CHARACTERIZATION OF PRESTRESSED CONCRETE AND STEEL BRIDGE GIRDERS AGAINST HEAVY TRUCK LOADING

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ABSTRACT: Heavy truck traffic affects the service life of highway bridge superstructures. Damage typically occurs in the bridge deck and in the superstructure main elements. This damage may be mainly due to a bending moment that could exceed the load capacity of the bridge, and/or fatigue damage of the super structure girders (steel bridges).

The goal of this research is to characterize bridge population sensitive to bending moment. This was done based on a static analysis of steel and prestressed concrete (PSC) girder bridges of different configurations subjected to the AASHTO design truck (HL-93), the 97-kips trucks (97-S and 97-TRB), and AASHTO legal rating truck (3S2). Moreover, based on the site-specific WIM data, the site-specific representative heavy vehicles (160 and 170 kip) and the site specific fatigue truck (85 kip) were analyzed.

For static analysis, five different steel and PSC girder bridges of different practical spans (30, 60, 90, 120, and 140 ft) and configurations were modeled by two different programs to provide confidence on the accuracy of the analysis, a commercial program (CSiBridge) and an AASHTOWare Bridge Rating program. The results provide the bending moment at the most critical sections of girders under the selective heavy truck presence case. For the PSC bridges, the site-specific representative heavy vehicle induced the most critical load case for the 60- to 100-ft long PSC bridges; however, the 30-ft-long steel bridge was unsafe under the application of the strength-I load factors but turned to be safe with the application of the strength-II load factors.

KEYWORDS: Prestressed girder bridge, Steel Girder Bridge, Heavy truck loading

1 INTRODUCTION

The use of heavy vehicles such as 18-wheelers is the backbone of logistics and economic success in the United States. National projections predict that freight shipments will double in the next 10 years. Economic projections indicate that

freight commodities are rapidly on the rise.

As freight volumes shipped by heavy vehicles in the United States continue to increase, and the weight and number trucks are still fixed, the "trickle-down effect" will take place. Commodity prices will increase if heavy vehicle size and weight limits are not reformed. The increase in freight demand must be accommodated by increasing the number of trucks, increasing the weight of heavy vehicles, or both. It is quite obvious that increasing the number of heavy vehicles or the weight of heavy vehicles is detrimental to bridge longevity. Today, the masses and dimensions of heavy vehicles are strictly regulated. There is an ongoing debate on this issue, with demands from several activists to allow longer and heavier vehicles on the roads. Legislation has been introduced in the Senate entitled," The Safe and Efficient Transportation Act of 2011." This act aims to increase the gross vehicle weight limit for trucks operating on the US Interstate Highway System.

This legislation hopes to have positive impacts on economic development, environment and safety on highways and interstates. However, the effects on bridges are expected to be negative. There is no doubt that any truck-weight limit increases could raise the number of structurally deficient and critical failure bridges all over the country.

Overstress usually occurs in cases of an occasional loading consisting of two or more trucks in close proximity. Such an extreme situation is a rare event; nevertheless it must be considered and designed for accordingly. This is usually done by magnifying the legal loading to make it similar to an extreme one, and using safety factors like the multiple presence factor, which accounts for the possibility of several trucks simultaneously.

Traditionally, engineers used conservative methods to evaluate the bridge elements sizes, so there is always a high strength reserve. So, despite the limitations of funds allocated for maintenance, bridges maintained significant levels of safety with few major collapses due to heavy vehicles overloads. This is because [1].

Therefore, a careful study with realistic bridge and truck modelling is critical to prevent potentially catastrophic impacts. Consideration was given to the congressionally proposed rating vehicle (97 kip) [2], AASHTO design truck (HL-93), and AASHTO legal rating truck (3S2). Moreover, other configurations of heavy vehicles based on the site-specific WIM data were considered.

This study aims to provide a policy architecture within which the current and future prestressed girder-type bridges can be evaluated and assessed based on their site-specific load WIM data (i.e. traffic volume and traffic load). This approach can be used to estimate the impacts of alternative vehicles on safety, infrastructure performance, and traffic-volume and loads. However, limitations in data and analytical methods preclude precise answers. The study is not intended to provide specific policy recommendations. Rather, it will provide a fact-based framework within which policy alternatives to the current regulations

may be considered.

2   BACKGROUND
2.1 History of Truck size and Weight Regulations
Most bridges in the United States were constructed during the 1950's and 1960's. Post- World War II economic expansion and transportation needs led to the introduction of higher capacity trucks. Increasing the amount a truck can legally weigh by changing regulations can have many positive effects, such as decreasing transport costs and allowing to faster economic development. Nevertheless, two main bridge responses must be carefully studied: overstress and fatigue.

Highway officials realized that increasingly heavy trucks were becoming a problem and needed to be regulated as early as 1918. In 1932, a recommendation was made by state highway officials to set a single-axle limit of 16,000 pounds and a tandem axle limit based on the distance between two axles [3].

In 1946, the American Association of State Highway Officials (AASHO) revised the previous policy by suggesting single-axle limits of 18,000 pounds and tandem axle limits of 32,000 pounds. Vehicles with extreme axles at least 57 feet apart were given a maximum weight limit of 73,280 pounds. In 1956 the federal aid highway legislation was issued applying the AASHO 1946 policy (18,000 pounds single axle limits, tandem axle limits of 32,000 pounds and gross vehicle weight of 73,280 pounds).

In order to protect bridges from excessively heavy loads, in 1975 the Congress issued truck weight regulations limiting the gross weight of trucks to 80,000 pounds, with the single-axle weight now being 20,000 and the tandem-axle weight now 34,000 pounds.

Although the weight of a truck is critical, the length of the truck is also important. Under a constant load, a shorter truck will cause more damage to bridges due to load concentration. Therefore, the legislation also introduced a formula to limit the weight-to-length ratio of a truck by spreading the weight over more axles or increasing the distance between axles. The weight-to-length formula is known as Formula B [4]:

$$W = 500 \left[\frac{LN}{(N-1)} + 12N + 36 \right] \tag{1}$$

Where, W is the maximum weight in pounds carried by any groups of two or more axles, L is the distance in feet between any groups of two or more axles, and N represents the number of axles is taken into consideration.

2.2 Utilized Programs

AASHTOWare Bridge Rating Program is a comprehensive bridge-rating tool developed by AASHTO and used by most of departments of transportation (DOTs). It is the tool for rating bridge superstructures in accordance with the AASHTO Manual for Condition Evaluation of Bridges, AASHTO Manual for Bridge Evaluation, AASHTO Standard Specification, and AASHTO LRFD Specification.

CSiBridge Program is a commercial program used by some of bridge engineering community. It is a tool for the modelling, analysis, and design of bridge structures tailored to meet the needs of engineering professionals.

3   IDEALIZATION OF BRIDGE STRUCTURES
3.1 Applied Vehicular Loads

In order to effectively analyze the effects of trucks on bridges and propose a solution to any issue, it was important to use a sufficient number of proposed models not only with varying weights but different lengths. The vehicular load includes the extreme lengths of the AASHTO LRFD truck (HL-93) (28 and 44 ft.) [5], Congress proposed truck 97 kip (97-TRB and 97-S) [2], and AASHTO legal rating truck (3S2) [2]. Moreover, the predicted site-specific fatigue and representative heavy vehicles from the recorded WIM data at site 915 in Alabama (85, 167, 170-kip trucks) [6], see figure 1.

The proposed 97-kip truck was designated in both models. The shorter truck is designated as 97-S (40 ft.), while the longer one is designated as 97-TRB (65 ft.). Both trucks have six axles; the front axle is 12 kips while the other 5 axles are 17 kips each. The AASHTO rating truck, 3S2, is one of five selective legal loads specific to the state of Alabama, weighing 80 kips with a length equal to 41 feet with 5 axles. The spacing of tandem axles is 4 feet [2].

The 85-kip truck is similar in effect to the 97-S truck, with a total length of 41 feet, and five axles with the front axle at 12 kip, while the other four axles are 21 kips weight each. The tandem axles are spaced 4 feet apart. The 167-kip truck has a total length of 57 feet and five axles; the front axle is 21 kip, while the other five are 36.5 kips each. It is the second heaviest truck used in the analysis. The tandem axles have a spacing of 5 feet. Finally, the 170-kip truck with a total length of 57 feet has five axles; the front axle is 22 kips while the other five are 37 kips each. It is the heaviest truck used in this study and expected to cause the most critical load to the analyzed bridges [6].

3.2 Bridge Configurations

Five simply supported PSC and steel girder bridges with spans of 30, 60, and 90 ft with four numbers of girders and 120 and 140 ft. with 6 numbers of girders were FE modeled and analyzed to investigate the flexure. These bridges have a

28-ft-width roadways with and concrete deck with thicknesses of 6 to 9 in. The bridge components parameters were designed based on AASHTO design specifications (2010). Both bridge types' configurations are shown in Figure 2 through Figure 5. The different bridges structural members' configurations and capacities are illustrated in Table 1 and Table 2.
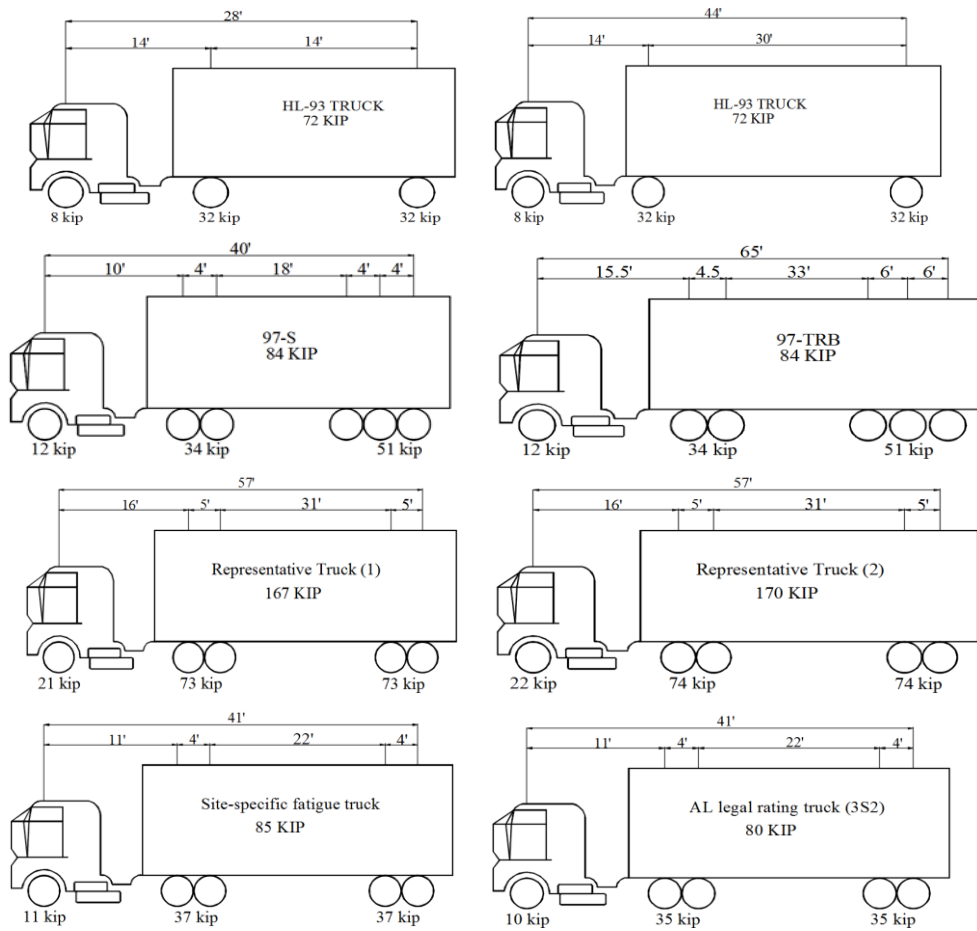

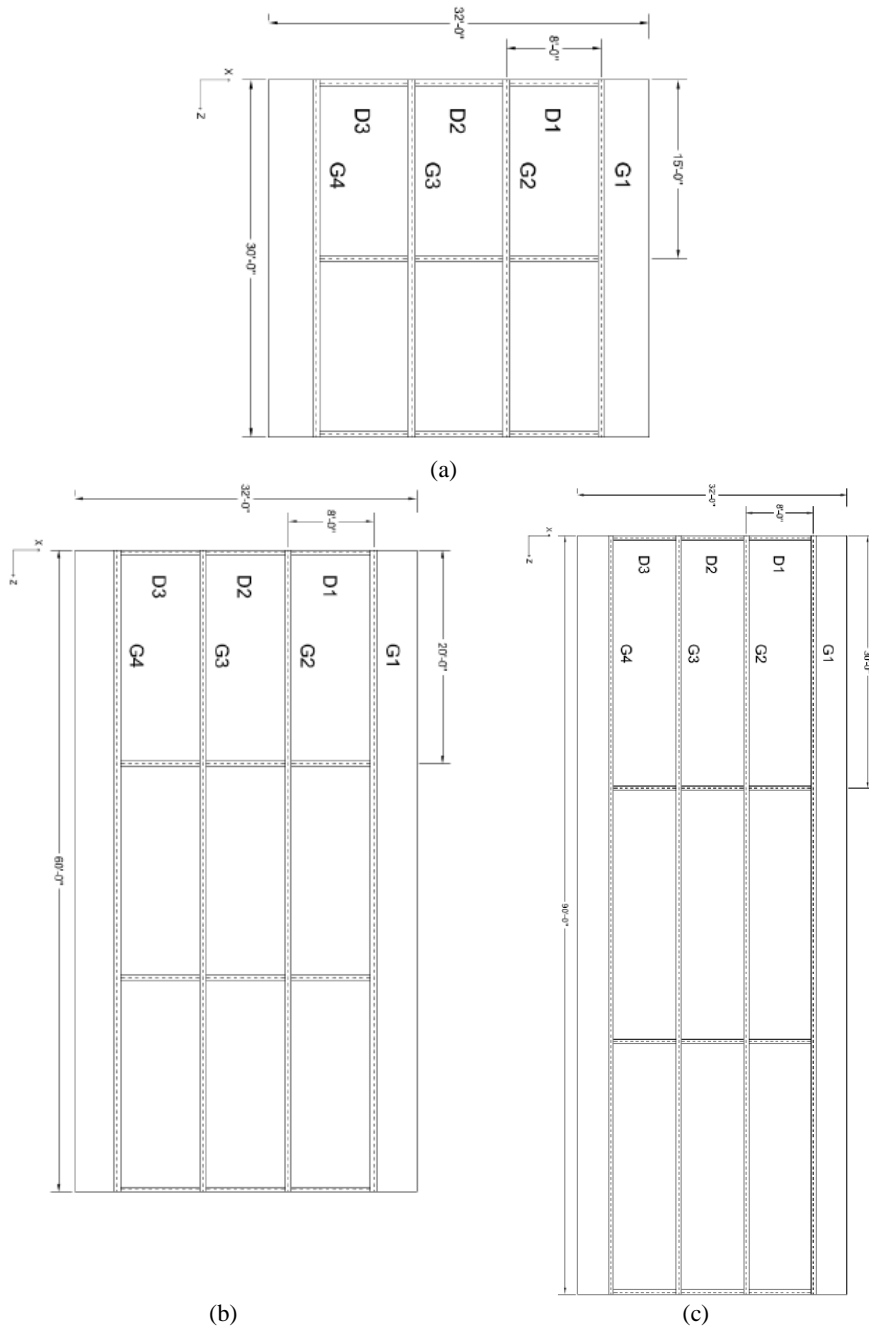*Figure 1.* Considered vehicular live load – trucks configuration

(a)

(b)

(c)

Figure 2. Schematic diagram of bridge configurations (a) 30 ft (b) 60 ft (c) 90 ft
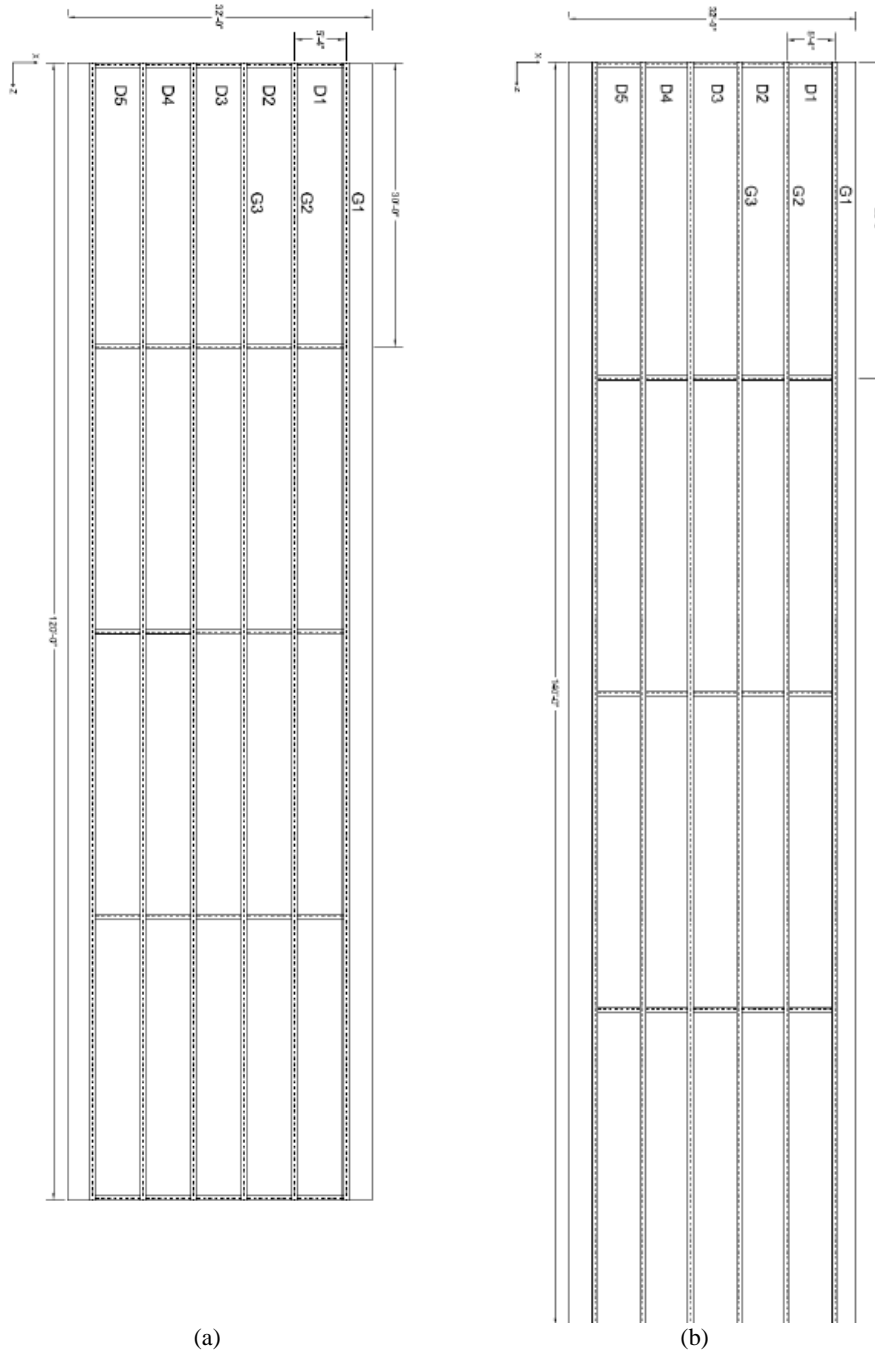
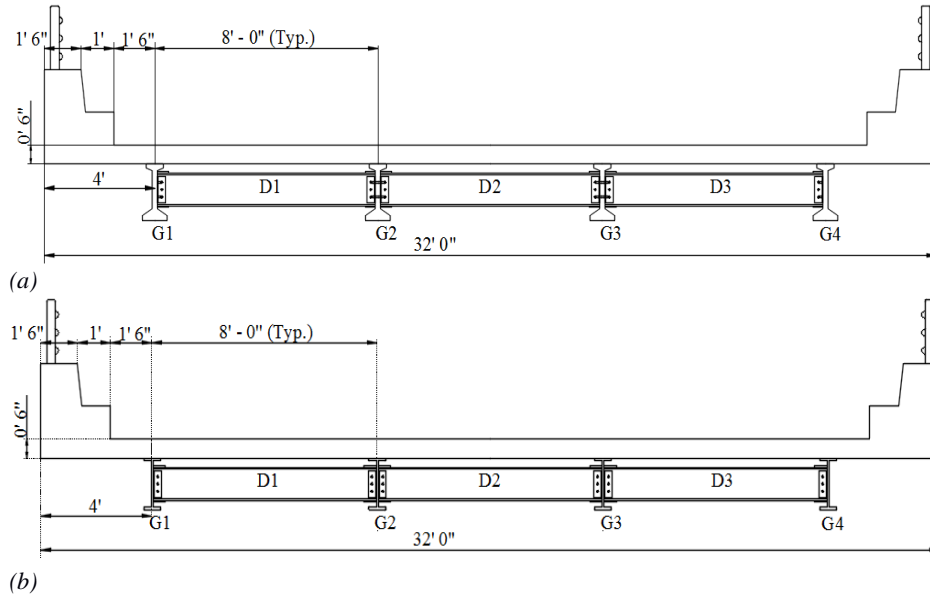*Figure 3.* Schematic diagram of bridge configurations (a) 120 ft (b) 140 ft

(a)

(b)

Figure 4. Typical schematic bridge cross-section (a) prestressed concrete (b) steel

Table 1. Prestressed concrete bridge girder configuration and capacities

Span (ft)	Girder Sec.	Diaphragm Section	Diaph. Spacing	No. of Strands	No. of Harped Strands	Slab Thickness (in)	Concrete Strength f_c'	Moment Capacity (kips.ft)
30	III	W10X30	15	12	4	8	5000	2041
60	III	W16X77	20	20	6	8	5000	3274
90	V	W21X101	30	32	6	8	5000	7049
120	VI	W24X131	30	38	8	9	6000	9429
140	VI	W24X131	35	56	10	9	6000	13203

4   MODELLING AND ANALYSIS

CSiBridge and AAHTOWare finite element models were developed for every single bridge length, including all structural (girders, deck, and diaphragm) and non-structural (wearing surface and barriers) superstructure components. Every bridge was subjected to different vehicular loads one at a time to capture the bending on the exterior and interior girders of each truck load. The captured bending moment depended on the strength-I limit state load factors for dead and live loads ($\gamma_{DC} = 1.25$, $\gamma_{DW} = 1.35$, $\gamma_{LL} = 1.75$) [7].
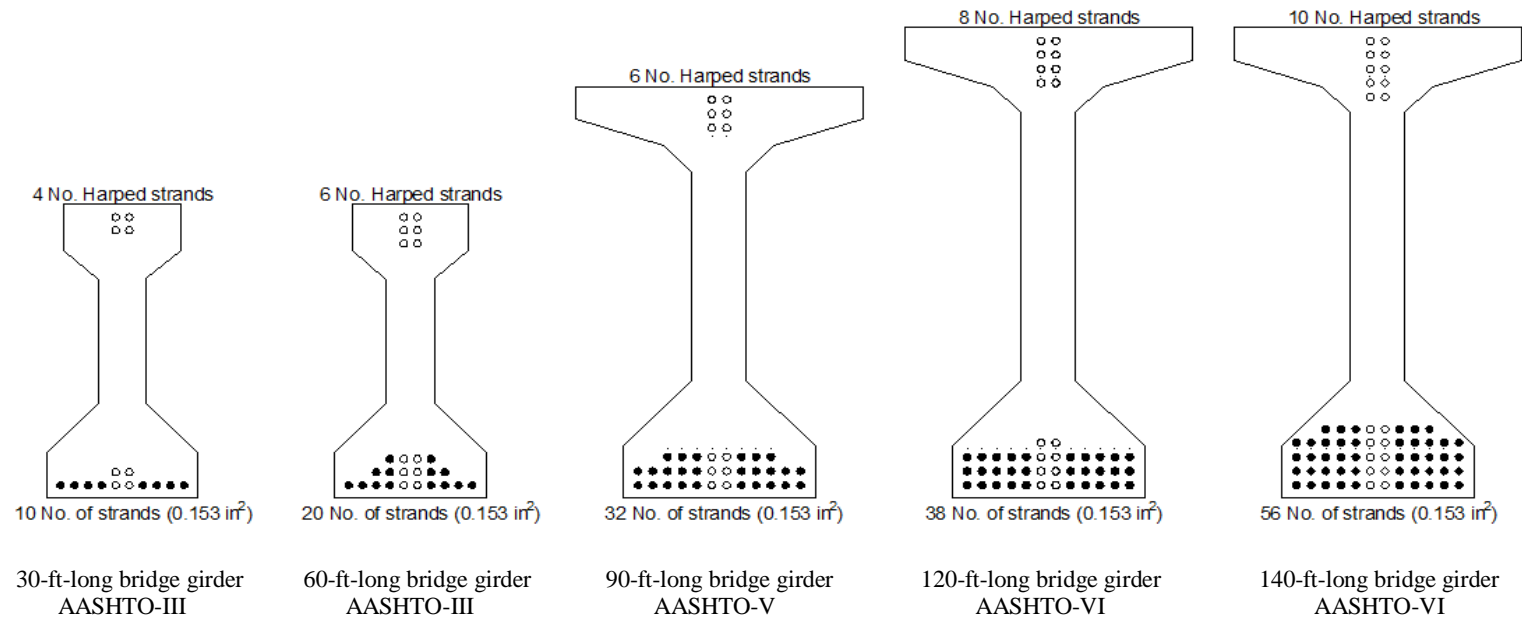
Figure 5. Girders prestrssing strands configurations

Table 2. Steel bridge girder configurations and capacities

Span (ft)	Girder Section	Diaphragm Section	Diaphragm Spacing (ft)	Slab Thickness (in)	Fy (ksi)	M_n (kip.ft)
30	W16x57	W10x30	15	6	50	901
60	W16x77	W16x77	20	6	50	2914
90	W30x292	W21x101	30	6	50	5763
120	W40x392	W24x131	30	6	50	9535
140	W40x431	W24x131	35	6	50	13239

Deck: Reinforced concrete deck of 4000 psi compressive strength, 6 in. thickness, and rests on steel girders having specific properties obtained from the American Institute of Steel construction (AISC) manual 14 edition [8]. A 4-ft overhang section acts as a cantilever on both ends of the deck. This section usually holds the barrier of the bridge, which prevents derailed cars from falling off it.

Asphalt: In general, asphalt ranges from 1.3 to 3.15 inches thick [9]. In this study an asphalt thickness of 3 inches.

Steel Diaphragm: The purpose of diaphragms is to resist wind loads and provide stability. They are considered secondary members of the superstructure and acts in a vertical plane. They are not used as bracing members, but are used to prevent lateral deformation [5].

5   RESULTS AND DISCUSSION

The BM developed by both FE modelling programs (CSiBridge and AASHTOWare) due to different vehicular load cases over the PSC bridges girders and those of steel bridges girders were captured and recorded.

Generally, except for of 30-ft-long PSC Bridges, the recorded bending moment over the exterior girders is greater than those over the interiors. Also, the heavier trucks (167 and 170 kip) have almost the same bending of the AASHTO design truck (HL-93, 28 to 44 ft). Moreover, bending moments induced by those vehicles over the exterior girders are nearly equal the nominal bending moment in the most common bridges span length (60 to 100 ft). This means that the best bridge design is for bridges of spans ranging between 60 and 100 ft.

In addition, the results captured for the same gross vehicle weight but different total length indicate that the shorter the truck length the more impact on the bridge, which clarifies the relationship between truck total length and its impact on bridges, as shown in Figure 6.
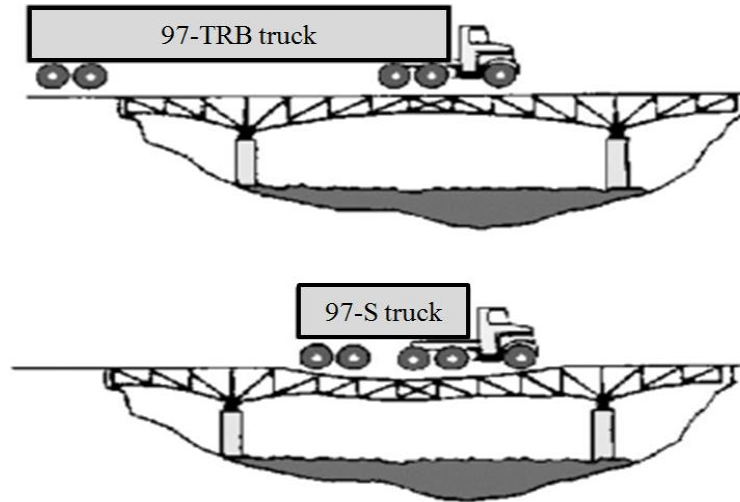
Figure 6. Interaction of bridge span length and spacing of truck axle groups [10]

Figure 7 to 10 depict the recorded total moments due to different vehicular loads and the nominal moment versus the bridge length of the PSC and steel bridges girders, respectively. Those show that the AASHTOWare FE models give higher bending moment values than those captured by the CSiBridge program FE models. For PSC bridges of span length less than 60 ft and greater than 100 ft, the captured bending moments in the exterior girders by both programs are almost the same under different vehicular loads.

For all bridges, under different vehicular load cases, the AASHTOWare program FE models give BM results closer to the nominal bending moment values than those captured by the CSiBridge-program FE models. Additionally, the bending moments extracted from the AASHTOWare program FE models have the same trend as the nominal bending moment at different bridges span lengths, but the CSiBridge FE models results have not except for spans less than 60 ft.

As seen in Figure 11, under the inventory load factors, representing the ratio of the ultimate bending moment to the nominal moment (M_u/M_n) for the PSC bridges exterior girders subjected to the heavier vehicle loads (HL-93, 167, and 170 kip) developed by both FE modelling programs illustrates that all bridges are safe in normal operation (inventory) conditions.

Under the inventory load factors (Strength-I, $\gamma_p =1.75$), Figure 12 (a) shows the ratio of the captured ultimate moment (M_u) of the most critical vehicle loads (HL-93, 167, and 170 kip) developed by CSiBridge and AASHTOWare models to the nominal moment (M_n). These illustrate that all steel bridges are safe in normal operation (inventory) conditions except the shortest bridge (30 ft) under

the application of the representative heavy vehicles (167 and 170 kip). Apply the operating load factors (Strength-II, γ_p =1.35) to check the safety of this bridge in case of unexpected seldom loads. Figure 12 (b) shows that the 30-ft-long bridge, due to the application of the operating load factor, turns out to be safe.

6 CONCLUSION

The goal of this research was to provide a method to characterize the bridge population sensitivity due to flexure. This was achieved by analyzing five PSC and steel bridges with spans of 30, 60, 90, 120, and 140 ft. subjected to the static load of a set of different configurations heavy vehicles.

These vehicular loads represent the current AASHTO design truck (HL-93) of extreme length (28 and 44 ft. long), AASHTO rating truck (3S2), 97-kips Congress proposed trucks (97-S and 97-TRB), and the site-specific representative heavy vehicles (167 and 170 kip) and the site-specific fatigue truck (85 kip). The bridges were loaded in such a way to produce the worst scenario, the maximum bending moment, over the girders.

The bridges were analyzed under the static load of those vehicular loads by two different FE modeling programs. One is developed by AASHTO and is known as the AASHTOWare Bridge Rating program and the other program is a commercial program called CSiBridge.

Generally, analysis showed that in most examined bridge populations, the exterior girders sustain a higher bending moment than the interiors, as expected. Also, the optimum design of PSC bridges occurs for those of spans 60 to 100 ft. Moreover, for the same GVW, results showed that the shorter the heavy vehicle, the higher the bending moment. In addition, the bending moment developed by the AASHTOWare program FE models have almost the same trend as the computed nominal bending moments, but the CSiBridge program FE models do not. The FE models in both programs develop almost the same bending moment for exterior and interior girders of the 120-ft-long bridge.

For short bridge spans, less than 60 ft., both live loads and dead loads are equally important. For longer spans, greater than 100 ft., where truck length is less than the bridge span, the weight of the traffic is much less significant than the weight of the bridge.

Specifically for this site, the bridges designed for the AASHTO design truck (HL-93) are capable of accommodating worst load scenarios for the representative heavy vehicle safely. Under the inventory load factor conditions, the vast majority of the examined bridge populations were safe. However, the 30-ft-long unsafe bridge turned out to be safe with the application of operating load conditions.
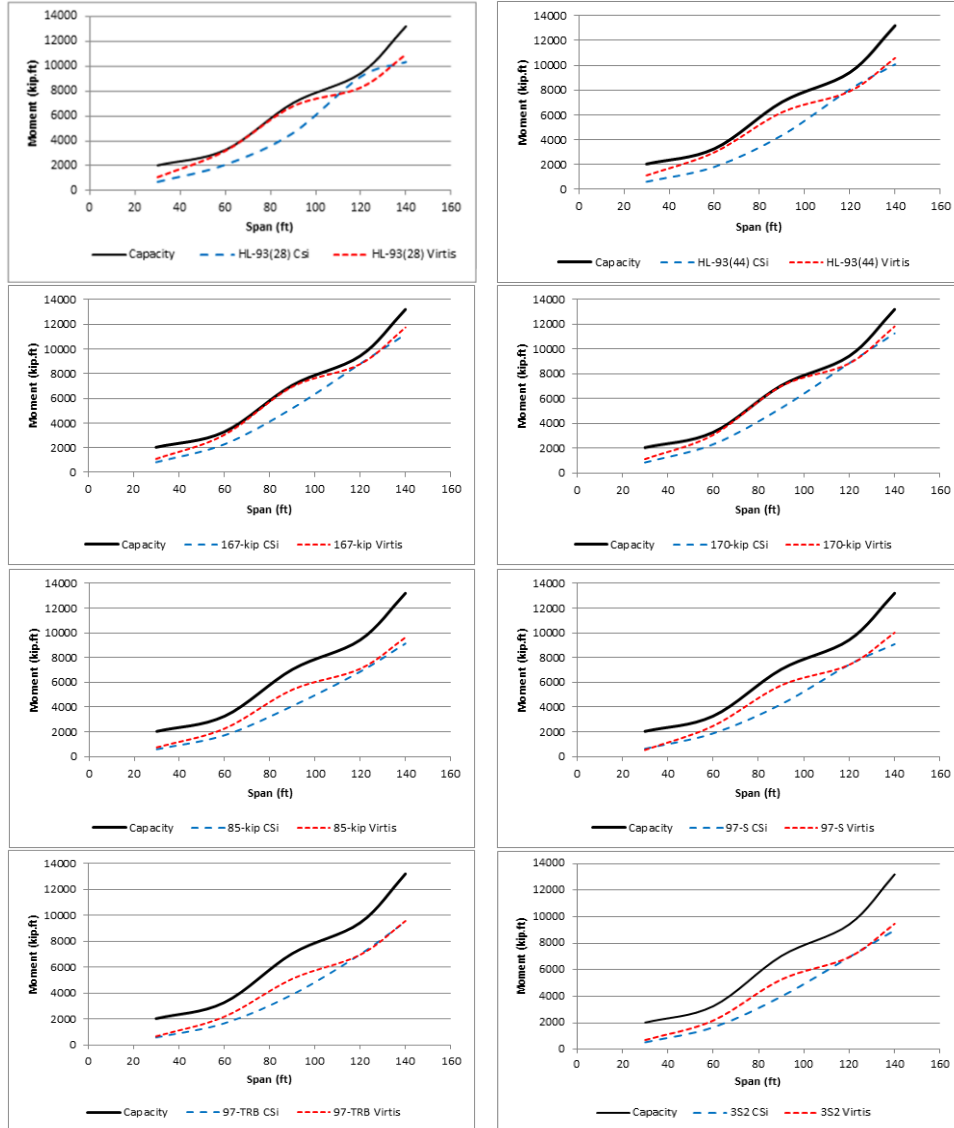
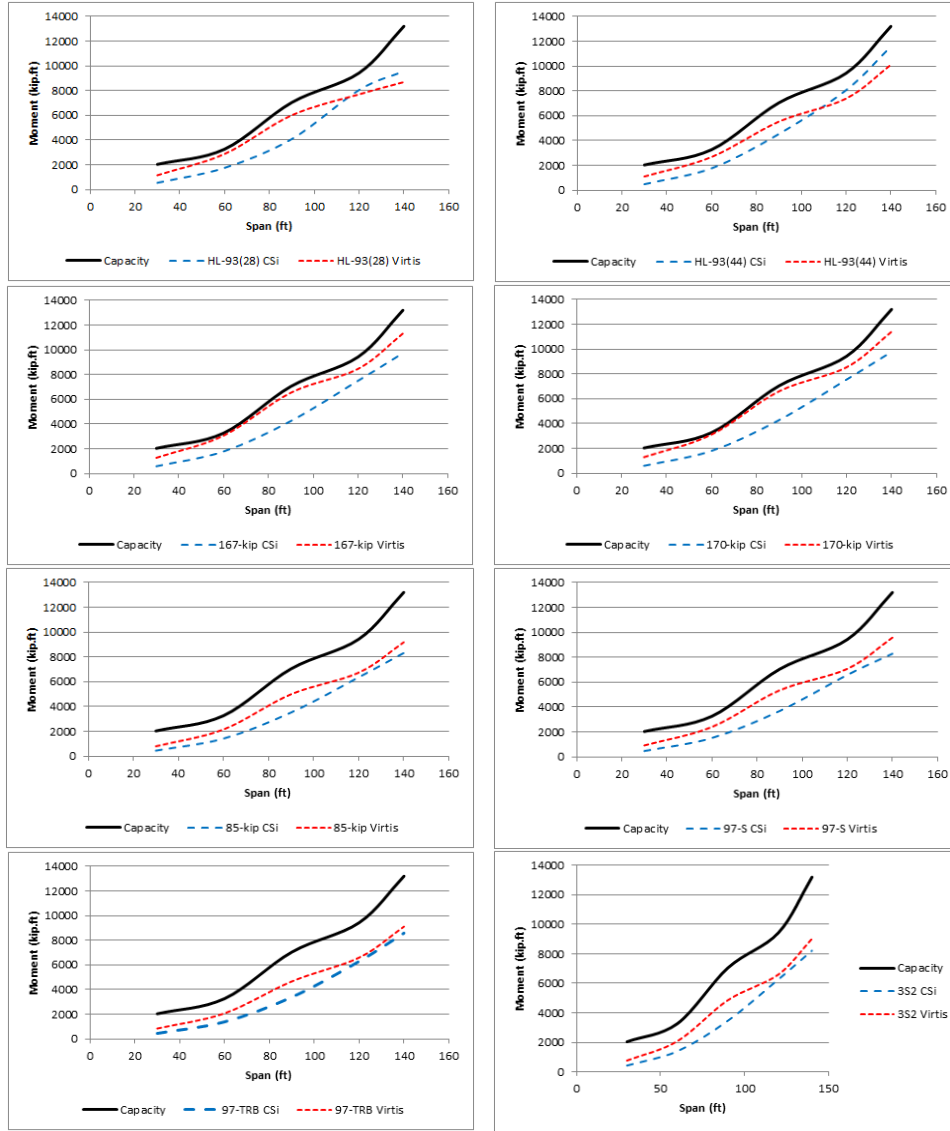*Figure 7.* Different trucks BM on PSC exterior girder and M_n vs. span length

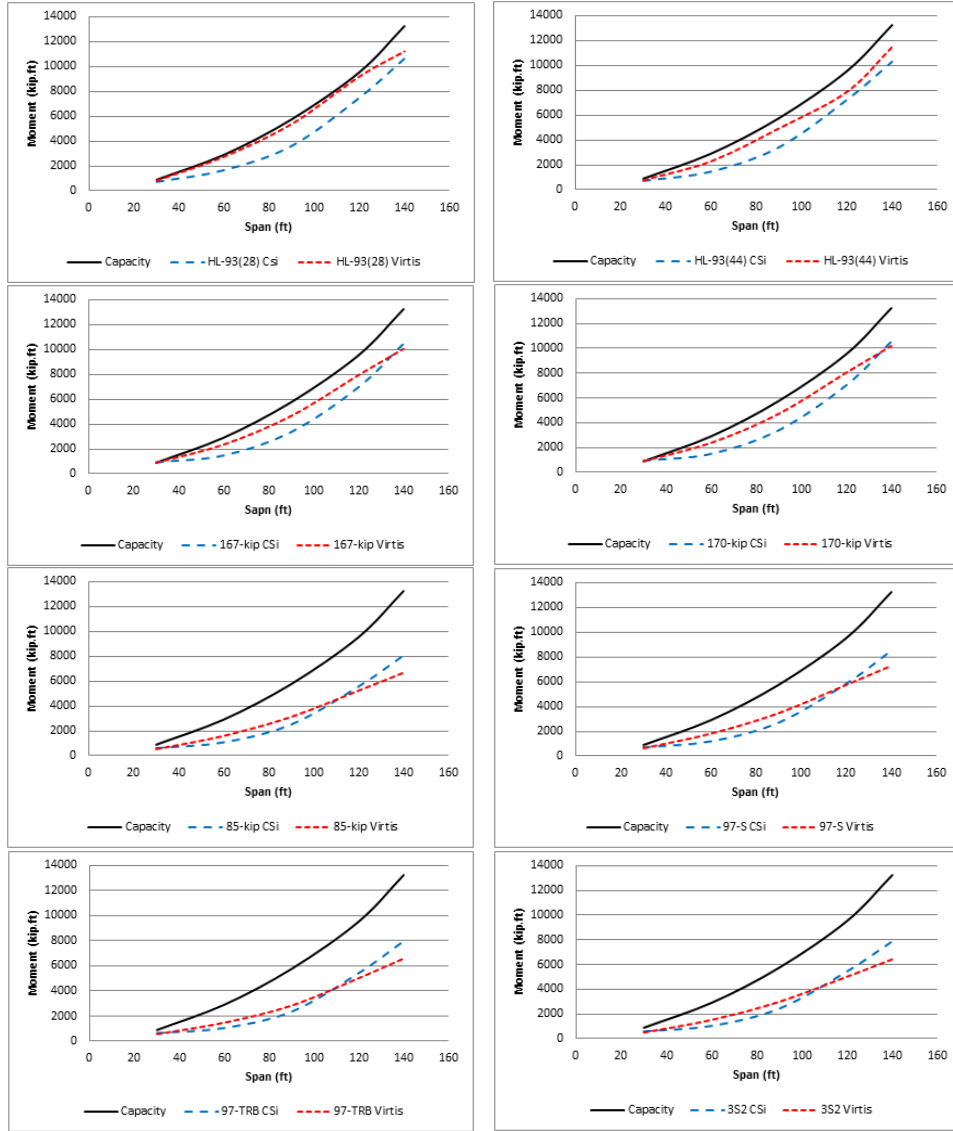*Figure 8.* Different trucks BM on PSC interior girder and M_n vs. span length

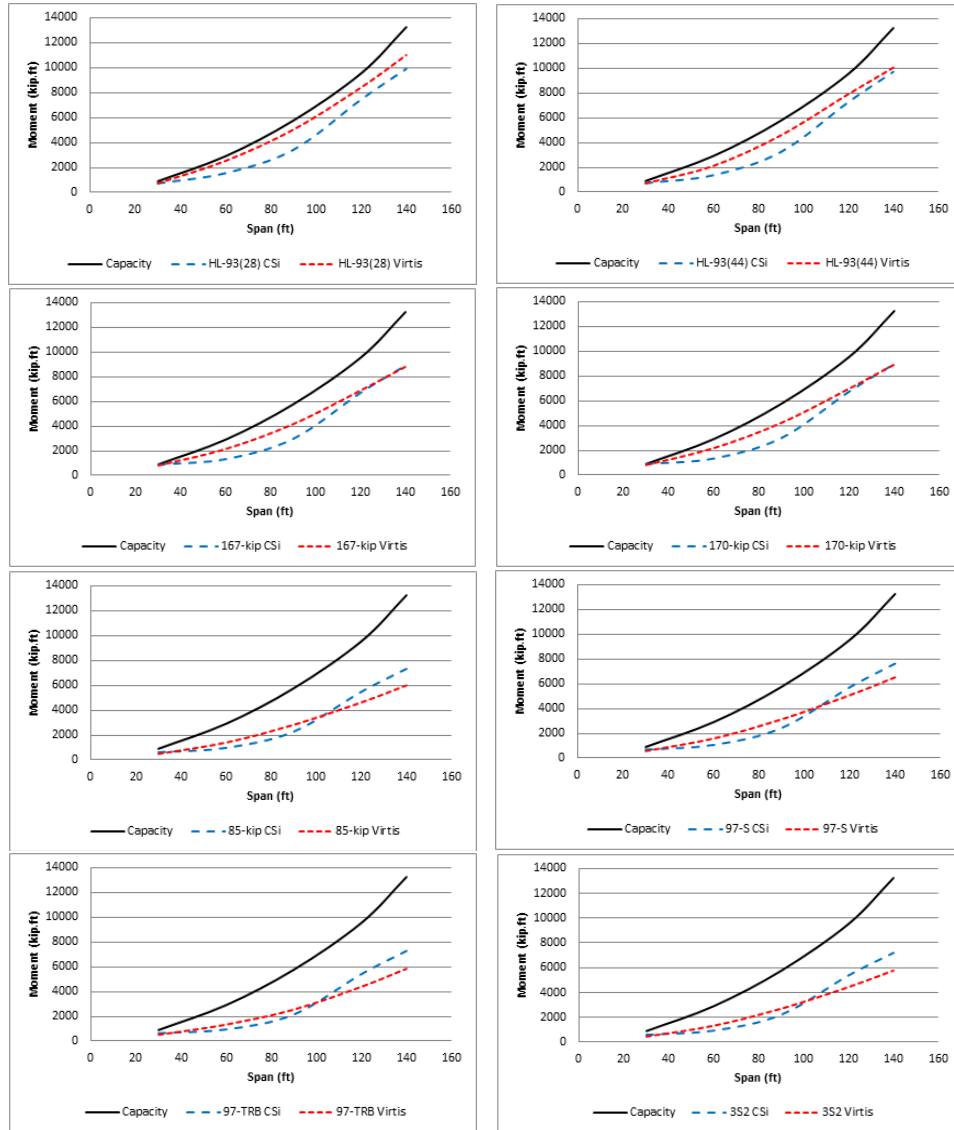*Figure 9.* Different trucks BM on steel exterior girder and M_n vs. span length

Figure 10. Different trucks BM on steel interior girder and M_n vs. span length
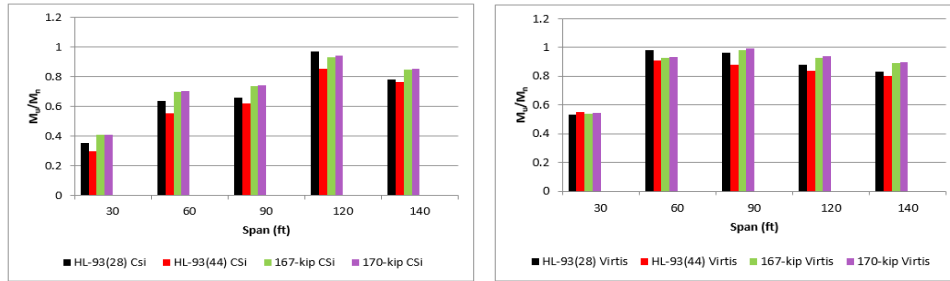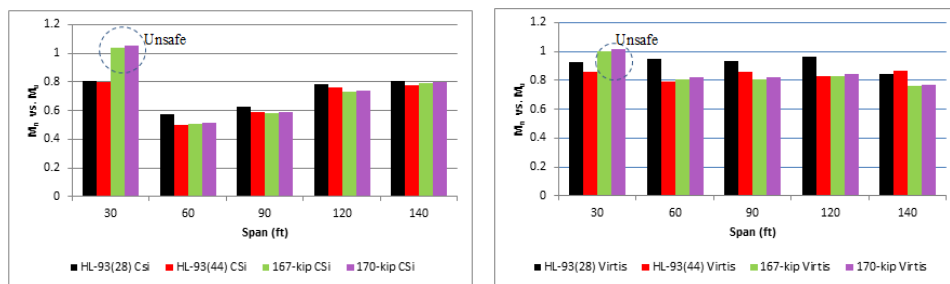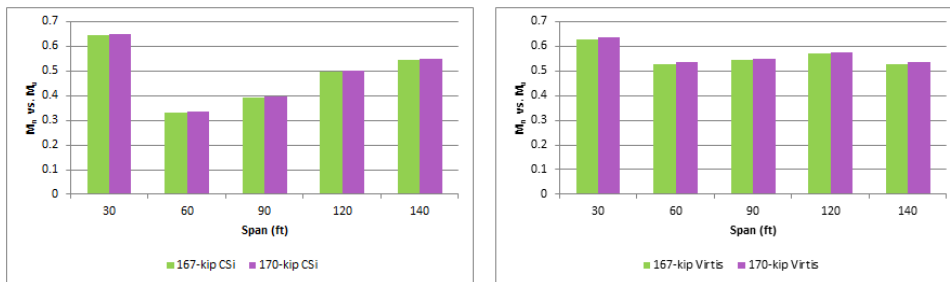
Figure 11. Exterior PSC girders M_u/M_n vs. span length - inventory conditions

(a)

(b)

Figure 12. Exterior steel bridge girders M_u/M_n vs. span length – (a) Inventory load factors (b) Operating load factors

7   FUTURE RESEARCH

More extensive and detailed studies are needed to better and thorough quantifying of the heavy truck weight effects over bridge population characterization by analyzing the effects of different truck configurations on bridges. The concepts of deflection and fatigue were not covered in this study. The effects of wind, earthquake, temperature and other geological factors were not analyzed. It is impossible to measure the impacts of heavier trucks without taking into consideration all of the specific factors surrounding the bridge itself.

ACKNOWLEDGEMENTS

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