44,000	25,000	44,000	25,000	25,000	44,000	25,000	44,000	25,000	25,000
TIRES PER LINE	2	4	4	8	8	8	8	8	8	8	8	8	8	8	8
TIRE LOADING	8,250	5,500	5,500	3,125	3,125	5,500	3,125	5,500	3,125	3,125	5,500	3,125	5,500	3,125	3,125
AXLE NUMBER	12	13	14	15	16	17	DOLLY	18	DOLLY	19	20	DOLLY	21	DOLLY	22
AXLE RANGE	12-13	13-14	14-15	15-16	16-17	17-18	---	18-19	---	19-20	20-21	---	21-22	---	----
AXLE SPACING	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"	4'-11"
LOADING	25,000	25,000	25,000	25,000	25,000	25,000	44,000	25,000	44,000	25,000	25,000	44,000	25,000	44,000	25,000
TIRES PER LINE	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
TIRE LOADING	3,125	3,125	3,125	3,125	3,125	3,125	5,500	3,125	5,500	3,125	3,125	5,500	3,125	5,500	3,125

Figure 265 Truck-5, Guy M. Turner 22 Axle-Line Singlewide Modular with Dollies Truck Schematic.[63]

[63] Source: NCDOT

C.2 LVECD Truck Inputs

Table 60 Truck-1: Tire Configuration Input (Estimated/Measured, lbs)

Truck Front						
Axle Group	Axle Line	*y* (ft)	+ *x* (ft)			Center Line (*x* = 0)
			4.615	3.865	3.594	
1	1	113.083		5700/6940		
2	2	95.583	4750/2950		4750/2950	
	3	91.917	4750/5385		4750/5385	
	4	87.333	4750/5180		4750/5180	
3	5	70.500	4958.5/5325		4958.5/5325	
	6	66.333	4958.5/4755		4958.5/4755	
	7	62.167	4958.5/4380		4958.5/4380	
4	8	29.667	3993.8/4230		3993.8/4230	
	9	25.000	3993.8/4040		3993.8/4040	
	10	20.333	3993.8/3930		3993.8/3930	
	11	15.667	3993.8/4260		3993.8/4260	
5	12	4.667	4612.5/4635		4612.5/4635	
	13	0	4612.5/4420		4612.5/4420	
Truck Rear						

Table 61 Truck-2: Tire Configuration Input (Estimated/Measured, lbs)

Truck Front

Axle Group	Axle Line	y (ft)	+ x (ft)						Center Line (x = 0)
			8.615	7.594	4.573	3.865	3.552	2.848	
1	1	229.167				7500/6050			
2	2	212.833				5000/3916.7		5000/3916.7	
	3	208.333				5000/3916.7		5000/3916.7	
	4	203.833				5000/3916.7		5000/3916.7	
3	5	182.583	5000/5137.5	5000/5137.5	5000/5137.5		5000/5137.5		
	6	176.833	5000/5137.5	5000/5137.5	5000/5137.5		5000/5137.5		
4	7	160.750	5000/4725	5000/4725	5000/4725		5000/4725		
	8	155.000	5000/4725	5000/4725	5000/4725		5000/4725		
5	9	141.000	5000/4643.8	5000/4643.8	5000/4643.8		5000/4643.8		
	10	135.250	5000/4643.8	5000/4643.8	5000/4643.8		5000/4643.8		
6	11	85.250	5000/4737.5	5000/4737.5	5000/4737.5		5000/4737.5		
	12	79.500	5000/4737.5	5000/4737.5	5000/4737.5		5000/4737.5		
7	13	63.417	5000/4712.5	5000/4712.5	5000/4712.5		5000/4712.5		
	14	57.667	5000/4712.5	5000/4712.5	5000/4712.5		5000/4712.5		
8	15	43.667	5000/4675	5000/4675	5000/4675		5000/4675		
	16	37.917	5000/4675	5000/4675	5000/4675		5000/4675		
9	17	24.083				6000/6350			
10	18	4.500				5000/3537.5		5000/3537.5	
	19	0				5000/3537.5		5000/3537.5	

Truck Rear

Table 62 Truck-3: Tire Configuration Input (Estimated/Measured, lbs)

Truck Front											
Axle Group	Axle Line	y (ft)	x (ft)								
			4.578	3.817	2.083	1.323	0	-1.323	-2.083	-3.817	-4.578
1	1	49.167	5497/ 4950	5497/ 4950	5497/ 4950	5497/ 4950	Center Line	5497/ 4600	5497/ 4600	5497/ 4600	5497/ 4600
	2	44.250	5497/ 4500	5497/ 4500	5497/ 4500	5497/ 4500		5497/ 4600	5497/ 4600	5497/ 4600	5497/ 4600
	3	39.333	5497/ 4300	5497/ 4300	5497/ 4300	5497/ 4300		5497/ 4150	5497/ 4150	5497/ 4150	5497/ 4150
2	4	34.417	5497/ 4250	5497/ 4250	5497/ 4250	5497/ 4250		5497/ 4700	5497/ 4700	5497/ 4700	5497/ 4700
	5	29.500	5497/ 4200	5497/ 4200	5497/ 4200	5497/ 4200		5497/ 4550	5497/ 4550	5497/ 4550	5497/ 4550
	6	24.583	5497/ 4300	5497/ 4300	5497/ 4300	5497/ 4300		5497/ 4550	5497/ 4550	5497/ 4550	5497/ 4550
3	7	19.667	5497/ 6500	5497/ 6500	5497/ 6500	5497/ 6500		5497/ 6050	5497/ 6050	5497/ 6050	5497/ 6050
	8	14.750	5497/ 6600	5497/ 6600	5497/ 6600	5497/ 6600		5497/ 5900	5497/ 5900	5497/ 5900	5497/ 5900
	9	9.833	5497/ 6500	5497/ 6500	5497/ 6500	5497/ 6500		5497/ 6200	5497/ 6200	5497/ 6200	5497/ 6200
4	10	4.917	5497/ 6700	5497/ 6700	5497/ 6700	5497/ 6700		5497/ 6200	5497/ 6200	5497/ 6200	5497/ 6200
	11	0	5497/ 6525	5497/ 6525	5497/ 6525	5497/ 6525		5497/ 6250	5497/ 6250	5497/ 6250	5497/ 6250
Truck Rear											

Note: For Truck-3 only the trailer information is available.

Table 63 Truck-4: Tire Configuration Input (Estimated Only, lbs)

Truck Front											
Axle Group	Axle Line	y (ft)	+ x (ft)								Center Line (x = 0)
			9.992	9.232	7.497	6.737	4.086	3.326	1.591	0.831	
1	1	73.750	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
2	2	68.833	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	3	63.917	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	4	59.000	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
3	5	54.083	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	6	49.167	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
4	7	44.250	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	8	39.333	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
5	9	34.417	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	10	29.500	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
6	11	24.583	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	12	19.667	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
7	13	14.750	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	14	9.833	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
8	15	4.917	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
	16	0	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	3955.5	
Truck Rear											

Table 64 Truck-5 without Dollies: Tire Configuration Input (Estimated Only, lbs)

Truck Front									
Axle Group	Axle Line	y (ft)	+ x (ft)						Center Line (x = 0)
			4.578	3.865	3.817	2.848	2.083	1.323	
1	1	118.000		8250					
2	2	103.000		5500		5500			
	3	98.000		5500		5500			
3	4	88.500	5202.9		5202.9		5202.9	5202.9	
	5	83.583	5202.9		5202.9		5202.9	5202.9	
	6	78.667	5202.9		5202.9		5202.9	5202.9	
4	7	73.750	5202.9		5202.9		5202.9	5202.9	
	8	68.833	5202.9		5202.9		5202.9	5202.9	
	9	63.917	5202.9		5202.9		5202.9	5202.9	
5	10	59.000	5202.9		5202.9		5202.9	5202.9	
	11	54.083	5202.9		5202.9		5202.9	5202.9	
	12	49.167	5202.9		5202.9		5202.9	5202.9	
6	13	44.250	5202.9		5202.9		5202.9	5202.9	
	14	39.333	5202.9		5202.9		5202.9	5202.9	
	15	34.417	5202.9		5202.9		5202.9	5202.9	
7	16	29.500	5202.9		5202.9		5202.9	5202.9	
	17	24.583	5202.9		5202.9		5202.9	5202.9	
	18	19.667	5202.9		5202.9		5202.9	5202.9	
8	19	14.750	5202.9		5202.9		5202.9	5202.9	
	20	9.833	5202.9		5202.9		5202.9	5202.9	
	21	4.917	5202.9		5202.9		5202.9	5202.9	
	22	0	5202.9		5202.9		5202.9	5202.9	
Truck Rear									

Table 65 Truck-5 with Dollies: Tire Configuration Input (Estimated Only, lbs)

Truck Front

Axle Group	Axle Line	y (ft)	+ x (ft)										Center Line (x = 0)
			10.672	9.911	6.672	5.911	4.578	3.865	3.817	2.848	2.083	1.323	
1	1	118.000						8250					
2	2	103.000						5500		5500			
	3	98.000						5500		5500			
3	4	88.500					3125		3125		3125	3125	
	5	83.583	5500	5500	5500	5500	3125		3125		3125	3125	
	6	78.667	5500	5500	5500	5500	3125		3125		3125	3125	
	7	73.750					3125		3125		3125	3125	
	8	68.833	5500	5500	5500	5500	3125		3125		3125	3125	
	9	63.917	5500	5500	5500	5500	3125		3125		3125	3125	
	10	59.000					3125		3125		3125	3125	
4	11	54.083					3125		3125		3125	3125	
	12	49.167					3125		3125		3125	3125	
	13	44.250					3125		3125		3125	3125	
	14	39.333					3125		3125		3125	3125	
	15	34.417					3125		3125		3125	3125	
5	16	29.500					3125		3125		3125	3125	
	17	24.583	5500	5500	5500	5500	3125		3125		3125	3125	
	18	19.667	5500	5500	5500	5500	3125		3125		3125	3125	
	19	14.750					3125		3125		3125	3125	
	20	9.833	5500	5500	5500	5500	3125		3125		3125	3125	
	21	4.917	5500	5500	5500	5500	3125		3125		3125	3125	
	22	0					3125		3125		3125	3125	

Truck Rear

Table 66 Standard Normal Truck: Tire Configuration Input (Estimated Only, lbs)

Truck Front					
Axle Group	Axle Line	*y* (ft)	+ *x* (ft)		Center Line (*x* = 0)
			3.854	2.833	
1	1	53.980		6000	
2	2	40.630	4000	4000	
	3	35.670	4000	4000	
3	4	4.840	4500	4500	
	5	0	4500	4500	
Truck Rear					

C.3 Wayne County Case Study

Case Studies of Superload Impacts on Pavement

Introduction

During 2011 the NCDOT Oversize and Overweight Unit issued 4800 permits for superloads. On average, this is just over ninety-two every week. 129 of these loads had a GVW greater than 350,000 pounds, thus requiring a pavement assessment from the NCDOT Pavement Management Unit.

A superload is defined as any vehicle with a gross vehicle weight (GVW) of greater than 132,000 pounds. Any super load with a GVW greater than 350,000 pounds requires a pavement study by the Pavement Management Unit. These loads are carried by a variety of hauler configurations. An example 1 million pound super load on a dual Goldhofer transporter is shown in Figure 266. It occurred in September 2011 in Wayne County. A gas turbine was carried from Dudley to the Progress Energy Plant.

Case Study Survey

To initiate the case study data collection, NCSU research team members developed a survey that the NCDOT Pavement Management Unit sent to each of the 100 District Engineers. Ten responses were received. Eight of the ten responded that their district had not experienced superloads. The districts which did report superloads on their roads stated that no visible damage occurred to the pavement surface from the runs. The following case studies were written from information provided by the District Engineers and the Pavement Inspectors that were on-site while the loads were moved.

Wayne County Case

Introduction

This case study reviews the effects of repeated super loads on a route in Wayne County, North Carolina. The route is primarily on US117 in addition to several side roads. It will represent a qualitative assessment of visible change, or lack thereof, in pavement quality on the route. 132 super load permits were issued for the route; seventy-six of which had a gross vehicle weight of greater than 350,000 pounds. The runs occurred predominantly from March 2011 to July 2011 with intermittent runs throughout the rest of the year.

Several questions are to be answered in this case study are:

- Do repeated, approved super loads along the road cause visible damage to the pavement?
- Does the use of steel plates covering small culverts have any negative effects to the surrounding pavement?
- Does the practice of covering box culverts with ramps (jumper bridges) have any adverse effects?

The initial thought entering this case study was that the repeated runs of the super loads would not have any visible, negative effects to pavement quality. Based on conversations with a director from the oversize/overweight permit unit, the lack of “called upon” bonds, and survey answers from surrounding district engineers, no visible, negative effects were expected in the pavement quality resulting from repeated runs of the super loads. The route was inspected before, during, and after the runs. As expected, no visible, adverse effects were observed.

The super load is transferred from the rail line to the carrier in Dudley, North Carolina. The route in this study travels from this location in Dudley, North Carolina, to the Progress Energy power plant in Goldsboro, North Carolina (Figure 267). A high number of super loads were required while the power plant was converted from coal powered to natural gas. The pavement along the route is the original pavement with one overlay, which was added at a later date.

The directions for the runs are as follows and can be visualized in the map in Figure 267. From the Georgia Pacific plant and rail siding at a point on SR1926 (Old Mount Olive Highway), go south to SR1120 (Sleepy Creek Road). Then, turn west and travel to SR1120 (Oberry Road). Travel west to US117 North, and go north on US117 to US13. Travel west on US13 to SR1220 (Providence Church Road) on which travel north to SR1219 (Old Grantham Road). Then, turn west and head to SR 1223 (Black Jack Church Road). Finally, turn north and travel on SR1223 (Black Jack Church Road) to the destination. The total route is 12.5 miles long.

This route was permitted for a super load 132 times total. The average gross vehicle weight of the 132 permits was 414,973 pounds. Eight of the loads were extremely heavy, weighing more than 740,000 pounds. Seventy-six of these permits were issued for loaded trailers with a gross vehicle weight greater than 350,000 pounds. The remaining permits were for unloaded trailers weighing less than 350,000 pounds. The 350,000-pound weight limit is significant because all super loads with gross vehicle weight greater than this require a pavement study by a State Pavement Design Engineer from the NCDOT Pavement Management Unit.

During a phone interview, Chris Pendergraph, District Engineer for NCDOT District 3, indicated that 56 super loads ran this particular route and that there were no other super loads on the surrounding streets. The discrepancy between the numbers 56 and 132 could be explained by issued permits that do not result in an actual super load trip. Permits are only valid for ten days. Therefore, if the company misses that ten-day window, they must renew the permit for the move.

This particular route was chosen because of its accessibility by rail and proximity to the Progress Energy plant. In addition, the high number of heavy loads and availability of pre-run and post-run pavement inspections made this route a significant and viable option for a case study. Gary Darden, a NCDOT pavement inspector, inspected the route prior to the super load runs and noted the initial condition of the pavement.

Wayne County Case Study Assessment

The initial thought is that if current NCDOT practices are followed for approving the route and moving the load, unacceptable pavement damage to the main section of road will not result from the passing super loads. This premise is based on conversations with practicing engineers at the NCDOT and with the Oversize/Overweight Permit unit. They have indicated that the bond required for some super loads have only been called upon once and that was over a decade ago at Newcor Steel. During this move, it was known that the load would destroy the pavement but no other viable option was available to the carrier. The lack of consistent, historical damage indicates that any destruction would typically result from running off of the road or running into infrastructure on the shoulder.

The data was collected through a visual inspection by a trained NCDOT inspector, Gary Darden. The inspector drove the route prior to the run and followed the load in a truck (Figure 268). The initial and final conditions of the pavement were noted. The three pavement conditions considered were edge cracking, pavement cracking, and rutting. In addition, pictures were taken during the run. Special measures taken by the carrier were also noted which included steel plates for small culverts and ramps (jumper bridges) for box culverts.

For all of the moves, there was no additional edge cracking, pavement cracking, or rutting. Steel plates were used to cross five small culverts and ramps (jumper bridges) covered three box culverts. Neither the steel plates nor the jumper brides caused any damage to the pavement and successfully prevented any damage to the culverts. Refer to the Figure 269 for an example of the jumper bridges used.

Wayne County Case Conclusions

The route was approved by the NCDOT Pavement Management Unit and granted a permit by the Oversize/Overweight Permit Unit. The multiple runs of the super loads caused no visible damage to the pavement surface of the route. Whether the lack of damage resulted from following the current NCDOT procedures or other reasons relating to the load and pavement is unknown. The only damage caused during any of the runs was that power lines were pulled down during one move. These results are consistent with other super load moves according to conversations between the project team and practicing engineers at the NCDOT and a director from the Oversize/Overweight Permit unit.

The table below represents relevant data that was available for this case study.

Relevant Statistics/Data	
Available Data	Not Available
Total number of super loads	Original pavement structure
Gross vehicle weight of each load	Weighed axle loads of each run
Observations of prior and final edge cracking	Laboratory tested cracking and rutting obtained through a core sample to back-up the visual inspection
Observations of prior and final pavement cracking	
Prior and final rutting	
History of additional pavement layers added (road maintenance)	
Estimated axle loads of each run	

Figure 266 Wayne County Super Load, Dual Goldhofer.

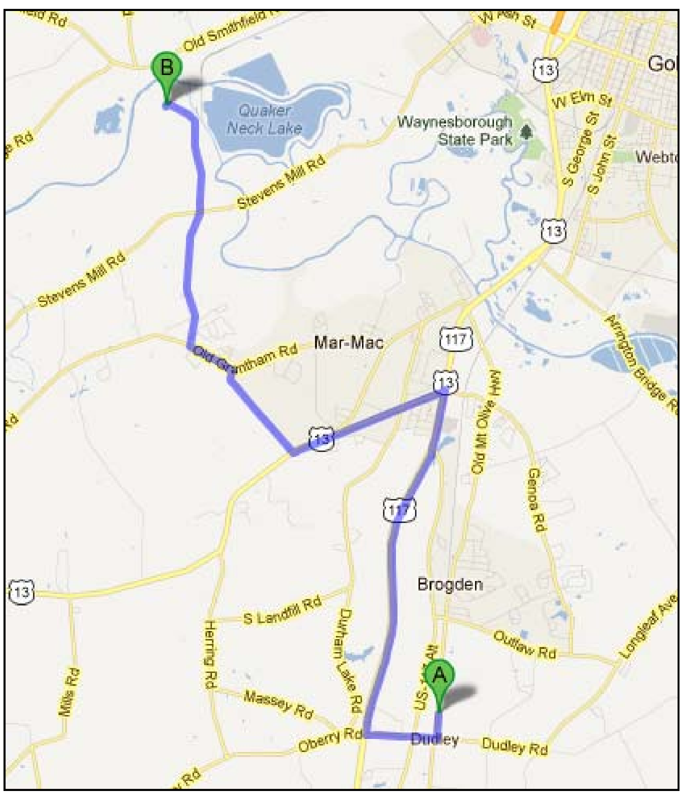


Figure 267 Wayne County Super Load Route.

Figure 268 Wayne County Super Load Carried by a Dual Goldhofer Truck.

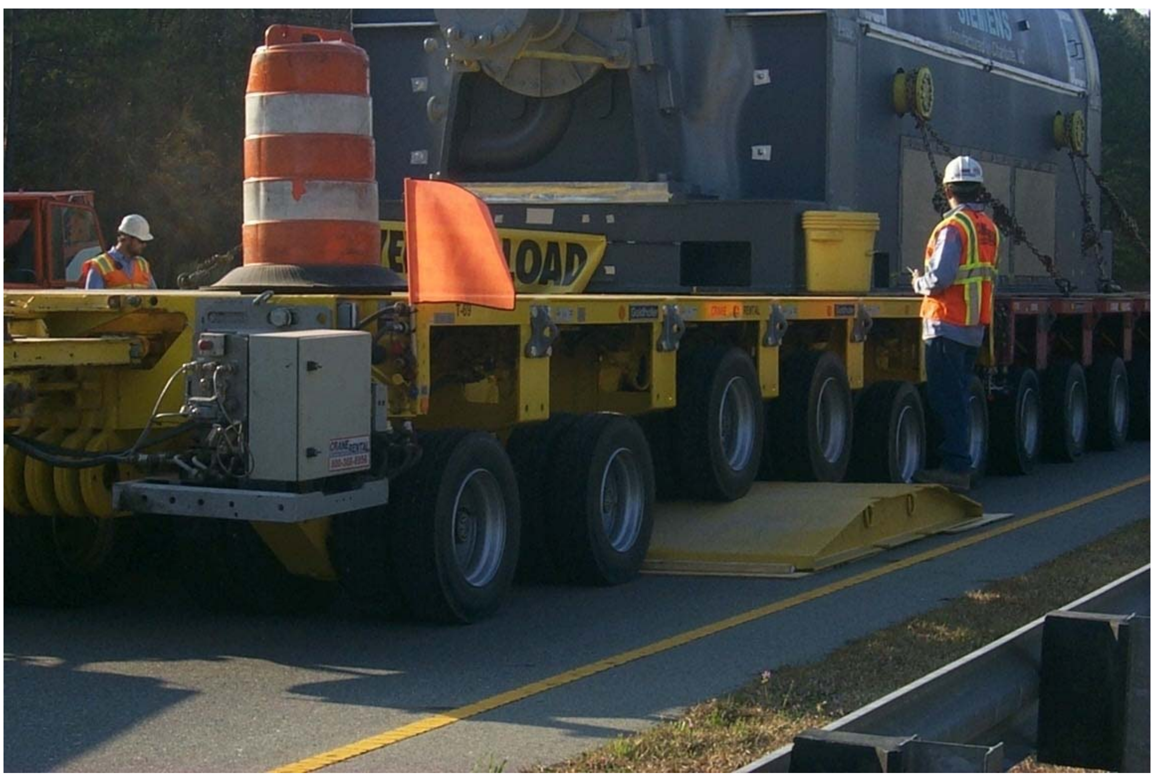


Figure 269 Wayne County Job and Jumper Bridge.

Superload Truck Survey

To: NCDOT District Engineers February 8, 2012

Re: Superload Truck Survey (> 350,000 lb)

The following short survey will support NCDOT Research Project 2012-10 “Analysis of Truck Load Weight Distribution in North Carolina” being conducted by NC State University. Part of the pavement task involves documenting several cases of multiple superload truck movements on the same route of flexible pavement segments. Your answers to the following questions will be very helpful. We intend to follow up with several District Engineers or Inspectors who can provide additional details.

Thanks for your help.

John Stone, PhD

Professor of Civil Engineering

NC State University

(919) 515-7732, stone@ncsu.edu

==

Your name, title, & contact information (phone, email):

1) In 2011 did your District have any recurrent super heavy movements (>350,000 lbs GVW) on the same highway route segments? Yes/No If “no”, please skip to the end, and return your survey.

2) In 2011 how many recurrent super heavy movements (>350,000 lbs GVW) occurred on the same route segments?

   Case 1

   Case 2

   Case 3

3) What months did the movements occur?

   Case 1

   Case 2

   Case 3

4) What were the origins and destinations of the recurrent movements:

   Case 1

   Case 2

   Case 3

5) What routes were used?

   Case 1

   Case 2

   Case 3

6) What were the names of the carrier trucking companies?

   Case 1

   Case 2

   Case 3

7) Identify any damage to the roadway either from an individual movement or collectively after all the super heavy loads passed over the segment.

   Case 1

   Case 2

   Case 3

8) If you report "no damage" in the previous question, have you ever had any pavement damage from superloads (either single or recurrent loads)? Explain.

9) Please identify any superloads (>350,000 lbs gross) movements scheduled for your district in March, April or May 2012.

10) Who should we contact with any follow-up questions?

    Name

    Title

Phone number

E-mail

Please return your survey by March 1 to Professor John R. Stone by email, fax or US Mail.

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Fax: (919) 515-7908