STRUCTURES RESEARCH ON CALL SERVICES

TASK 1 FINAL REPORT –
ASSESSMENT OF THE LOAD RATING OF BRIDGES WITH A LOAD RATING FACTOR GREATER THAN 1.35 TO MEET SPECIALIZED HAULING VEHICLE REQUIREMENTS

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16. Abstract

The statistical study considered real bridges in Ohio with a rating factor (RF) ≥ 1.35 whose section properties may vary along the length of the bridge. A sample of these bridges was examined. The sample included a minimum of thirty bridges of the each of the six common types studied. No actual bridge was found to have an SHV RF < 1.00. To extend the study the ratio of the Ohio legal RF to the SHV RF was calculated for all bridges in the sample. Three simple span bridges whose spans were from 70 – 80 ft. had a ratio greater than 1.35. The maximum ratio was 1.37.

Because the sample size of a statistical study is limited, a parametric study of single and multi-span bridges was conducted. The parametric study considers live load effects on a hypothetical bridge with uniform stiffness and addresses all practical spans for simple span bridges and all practical ratios on interior to exterior spans for multi-span bridges. The maximum span length considered for simple and multi-span bridges was 200 ft. For simple span bridges, the highest ratio of RFs was 1.36 for an 80 ft. span. For multi-span bridges, the highest ratio of RFs for positive moment and negative moment was 1.35 and 1.37, respectively. Shear did not govern in the parametric study for any bridges.

The consistency of the statistical and parametric studies shows the general applicable of the parametric model.

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EXECUTIVE SUMMARY

Background

NCHRP Project 12-63 (Report 575) found that typical AASHTO Type 3, 3-S2, and 3-3 legal trucks used as the basis for load-rating do not envelope all legal loads. Short, single-unit trucks with heavy closely spaced axle-loads, referred to as Specialized Hauling Vehicles (SHVs) have lower load ratings than AASHTO legal loads. SHVs weighing up to 80,000 pounds and meeting the Federal Bridge Formula B requirements may cause forces exceeding the forces due to HS20 loading by up to 22% and AASHTO Type 3, 3S2 and 3-3 loads by more than 50% in certain cases. These higher-force effects are for bridges with shorter spans or elements with shorter load lengths, such as transverse floor beams.

Per the FHWA memo HIBT-10, dated November 15, 2013, State Departments of Transportation (DOTs) are required to incorporate SHVs in their load-rating basis and post bridges. Unless:

- The state verifies that the State laws preclude SHV use
- The State has its own set of vehicle models for legal loads that envelope the applicable AASHTO SHV loading models

Previously, Ohio used its own set of legal trucks (2F1, 3F1, 4F1 and 5C1) for load rating. The SHVs are legal in Ohio and the Ohio Legal Loads do not envelop the SHVs. Thus, ODOT is required to incorporate SHVs in their load ratings as directed by the FHWA memo. An initial comparison of moments produced by SHVs showed an increase of approximately 25% over the Ohio legal trucks. Therefore, ODOT divided its bridge inventory into three groups:

- Group A - Ohio Legal Rating Factor ≥ 1.35
- Group B - $1.00 \leq$ Ohio Legal Rating Factor ≤ 1.35
- Group C - Ohio Legal Rating Factor ≤ 1.00

ODOT hypothesized that common types of Ohio bridges with their longest span less than 200 ft. and rating factor (RF) ≥ 1.35 for Ohio legal loads will have a RF ≥ 1.0 under SHV loads. Thus, bridges with a rating factor greater than 1.35 would not require posting for SHVs. This hypothesis was tested through statistical and parametric studies. This report presents the results of those studies.

Statistical Study

The statistical study was conducted by examining a random sample of bridges with a RF ≥ 1.35. A sample of 187 bridges from Group A with the longest span less than 200 ft. were selected. The bridges in the sample were load rated for the Ohio legal loads and the SHV loads using AASHTOWare BrR software. A six common bridge types were considered: concrete slab simple spans, concrete slab continuous, prestressed concrete beam simple and continuous, prestressed concrete box beam simple and continuous, steel beam simple and steel beam continuous. In Ohio, multi-span prestressed bridges are designed as continuous, but load rated as simple spans. Therefore, for prestressed bridges, the simple and continuous spans were lumped together. A variety of spans, and skews were chosen to represent the bridge population in Ohio. At least, thirty bridges chosen from each type.

In the sample taken for statistical study, none of the bridges have a controlling SHV RF less than 1.0. However, two out of 33 prestressed box beam bridges and one out of 30 steel simple span bridges had a ratio of Ohio legal load RF to SHV RF greater than 1.35. This means that a similar bridge with an Ohio legal load RF equal to 1.35 would have had an SHV RF less than 1.00. The highest ratio of RF for the box bridges were 1.36 and 1.37 for 76 ft. and 80 ft. simple span bridges respectively. The highest ratio of RF for a simple span steel bridge was 1.36 for 70 ft. span bridge. All three bridges with a RF ratio greater than the 1.35 value were simple span and have a span from 70 to 80 ft.

Parametric Study

The parametric study was done by examining the ratio of live load forces for Ohio legal loads and SHVs on theoretical single and multiple span bridges of uniform stiffness. This ratio leads to the same results as the ratio of the RFs. The characteristics of the parametric study were:

- The only parameter that was varied was span length.
- A constant unit stiffness along the entire length of the bridge was considered for the parametric study.
- The parametric study included single and multiple spans bridges with a span range from 10 ft. to 200 ft. with an increment of 5 ft.
- A ratio of 0.5 to 1.0 for exterior to interior span was considered for multi-span bridges.
- The bridges were loaded with all the Ohio legal trucks and the SHV SU4, SU5, SU6 and SU7 trucks sequentially.
- Only live load effects were considered.
- A single truck was considered on the bridge at a time.

For the parametric study of simple span bridges, the ratio of controlling RFs increases from 15 to 80 ft., having 1.35 ratio at a span of 70 ft. and a maximum ratio of 1.36 for span 80 ft. followed by a decreasing trend. A ratio of 1.36 means the controlling RF for SHV could fall to 0.99 for a bridge if its controlling RF for Ohio Legal Load is 1.35. Shear did not control in any of the cases. This was consistent with the statistical study.

The parametric study of multi-span bridges was done in two stages. Since thousands of span combinations could be possible in the inventory, the first stage was to find the most conservative span configurations. It was found that two-span bridges are more conservative than other multi-span configurations, except for negative moment when the ratio of exterior to interior span is equal or greater than 0.96. However, when the ratio of exterior to interior span is greater or equal to 0.96, positive moment controls over negative moment. Therefore, a two-span bridge configuration always produce conservative load rating results and analysis was performed only on a series of theoretical two-span bridges with exterior to interior span ratio of 0.5 to 1.0. The second stage of the parametric analysis was to evaluate the ratio of controlling RFs for the series of two span configurations.

For multi-span bridges, none of the ratios of RF fall below 1.35 for positive moment and the critical configuration was 85 ft. – 55 ft. which had a rating factor of 1.35. The critical ratio of RF for negative moment was found to be 1.37 for a 30 ft. – 20 ft. span configuration. There was no bridge of these dimensions selected in the statistical study. The closest was a continuous slab bridge having a span configuration of 22 ft. – 22 ft. which had a ratio of RFs 1.25. Therefore, the parametric study was consistent with the statistical study.

Conclusion

The statistical study considered real bridges in Ohio with a rating factor ≥ 1.35 whose section properties may vary along the length of the bridge. A sample of these bridges was examined. The sample included a minimum of thirty bridges of the each of the six common types studied. No actual bridge was found to have an SHV RF < 1.00. To extend the study the ratio of the Ohio legal RF to the SHV RF was calculated for all bridges in the sample. Three simple span bridges whose spans were from 70 – 80 ft. had a ratio greater than 1.35. The maximum ratio was 1.37.

Because the sample size of a statistical study is limited, a parametric study of single and multi-span bridges was conducted. The parametric study considers live load effects on a hypothetical bridge with uniform stiffness and addresses all practical spans for simple span bridges and all practical ratios on interior to exterior spans for multi-span bridges. The maximum span length considered for simple and multi-span bridges was 200 ft. For simple span bridges, the highest ratio of RFs was 1.36 for an 80 ft. span. For multi-span bridges, the highest ratio of RFs for positive moment and negative moment was 1.35 and 1.37, respectively. Shear did not govern in the parametric study for any bridges.

The consistency of the statistical and parametric studies shows the general applicable of the parametric model.

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Assessment of Bridges Of Specialized Hauling Vehicle Requirement

1 Problem Statement

NCHRP Project 12-63 (Report 575) found that typical AASHTO Type 3, 3-S2, and 3-3 legal trucks (Fig. 1) used as the basis for load-rating do not envelope all legal loads. Short, single-unit trucks with heavy closely spaced axle-loads, referred to as Specialized Hauling Vehicles (SHVs) have lower load ratings than AASHTO legal loads. SHVs weighing up to 80,000 lbs. and meeting the Federal Bridge Formula B requirements may cause stresses exceeding the stresses due to the HS20 loading by up to 22% and Type 3, 3S2 and 3-3 loads by more than 50% in certain cases (*1*). The federal weight law states-

- Single axle limited to 20,000 lbs.
- Axles closer than 96 inches apart (tandem axles) limited to 34,000 lbs.
- Gross vehicle weight is limited to 80,000 lbs.

These higher-force effects are for bridges with shorter spans or elements with shorter load lengths, such as transverse floor beams. Per the FHWA memo HIBT-10, dated November 15, 2013, state Departments of Transportation (DOTs) are required to incorporate SHVs in their load-rating basis and post bridges. Unless:

- The state verifies that the State laws preclude SHV use
- The State has its own set of vehicle models for legal loads that envelope the applicable AASHTO SHV loading models

Previously Ohio were using its own set of legal trucks (2F1, 3F1, 4F1 and 5C1) (Fig. 2) for load rating. The SHVs (Fig. 3) are legal in Ohio and the Ohio Legal Loads do not envelop the SHVs. So, ODOT has to incorporate SHVs in their load rating scheme as per FHWA. A simple in-house comparison of moments produced by SHVs showed an increase of approximately 25% over the Ohio legal trucks.

ODOT bridge inventory is divided into three groups-

- Group A- Ohio Legal RF $\geq$ 1.35
- Group B- 1.00 $\leq$ Ohio Legal RF $\leq$ 1.35
- Group C- Ohio Legal RF $\leq$ 1.00

ODOT hypothesized that Ohio bridges with a span less than 200 ft. and current RF $\geq$ 1.35 (Group A), based on Ohio legal loads will not require load posting for SHVs, unless a change in conditions occurred which would require an updated load rating analysis, e.g. new wearing surface or, deterioration.

2 Goal

To test the hypothesis that Ohio bridges with a span less than 200 ft. and current RF $\geq$ 1.35 (Group A), based on Ohio legal loads will not require load posting for SHVs through a statistical study and a parametric study. The statistical study was conducted by examining a sample of bridges in Group A to investigate the reduction in load rating for SHVs. The parametric study was done by examining theoretical single and multiple span bridges of uniform stiffness.

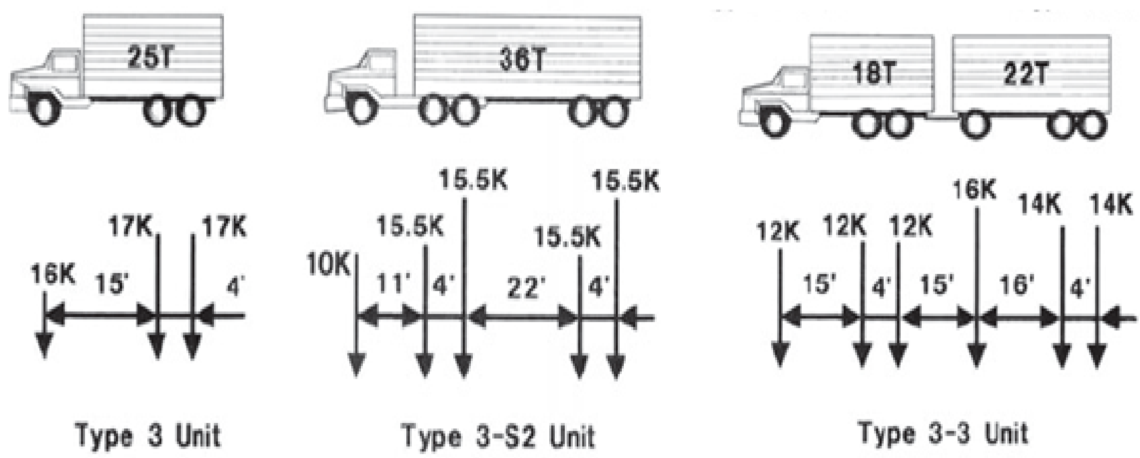


Fig. 1 AASHTO Legal Loads Type 3, 3-S2, 3-3 (FHWA 2005)

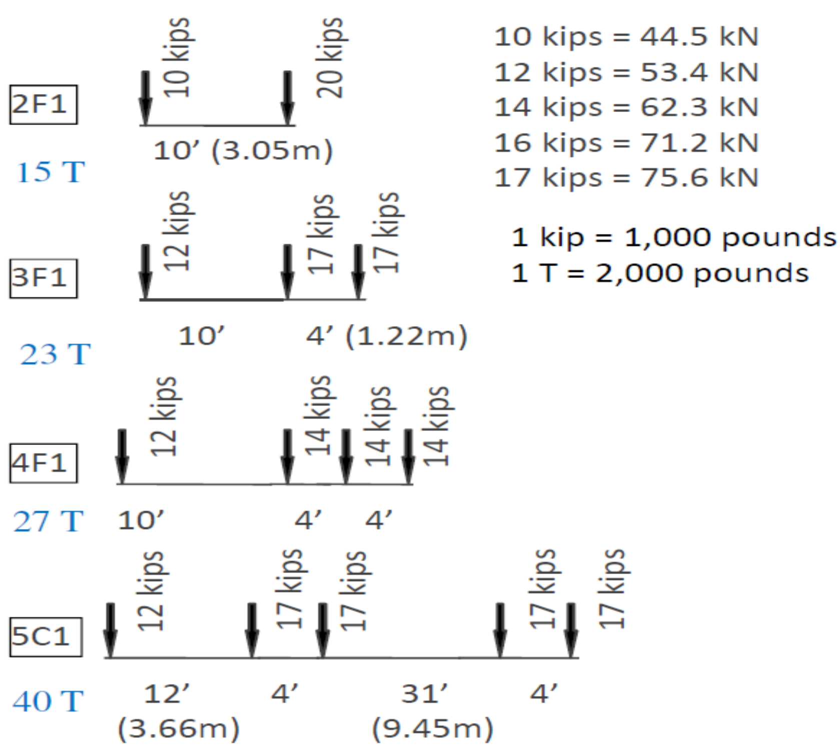


Fig. 2 Ohio Legal Loads 2F1, 3F1, 4F1, 5C1

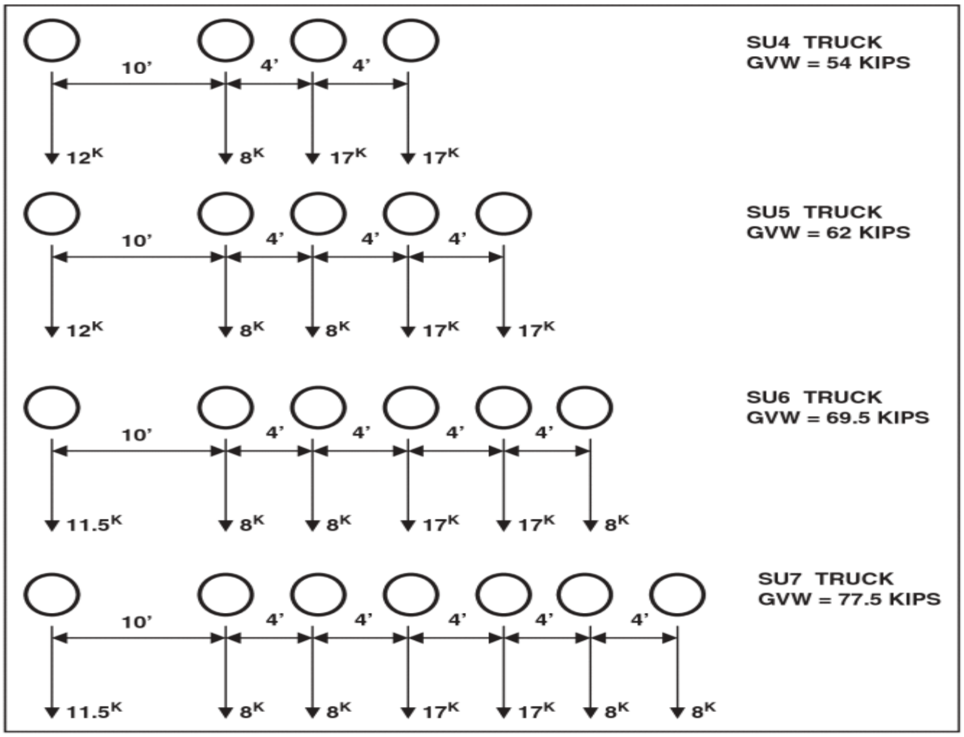


Fig. 3 AASHTO SHV Load Models

3 OBJECTIVES

The main objectives of this research were to

1. Load rate approximately 200 bridges from Ohio's National Bridge Inventory. Perform statistical analysis and determine if load rating along with statistical analysis on bridges with RF ≥ 1.35 for Ohio Legal Loads can be used in lieu of load rating each individual bridge to determine if those bridges have a satisfactory load rating for Specialized Hauling Vehicle (SHV)
2. Perform parametric study of bridges with single and multiple span bridges with spans from 10 ft. to 200 ft.

4 LOAD RATING AND STATISTICAL STUDY

4.1 Statistical Background

The distributions of the SHV load-rating results are not normal or log-normal. Therefore, the distribution was treated as a general non-normal distribution.

The confidence interval at x% confidence level is the probability that the mean of the population would fall within the interval (2). The confidence interval is calculated by using mean, standard deviation and desired confidence level. For a normal distribution, Z statistic is used. For a non-normal distribution, "if the distribution has finite mean and variance and if *n* is sufficiently large" then the standardized Z statistic can be used (3). *n* refers to the sample size. Regarding the sample size required, "[if] the data are not normally distributed, then make sure you have a large enough sample ($n \geq 30$ generally suffices, but recall that it depends on the skewness of the distribution)" (4). If infinite samples were taken from a population and their means calculated each time, the distribution of means will always be a perfect bell curve when samples with $n \geq 30$ are used (5).

The minimum sample size of 30 adopted for every bridge type analyzed in this research was based on the above references.

4.2 Load Rating Methodology

A sample of 187 bridges from Group A was selected for this study based on statistical sampling. Data on the bridges such as the drawings, inspection reports, Bridge Analysis and Rating System (BARS) files and Bridge Load Rating Summary Reports were provided by ODOT. AASHTOWare Bridge Rating (BrR) software was primarily used to conduct the load ratings. BARS data files were imported in BrR, when available. BrR bridge models were prepared from drawings when BARS data files were unavailable. While BARS data files had girder-line models of bridges, complete system models (except for slab bridges) were defined in BrR. This served two purposes: dead loads and distribution factors could automatically be calculated by the software, and these system files can be used in the future if a need arises to switch to a system or 3D Finite Element Analysis. Concrete slab bridges were rated as 12-inch interior strips. A girder-line analysis was performed for all bridges.

Bridges were load rated by either Load Factor Rating (LFR) or Load and Resistance Factor Rating (LRFR) method, depending on whether it was designed by Load Factor Design (LFD)/Allowable Stress Design (ASD) or Load and Resistance Factor Design (LRFD) method. Refer to Fig. 4 for a flow chart of the load rating process.

Since ODOT implemented the LRFD method on July 1, 2007, most of the bridges in the sample were designed by ASD or LFD method and have been rated by LFR method. Just 8 out of 187 were rated by LRFR method.

Only the members comprising the bridge superstructure were load rated. Decks and substructures were omitted as they are evaluated only when significant deterioration warrants load rating (6). Since all the bridges in the sample had Ohio legal RFs > 1.35, they were mostly in good condition and load rating of decks and substructures could be safely omitted.

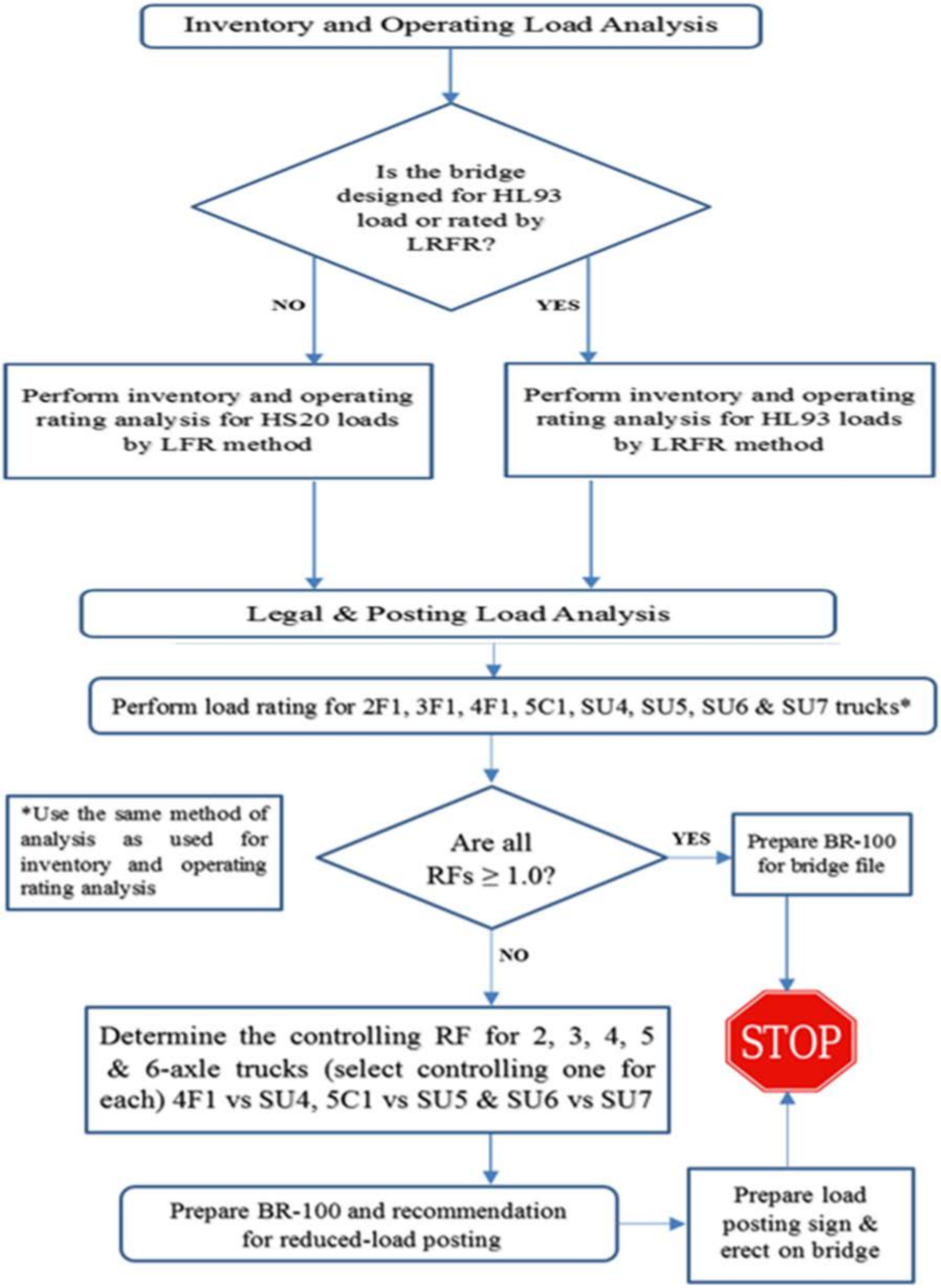


Fig. 4 Load Rating Procedure – Flow Chart

The bridges were load rated for all the Ohio legal loads and SHV loads SU4, SU5, SU6 and SU7. One truck at a time was considered on the bridge.

4.3 Bridge Sampling

The University research Team (URT) and ODOT selected 187 bridges with the longest span less than 200 ft. and Ohio Legal RF $\geq$ 1.35 from Ohio's National Bridge Inventory for load rating. A variety of bridge types, spans, and skews were chosen to represent the bridge population in Ohio. Bridges were selected from counties across Ohio (Fig. 5). Bridges were selected from the six common types listed in table 1 with at least 30 bridges from each type. Less common bridge types, such as cable-stayed, suspension, and arch bridges were not chosen for this research. Bridges were selected from six common types, with at least 30 bridges from each type. This type of sampling was based on NCHRP Report 700 in which 1,500 bridges of different material types and structural configurations were selected to compare LFR and LRFR rating methods (*7*).

Table 1- Bridge Distribution by Structure Type

Bridge Type	ODOT Structural Type Code	No. of Bridges
Concrete Slab Simple	111	30
Concrete Slab Continuous	112	34
PS Concrete I-Beam – Simple/Continuous	221/222	30
PS Concrete Box Beam – Simple/Continuous	231/232	33
Steel Beam – Simple	321	30
Steel Beam - Continuous	322	30
Total		187

Table 1 shows the bridge distribution and sample size by structure type. Simple and continuous prestressed girder bridges were both analyzed as simple spans and have been grouped together. Ohio's multi-span prestressed girder bridges are designed continuous for live loads but rated as simple spans (*8*). Bridges with span lengths ranging from 15 ft. (concrete slab simple) to 191 ft. (steel beam continuous) were selected to study the effect of SHVs on rating factors. Bridges with both left-forward and right-forward skews ranging from 0 to 65 degrees were selected.

Ohio's bridge inventory consists of 53% county bridges, 37% ODOT bridges and 10% other bridges. Eighty-five percent of the bridges in the sample are ODOT bridges and 15% are county bridges. This is acceptable because the county bridges are designed to the same guidelines, specifications, and loadings as ODOT bridges, including some bridges designed based on the same standard drawings. Also, bridges with a load rating greater than 1.35 have no significant maintenance issues. Further, the parmatric study was consistent with the statistical study showing that the variation in stiffnesses along the length of real bridges does not have significant impact on the ratings.

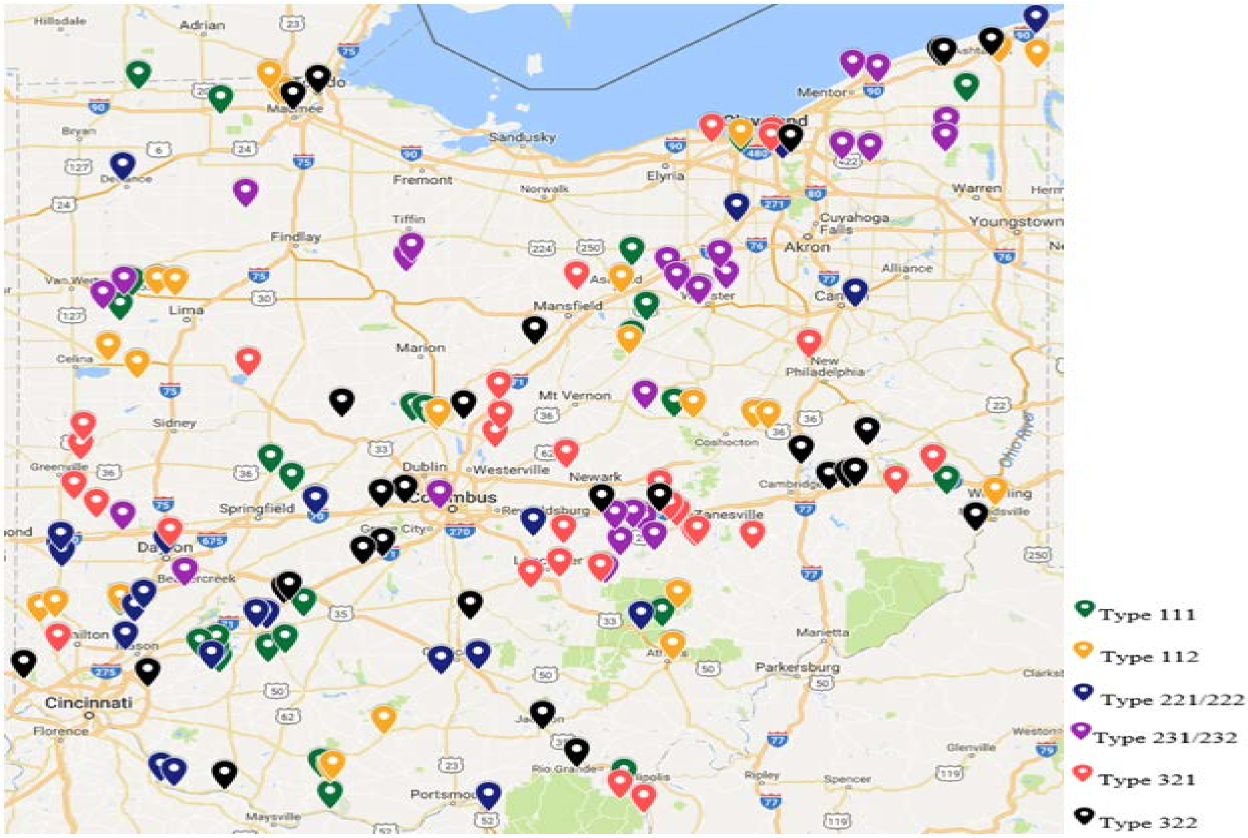


Fig. 5 Ohio Map Showing Bridge Locations

4.4 Findings

Fig. 6 shows a comparison of controlling Ohio Legal RFs and controlling SHV RFs for all six categories of bridges grouped together. The perpendicular red lines show the cut-off values of 1.35 and 1.0 for Ohio Legal RFs and SHV RFs, respectively. Most of the bridges are clustered within the range of Ohio Legal RF 1.35-3.0, with a few outliers to the left and right. None of the bridges in Group A (i.e. bridges with a controlling Ohio Legal RF greater than 1.35) gave a RF less than 1.0 when analyzed for SHVs. The six bridges to the left of the vertical cut-off line at 1.35 show Group A bridges which, when re-analyzed for Ohio Legal Loads, went below 1.35 due to some minor changes in the condition of the bridge, i. e., addition of new wearing surfaces or replacing of aluminium railing with concrete parapet. They were included on the graph to show that none of the bridges analyzed, out of 187, gave a controlling SHV RF less than 1.0.

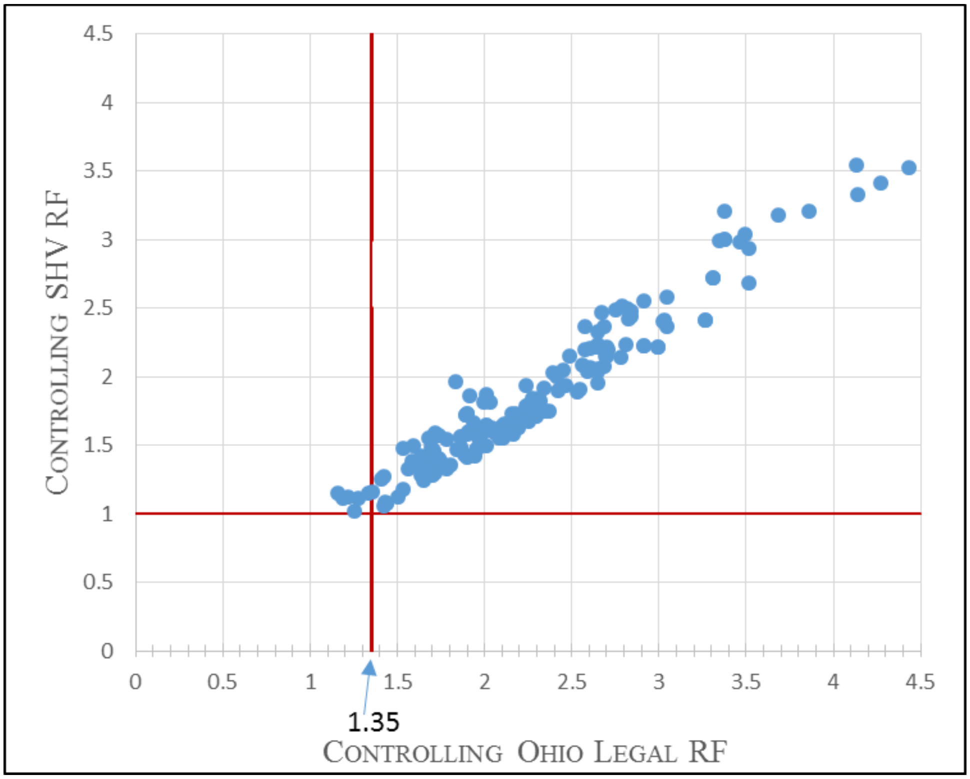
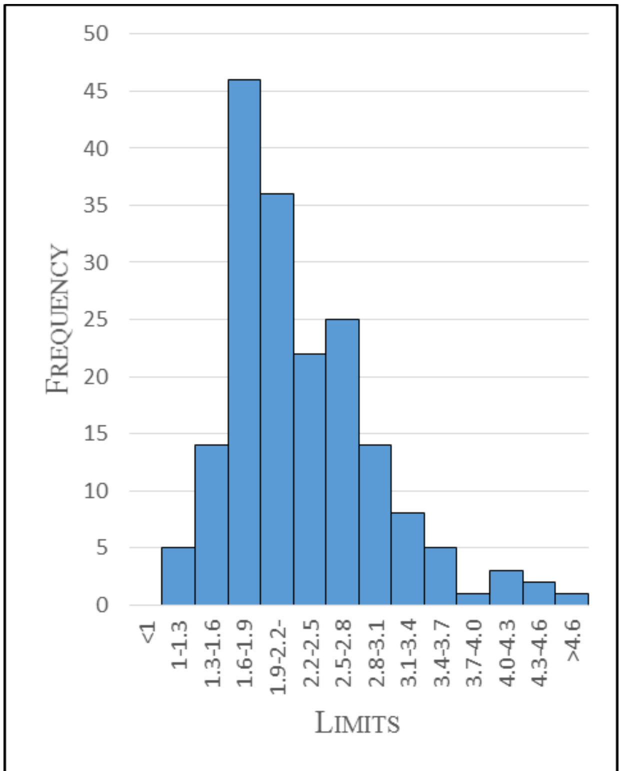


Fig. 6 Comparison of Controlling Ohio Legal RFs and Controlling SHV RFs

In addition to checking the SHV rating, the ratio of the minimum Ohio legal load RF to the minimum SHV RF was calulcated. This was done to look for bridge types whose SHV RF would drop below 1.00 if a bridge of that type had an Ohio legal RF of 1.35. If the ratio was greater than 1.35, it was indicative of a bridge type that may require further investigation.For the six types of bridges grouped together, the data has a skewness of 1.21 for controlling Ohio Legal RFs and 1.23 for controlling SHV RFs. The respective kurtoses are 1.84 and 1.52. For both distributions, data are asymmetric, positively/right skewed, and clustered around the mean with few outliers (Fig. 7 and Fig. 8).



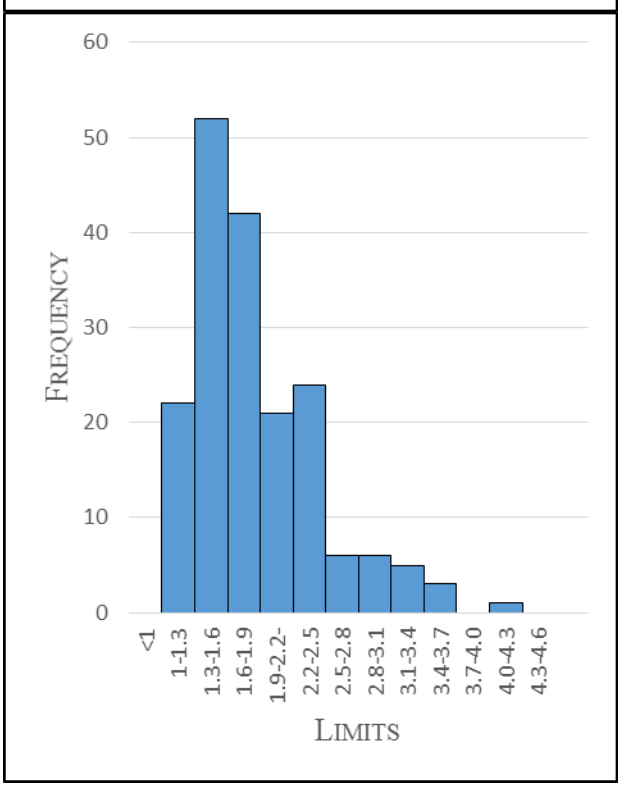


Fig. 7 Histogram - Controlling Ohio Legal RF ***Fig. 8 Histogram - Controlling SHV RF***

The distribution of RFs is not normal. Since the histograms are positively skewed with no negative values, they were checked for log-normality. Log-normally distributed data gives a normal distribution upon transformation. Data sets from Figure 4 and Figure 5 were transformed by taking their natural log and plotted as histograms. A skewness value of 0.372 was obtained from transformed controlling Ohio Legal RF data and a value of 0.491 was obtained from transformed controlling SHV RF data. This shows that the two data sets cannot be classified as log-normal either.

SHV RFs were found to control over Ohio Legal RFs in almost all instances. The descriptive statistics of controlling SHV RFs for all bridge types are provided in Table 2.

The six bridge types were then looked at individually to search for a relation between change in RFs and bridge type or span length, etc. Separate bridge types also failed the test for log-normality.

4.4.1 Bridge Type 111 (Concrete Slab Simple)

Thirty concrete slab simple bridges were analyzed. Slabs designed for bending moment in accordance with code are considered satisfactory in bond and shear (*9*), hence the bridges were not rated for shear. Concrete flexure was the controlling failure mode for all bridges with controlling locations near mid-span between 40%-60% of the span length.

The bridges were arranged in ascending order of length to compare the ratio of RF from controlling Ohio legal to controlling SHV load (Fig. 9). It was found that the ratio of RFs increased linearly from a span of 15 ft. to 28 ft. and then became almost constant for span lengths greater than 28

TABLE 2 Descriptive Statistics by Bridge Type – Controlling SHV RF

Bridge Type	Count	Max.	Min.	Mean	Std. Dev.	Skewness	Kurtosis	Confidence Interval (CL 95%) Lower Bound	Confidence Interval (CL 95%) Upper Bound
Combined	187	4.20	1.02	1.84	0.58	1.23	1.52	1.76	1.92
Conc. Slab Simple	30	3.53	1.12	1.91	0.72	1.08	0.036	1.64	2.18
Conc. Slab Cont.	34	2.45	1.12	1.60	0.29	0.58	1.58	1.50	1.70
PS I	30	3.54	1.37	2.31	0.48	0.24	0.48	2.13	2.49
PS Box	33	2.68	1.34	1.82	0.32	0.73	0.036	1.70	1.93
Steel Simple	30	3.35	1.02	1.85	0.63	1.22	0.71	1.61	2.08
Steel Cont.	30	4.20	1.06	1.61	0.68	2.45	6.85	1.36	1.87

ft. Thirty-nine ft. was the largest span analyzed as Ohio has few Type 111 bridges greater than 40 ft. The ratio of RFs was less than 1.35 for all the bridges in the sample.

Twenty-eight out of 30 or 93.3% of the bridges fall within two standard deviations of the mean with the minimum SHV RF of 1.12.

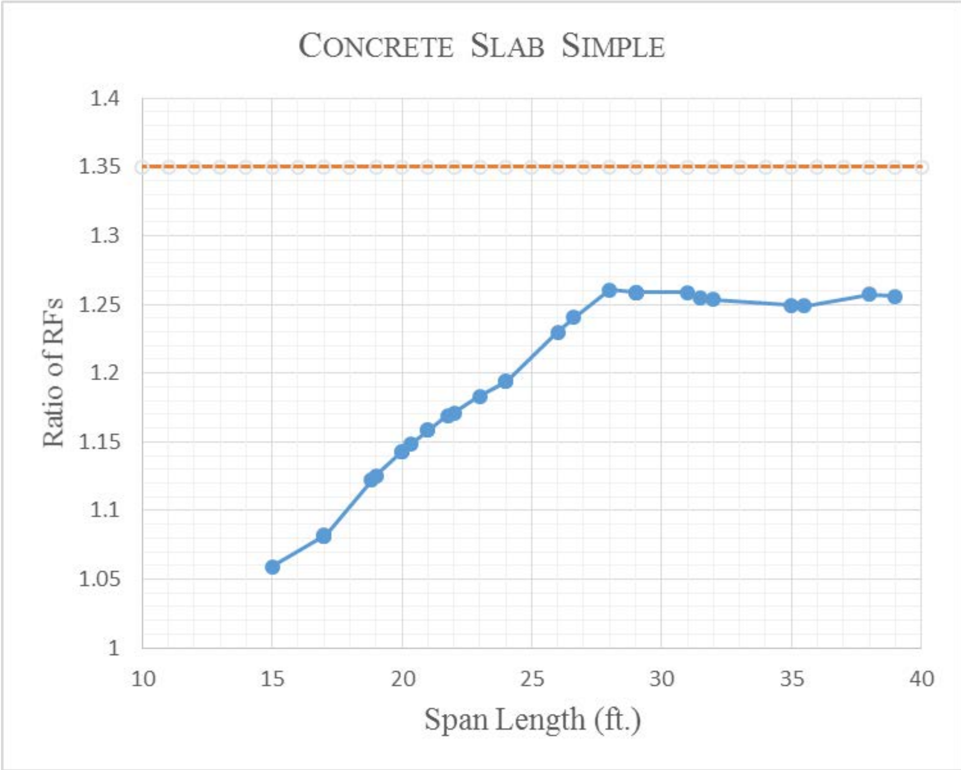


Fig. 9 Concrete Slab Simple (Bridge Type 111)

4.4.2 Bridge Type 112 (Concrete Slab Continuous)

Thirty-four Concrete Slab Continuous bridges were analyzed. Almost all of these bridges had three spans with outer spans of equal length and a longer middle span.

The comparison of RFs for continuous span bridges was not as straightforward as simple span bridges because the controlling locations for Ohio legal loads and SHV loads were often in different spans. Since the controlling location was usually in different spans, no relation could be found between span lengths and ratio of RFs. None of the bridges gave a ratio of RF more than 1.35.

Thirty-two out of 34 or 94.1% of the bridges fall within two standard deviations of the mean with a lowest controlling SHV RF of 1.12.

4.4.3 Bridge Type 221/222 (Prestressed Concrete Beam Simple/Continuous)

Thirty-one prestressed concrete I-beam bridges were analyzed. Bridges from one to four spans have been included in this category to cover a wide range of prestressed I-beam bridges. For some bridges, concrete flexure near the mid-span was the controlling failure mode while others were controlled by concrete shear near the supports.

Prestressed I-beam bridges with single-span lengths from 39 ft. to 148 ft., a range of almost 110 ft., were considered in this category. No relation was found between ratio of RFs and controlling span lengths (Fig. 10).

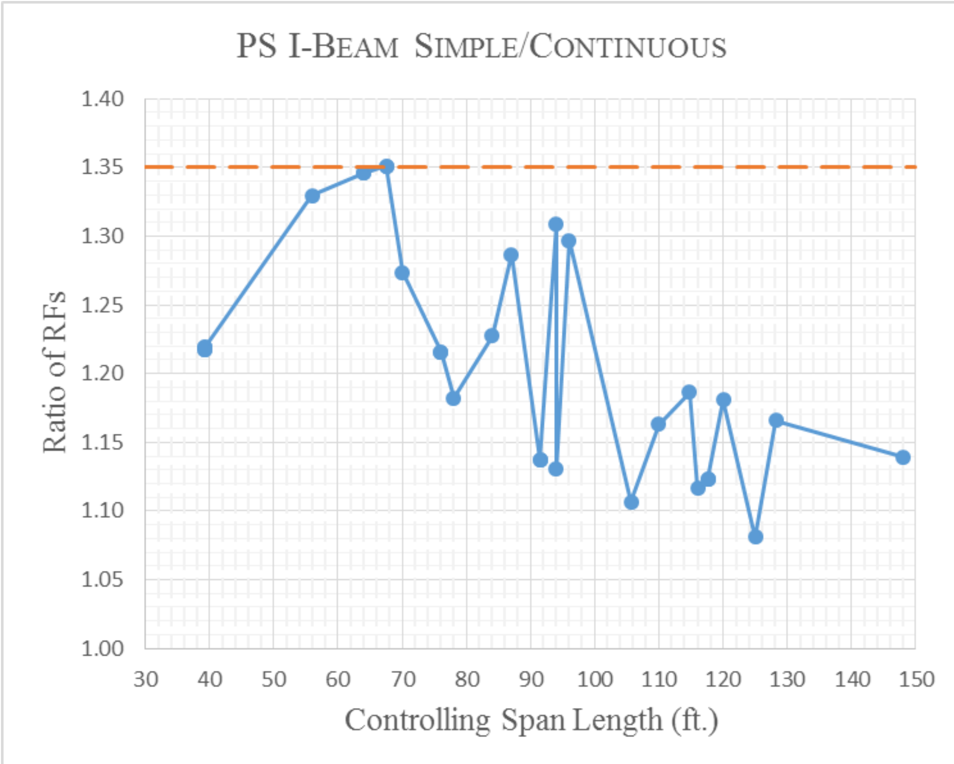


Fig. 10 PS Concrete I-Beam Simple/Continuous (Bridge Type 221/222)

This is because prestressed bridges cover a range of span lengths and the materials, area of prestressing strand and shear reinforcement keep changing to account for increasing moments and shear. Thus, the controlling RFs are dependent not only on the span lengths but also the materials used, their quantity, and spacing etc. All the bridges in the sample had ratio of RFs less than 1.35.

Twenty-nine out of 30, or 96.7%, of the bridges are within two standard deviations of the mean with a minimum RF of 1.37. The mean controlling SHV RF for Type 221/222 bridges was much higher than other bridge types because most of these bridges in the sample were designed for HS25.

4.4.4 Bridge Type 231/232 (Prestressed Concrete Box Beam Simple/Continuous)

Thirty-three prestressed concrete box beam bridges were analyzed. Bridges from one to three spans have been included in this category to cover a range of prestressed concrete box beam bridges. Controlling failure mode was either concrete flexure at or near the mid-span or concrete shear near the supports.

The spans considered in this category were from 25 ft. to 80 ft., a range of 55 ft.. In Figure 11, an almost linear relation can be seen between ratio of RFs and controlling span lengths, with a few outliers. The outliers with a small ratio of RFs were controlled by shear.

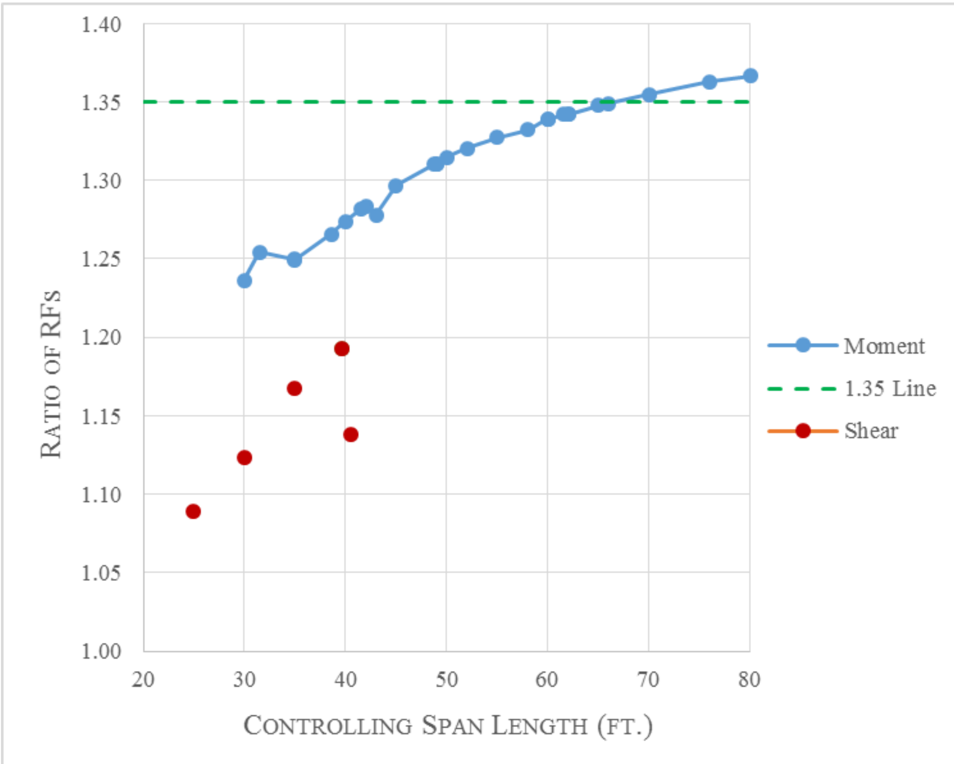


Fig. 11 PS Concrete Box Beam Simple/Continuous (Bridge Type 231/23

For three bridges (all with span lengths between 70 -80 ft.) out of 33, the ratio of RFs exceeds 1.35, with 1.37 being the highest for a span of 80 ft. The controlling SHV RFs of these bridges are still above 1.0 as the controlling Ohio Legal RFs are much greater than 1.35. However, ODOT may need to identify and analyze more bridges with simple span lengths greater than or equal to 70 ft. and controlling Ohio Legal RFs close to 1.35 to confirm the controlling SHV RFs do not fall below 1.00 in such cases.

Thirty-two out of 33, or 96.9%, of the bridges lay within two standard deviations of the mean with a minimum RF of 1.34.

4.4.5 Bridge Type 321(Steel Beam Simple)

Thirty steel beam simple bridges were analyzed. Bridges with span lengths from 22.67 ft. to 154 ft., a range of almost 130 ft. were examined. Plastic analysis of beams and cover plates, and moment redistribution were allowed. Ratio of RFs increase with span length up to 70 ft. (Fig. 12).

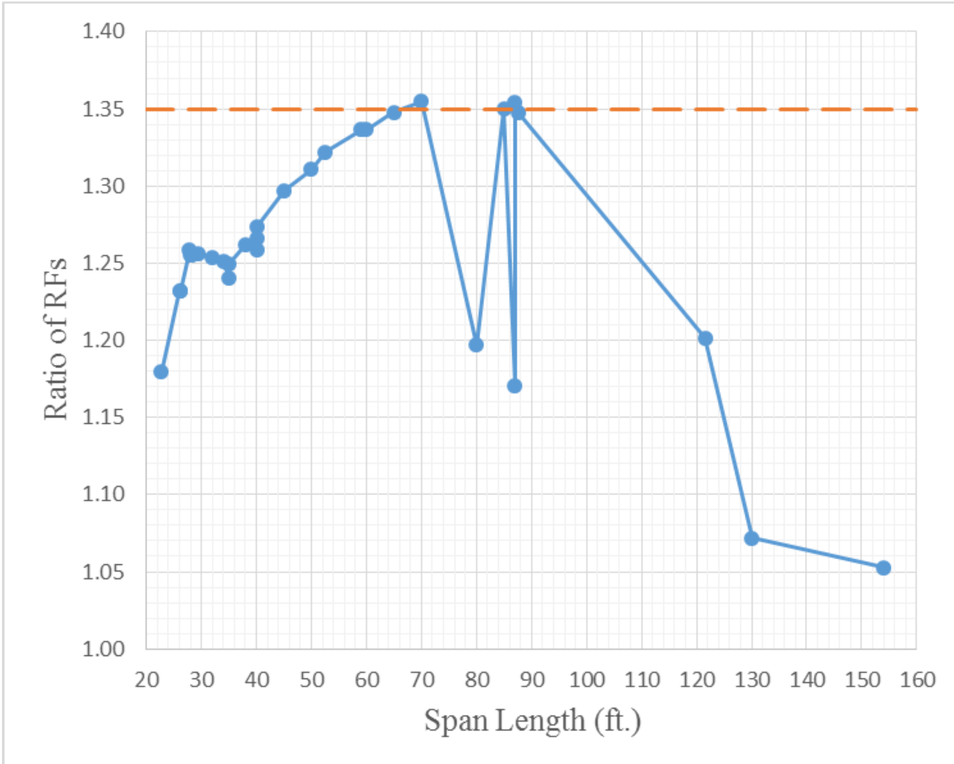


Fig. 12 Steel Beam Simple (Bridge Type 321)

Steel flexure near the mid-span was the controlling failure modes in 26 bridges. Four bridges were controlled by shear near the supports. The bridges controlled by shear had span lengths of 80, 121.5, 130, and 154 ft. Those bridges are plate girder bridges and were significantly over-designed in flexure and did not have enough transverse stiffeners to make it moment controlled. Hence, shear was the controlling failure mode. The ratio of RFs for shear controlled bridges were small compared to flexure controlled beams.

One bridge with span lengths of 70 ft. had ratio of RFs of 1.36 which exceeded the 1.35 threshold. It is recommended that ODOT should examine more bridges with span between 70 and 85 ft..

Twenty-seven out of 30, or 90%, of the bridges are within two standard deviations of the mean with a minimum RF of 1.02.

4.4.6 Bridge Type 322 (Steel Continuous)

Thirty continuous steel bridges were analyzed. Two-, three-, four- and five-span bridges were examined. Bridges with a shortest span from 32 ft. to 177 ft. and longest span from 40 ft. to 191 ft. were in the sample.

Plastic analysis of girders and cover plates, and moment redistribution were allowed. Controlling failure modes were either steel flexure at or near the mid-span or over the piers in the negative moment region. Shear did not control in any of the cases.

Like continuous concrete slabs, the controlling locations for Ohio Legal and SHV loads were often in different spans. Comparing RFs from different locations in different spans does not give an insight into the change in RF within a span, hence a relation between ratio of RFs and controlling span lengths could not be found. None of the bridges gave a ratio of RFs more than 1.35.

Twenty-eight out of 30 or 93.3% of the bridges fall within two standard deviations of the mean with a lowest controlling SHV RF of 1.06.

4.5 Summary of Statistical Study

Figure 13 summarizes the findings with a box plot showing the minimum RF, first quartile, median, third quartile and outliers of all six bridge types. PS I-Beam bridges (bridge type 221/222) has higher mean and median values as compared to other bridge types. The reason being a large number of those bridges in the sample were designed for HS25. Since the bridges were designed to higher loads, the controlling RFs were higher compared to the other bridge types. More detail on the statistical study are available in Islam's thesis (10).

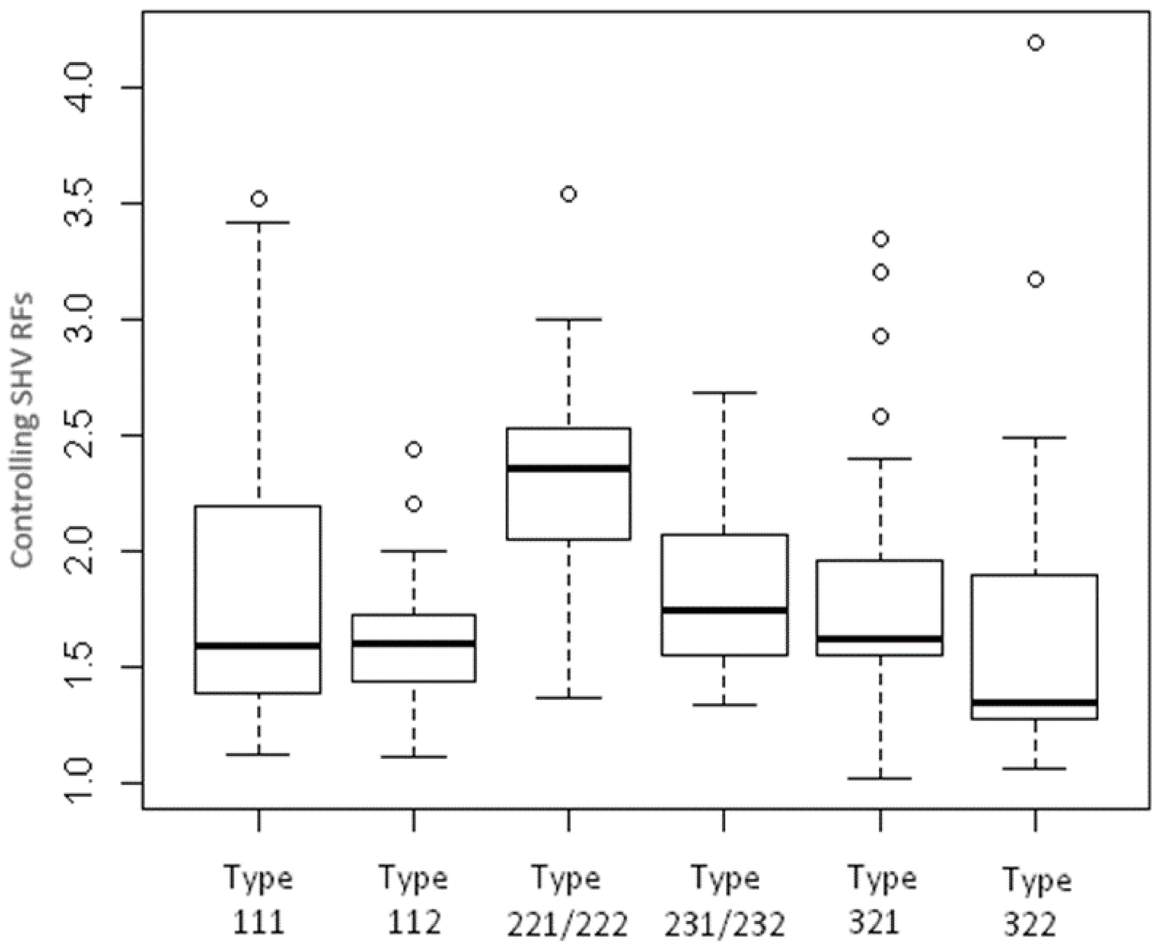


Fig. 13 Box Plot Comparison for Six Bridge Types

5 PARAMETRIC STUDY

5.1 Background

Upon successful completion and presentation of the load rating of a sample of 187 existing bridges including statistical analysis, the FHWA requested further testing of the hypothesis for SHV load ratings by a parametric study. The characteristics of the parametric study were:

- The only parameter that was varied was span length.
- A constant unit stiffness along the entire length of the bridge was considered for the parametric study.
- The parametric study included single and multiple spans bridges with a span range from 10 ft. to 200 ft. with an increment of 5 ft.
- A ratio of 0.5 to 1.0 for exterior to interior span was considered for multi-span bridges.
- The bridges were loaded with all the Ohio legal trucks and the SHV SU4, SU5, SU6 and SU7 trucks sequentially.
- Only live load effects were considered.
- A single truck was considered on the bridge at a time.

The University of Toledo research team has performed the following activities:

- Developed computer models that determine the ratio of the maximum moment and shear effects due to ODOT legal loads to the SHV loads for single and multiple span bridges. Copies of the codes are in the appendix.
- Analyzed the bridges with these models.
- Summarized the results in spreadsheets, tables, figures and charts of the rating results have been generated to provide to ODOT.

The results are summarized here with additional details in the appendix and further elaboration and detail is provided in Islam's thesis (10) and Gyawal's thesis (11).

5.2 Simple Span Bridge

5.2.1 Overview

The parametric study of simple span bridge was straightforward. A calculation sheet was developed (Appendix-C) manually in Mathcad to find out the maximum moments and shear due to Ohio Legal Loads and AASHTO SHVs.

The maximum moment due to truck was found by position the loads in such a way that mid-span of the beam is halfway between the centroid and the nearest load to the centroid. Finally, the moment was calculated beneath the load nearest to the centroid.

Unit stiffness for the bridge section was considered during the analysis and instead of comparing RFs between Ohio Legal Loads and AASHTO SHVs, maximum forces produced by SHVs and Ohio Legal Loads have been compared which produces the same results.

5.2.2 Moment

The ratio of controlling RFs increases from 15 to 80 ft., having 1.35 ratio at a span of 70 ft. and a maximum ratio of 1.36 for span 80 ft. (Fig. 14). A ratio of 1.36 means the controlling RF for SHV could fall to 0.99 for a bridge if its controlling RF for Ohio Legal Load is 1.35.

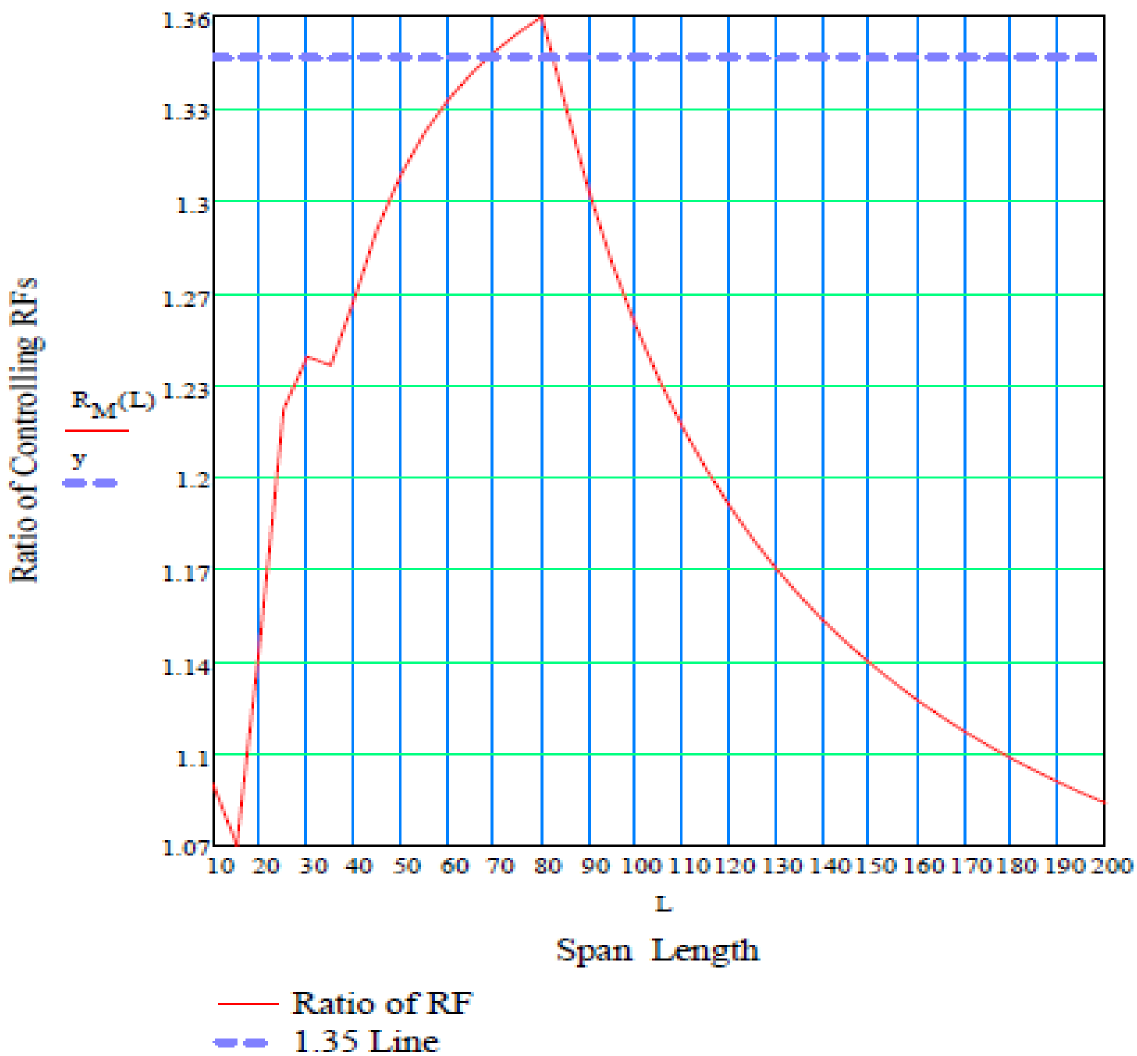


Fig. 14 Simple Span- Moment

5.2.3 Shear

Shear was not controlling in case of simple span. The max ratio of RF for shear was found to be 1.27 for a span length of 60 ft. (Fig. 15).

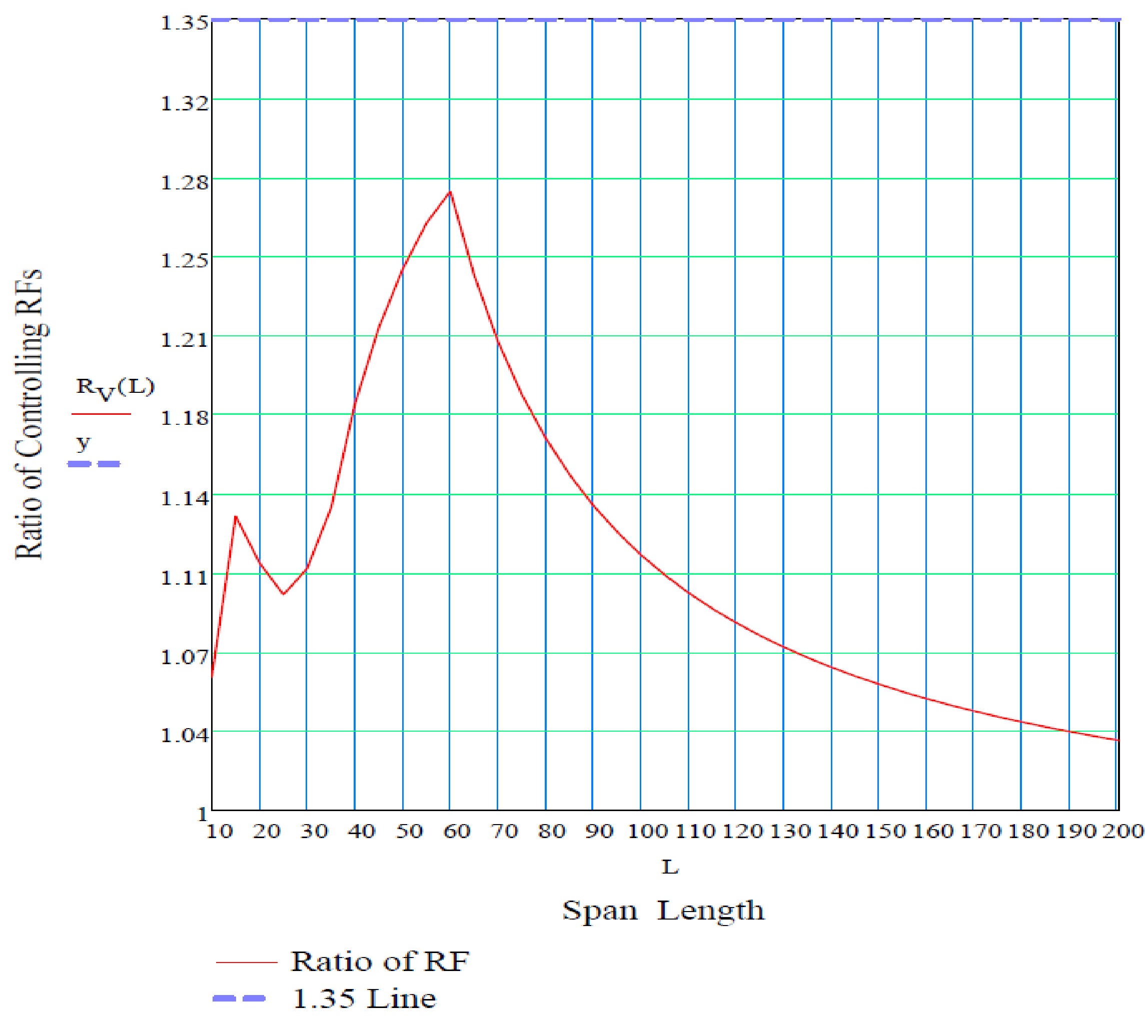


Fig. 15 Simple Span- Shear

5.3 Parametric Study of Multi-Span Bridges

5.3.1 Overview

The parametric study of multi-span bridges was done in two stages. Since thousands of span combinations could be possible in the inventory, the first step was to find the most conservative span configuration. It was found that two-span bridges are more conservative than other multi-span configurations, except for negative moment when the ratio of exterior to interior span is equal or greater than 0.96. When the ratio of exterior to interior span length is greater or equal to 0.96, positive moment controls over negative moment. So, a two-span bridge configuration always produce conservative result and analysis was involved only with a series of theoretical two-span bridges with exterior to interior span ratio of 0.5 to 1.0 (Fig. 16).

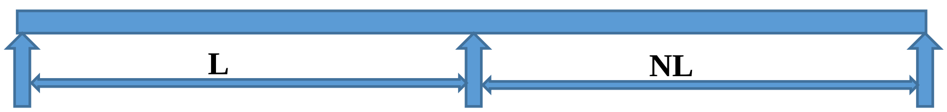


Fig. 16 Schematic of Two-Span Bridge

N is the ratio of exterior span to interior span and was varied from 0.5 to 1.0 based on ODOT inventory.

The second part of the analysis process was to evaluate the ratio of controlling RFs for the series of two span configurations. Figures 17-22 show the ratio of controlling RFs versus span length for positive moment, negative moment and shear for multi-span bridges.

Hence, for the simplicity of analysis, only two span bridges have been analyzed which can represent all type multi-span bridges with similar exterior to interior span ratio.

5.3.2 Positive Moment

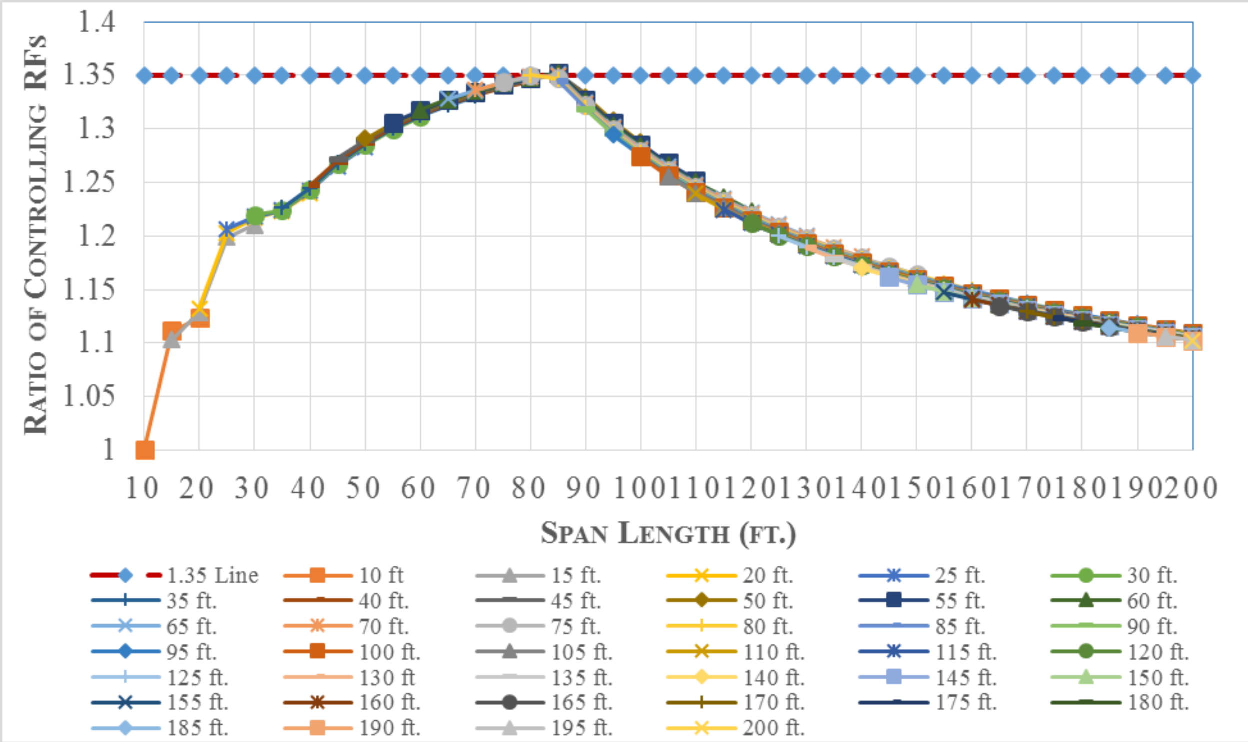


Fig. 17 Ratio of Controlling Ohio Legal Load RF to Controlling SHV RF with Constant First Span for +VE Moment

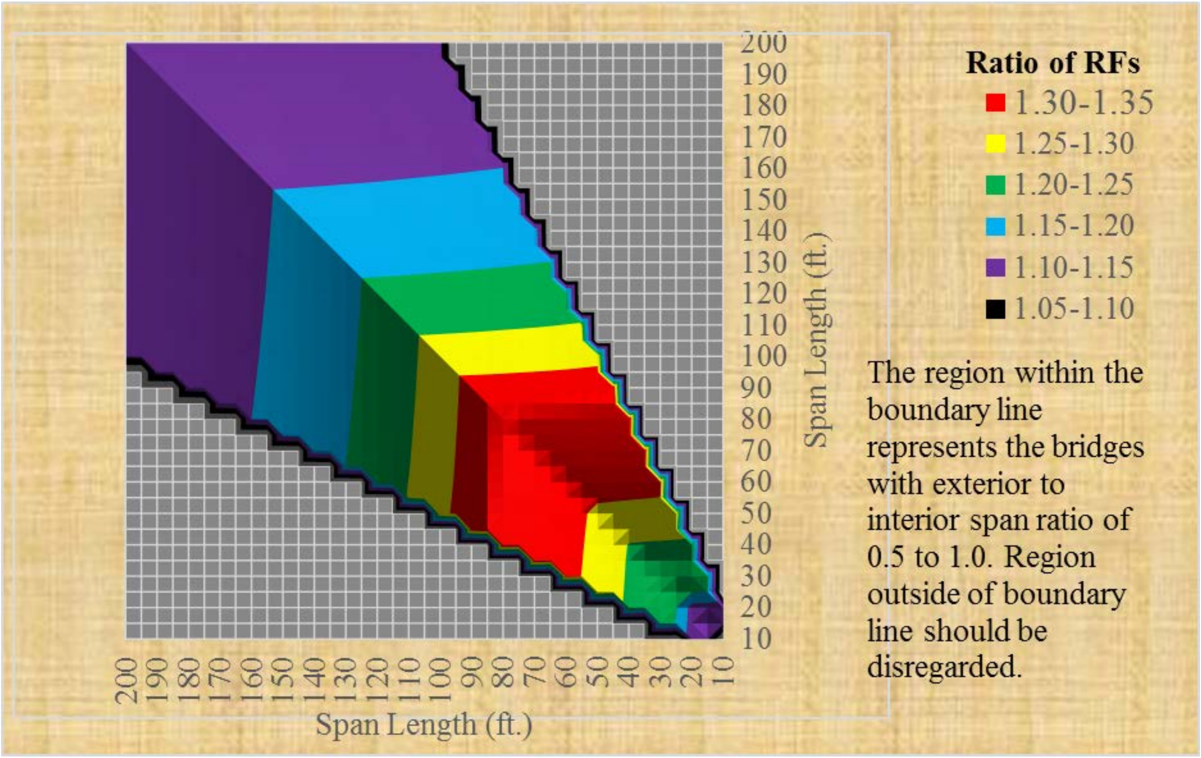


Fig. 18 Contour Plot for Positive Moment- Two Span

5.3.3 Negative Moment

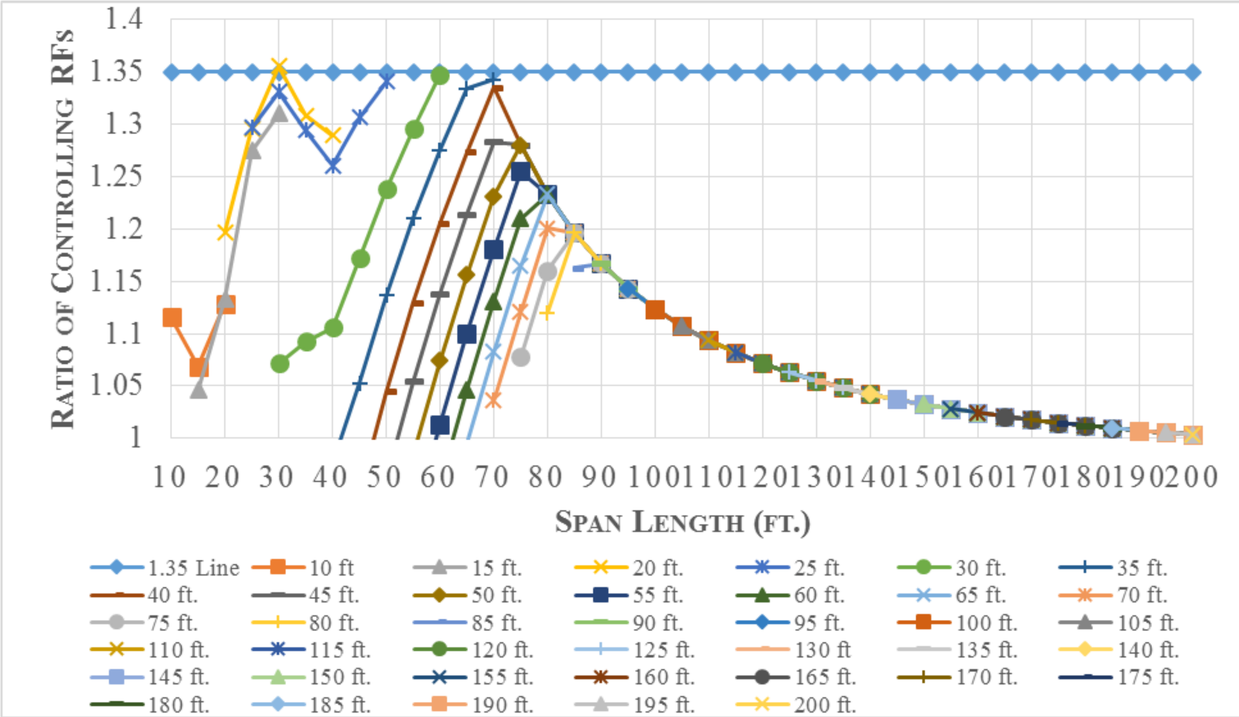


Fig. 19 Ratio of Controlling Ohio Legal Load RF to Controlling SHV RF with Constant First Span for -VE Moment

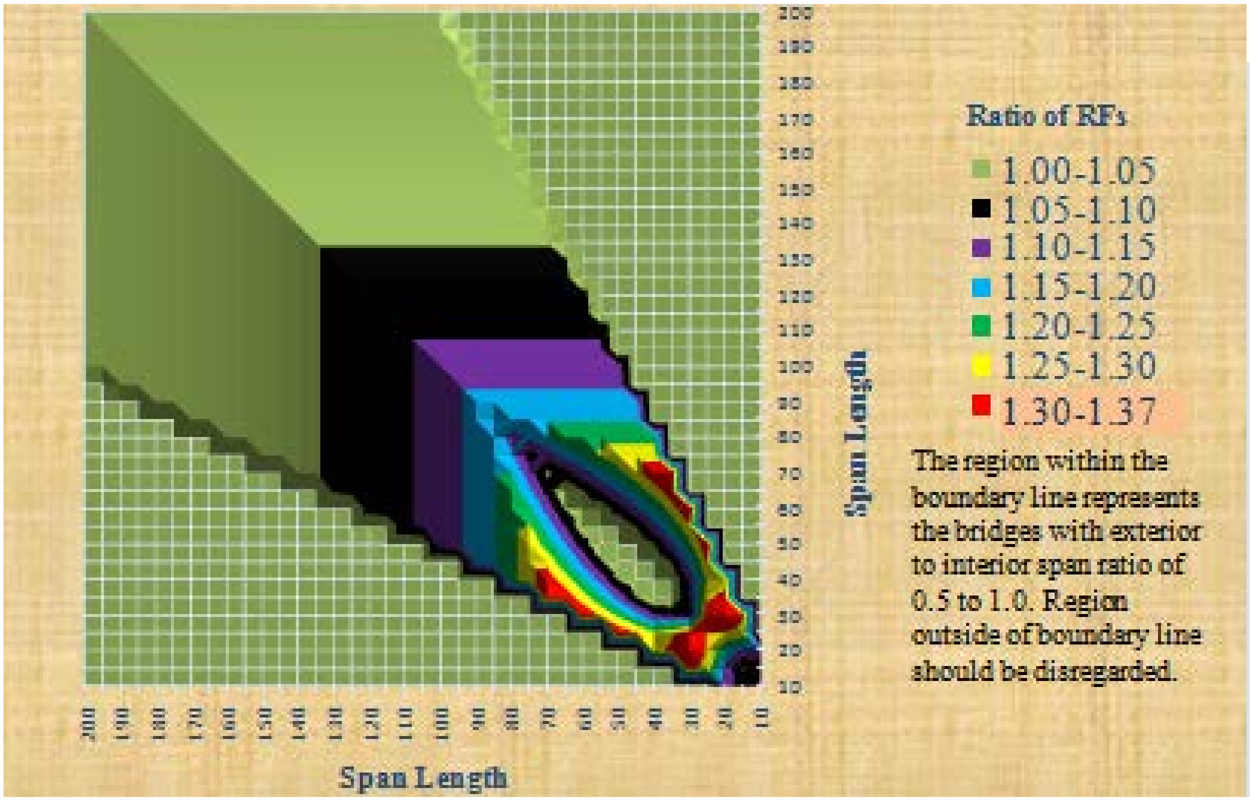


Fig. 20 Contour Plot for Negative Moment- Two Span

5.3.4 Shear

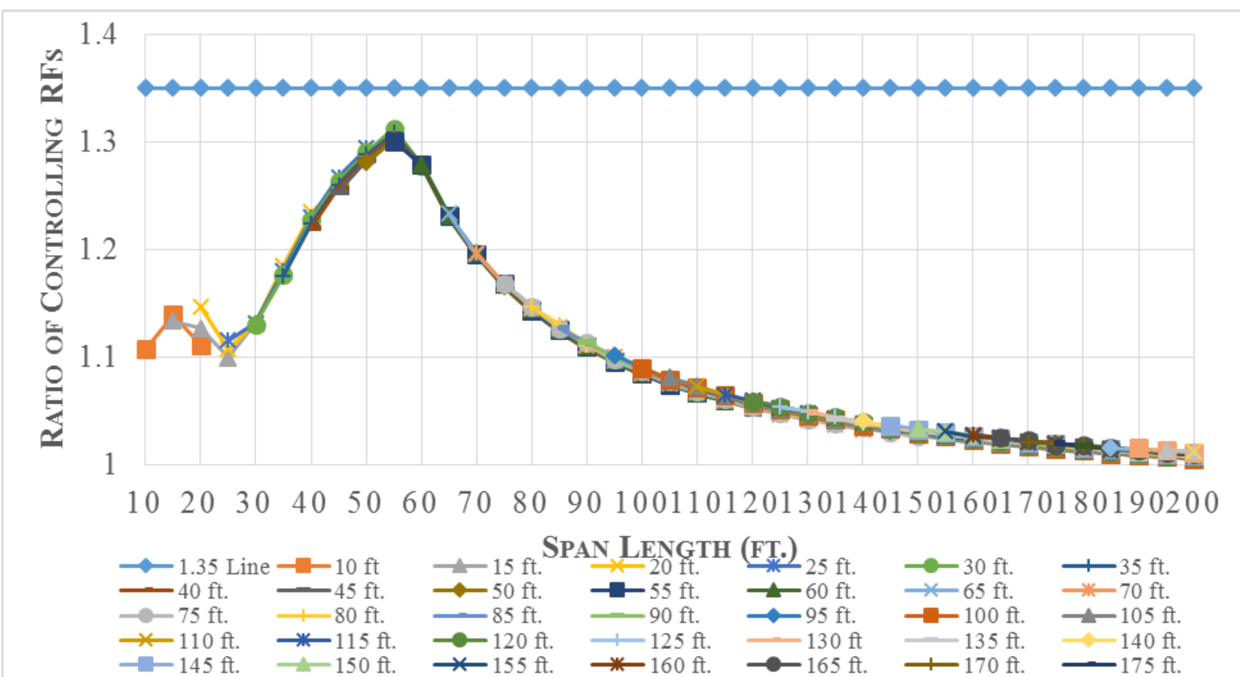


Fig. 21 Ratio of Controlling Ohio Legal Load RF to Controlling SHV RF with Constant First Span for Max +VE Shear

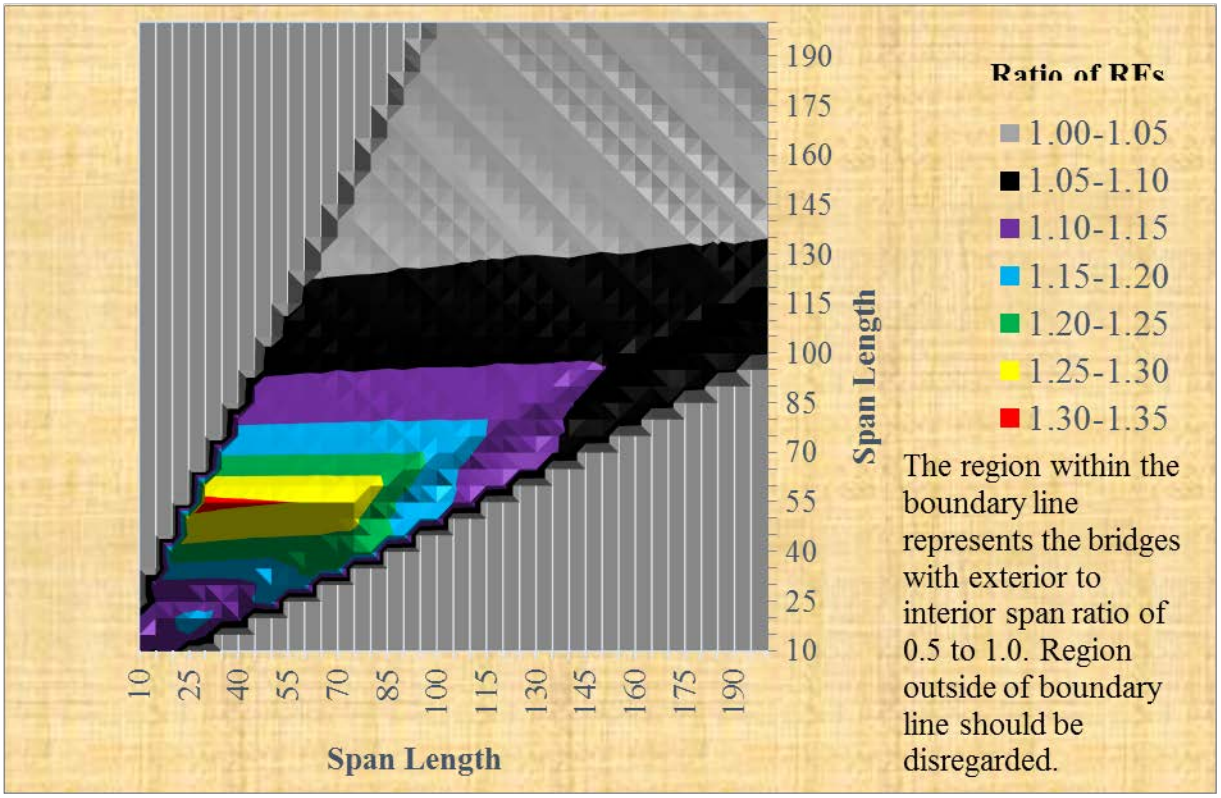


Fig. 22 Contour Plot for Shear- Two Span

5.4 Summary of Parametric Study

The parametric study was conducted to extend the results and extent of the load rating statistical study of bridges. The study was carried out considering a unit stiffness throughout the span. The trucks were being moved back and forth on the span to create maximum force effect.

For the parametric study of simple span bridges, the maximum moment equations for Ohio legal trucks and AASHTO SHVs were developed by hand calculation and maximum moment locations were determined. Then a MathCAD calculation sheet was generated for a span range from 10 ft. to 200 ft. with 5 ft. increment. The MathCAD calculation sheet presents the ratio of RFs for different span lengths including graph and force effect by individual truck (Appendix C).

The two span bridge configuration was found to be conservative over other multi-span bridges; a program in C- program was developed for the force effects due to trucks on two span bridges. SAP2000 was being used to verify the force effects found from the C-Program. Finally, the force effect values including ratio of RFs were further investigated in Excel and charts/graphs were generated.

For parametric study of simple span bridges, the critical span was found 80 ft. with a critical ratio of RF 1.36. For multi-span bridges, none of the ratio of RF fall above 1.35 for positive moment and the critical configuration was 85 ft. – 55 ft. whereas the critical ratio of RF for negative moment was found 1.36 for a 30 ft. – 20 ft. span configuration. A ratio of RF 1.36 means, if the controlling Ohio Legal Load RF was 1.35, the new RF for SHV would be 0.99.

6 CONCLUSIONS

The short, single-unit trucks called Specialized Hauling Vehicles (SHVs) create higher force effects for bridges with shorter spans. ODOT hypothesized that bridges with controlling Ohio Legal RF ≥ 1.35 would have the controlling RF ≥ 1.0 for SHV loads. The goal of this study was to test ODOT's hypothesis by load rating a sample of 187 bridges and conducting a parametric study for the SHV loads.

For the statistical study, the sample included at least 30 bridges of each of the six common structure types in Ohio, concrete slab simple span and continuous, prestressed concrete simple and continuous and steel simple and continuous, all with no span longer than 200 feet. The bridges in the sample were analyzed using AASHTOWare BrR software. None of the bridges studied had a controlling SHV RF less than 1.0. However, two out of 33 box bridges and one out of 30 steel simple bridges had a ratio of controlling SHV RF to maximum Ohio Legal RF greater than 1.35. The ratio of RF for the box bridges were 1.36 and 1.37 for 76 ft. and 80 ft. respectively and the ratio of RF for simple steel bridge was 1.36 for 70 ft. span length. All three bridges with a RF greater than the threshold 1.35 value were simple spans and had a span from 70 to 80 ft.

The parametric study of simple span bridges showed that the ratio of controlling RFs increases from 15 to 80 ft., having 1.35 ratio at a span of 70 ft. and a maximum ratio of 1.36 for span 80 ft. followed by a decreasing trend. This was consistent with the statistical study. The parametric study of the multi-span bridges showed the critical ratio of RFs for positive moments was 1.35 and the critical ratio for negative moment was 1.37.

The statistical study examines real bridges while the parametric considers hypothetical bridges with uniform properties along the length. The parametric study gives insight into the overall behavior while the statistical study shows that real bridges with section properties that vary along the length behave consistently with the parametric model.

The statistical and parametric studies show that

- All bridges with an Ohio Legal RF ≥ 1.37 have an RF ≥ 1.0 for SHV loads.
- Bridges with Ohio Legal RF ≥ 1.35 and ≤ 1.37 should be load rated if one of the following conditions is met
    - It is a simple span bridge with the span length from 65 - 85 ft.
    - It is a multispan bridge with one span from 15 - 25 ft and an adjacent span from 25 - 35 feet.

  All other bridges with Ohio Legal RF ≥ 1.35 and ≤ 1.37 have an RF ≥ 1.0 for SHV loads.

7 REFERENCES

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8 APPENDICES

8.1 Appendix A - FHWA Memo: Load Rating of Specialized Hauling Vehicles

U.S. Department of Transportation
Federal Highway Administration

Memorandum

Subject: **ACTION**: Load Rating of Specialized Hauling Vehicles

Date: November 15, 2013

/s/ Original Signed by

From: Joseph S. Krolak
Acting Director, Office of Bridge Technology

In Reply Refer To: HIBT-10

To: Federal Lands Highway Division Engineers
Division Administrators

The purpose of this memorandum is to clarify FHWA's position on the analysis of *Specialized Hauling Vehicles* (SHVs) as defined in the AASHTO Manual for Bridge Evaluation (MBE) during bridge load rating and posting to comply with the requirements of the *National Bridge Inspection Standards* (NBIS). The intent of the load rating and posting provisions of the NBIS is to insure that all bridges are appropriately evaluated to determine their safe live load carrying capacity considering all unrestricted legal loads, including State routine permits, and that bridges are appropriately posted if required, in accordance with the MBE.

The SHVs are closely-spaced multi-axle single unit trucks introduced by the trucking industry in the last decade. Examples include dump trucks, construction vehicles, solid waste trucks and other hauling trucks. SHVs generally comply with Bridge Formula B and are for this reason considered legal in all States, if a States' laws do not explicitly exclude the use of such vehicles.

NCHRP Project 12-63 (Report 575, 2007) studied the developments in truck configurations and State legal loads and found that AASHTO Type 3, 3-S2 and 3-3 legal vehicles are not representative of all legal loads, specifically SHVs. As a result, legal load models for SHVs were developed and adopted by AASHTO in 2005 , recognizing that there is an immediate need to incorporate SHVs into a State's load rating process, if SHVs operate within a State. The SHV load models in the MBE include SU4, SU5, SU6 and SU7 representing four- to seven-axle SHVs respectively, and a Notional Rating Load (NRL) model that envelopes the four single unit load models and serves as a screening load. If the load rating factor for the NRL model is 1.0 or greater, then there is no need to rate for the single-unit SU4, SU5, SU6 and SU7 loads. However, if the load rating factor for the NRL is less than 1.0, then the single-unit SU4, SU5, SU6 and SU7 loads need to be considered during load rating and posting.

The SHVs create higher force effects, and thus result in lower load ratings for certain bridges, especially those with a shorter span or shorter loading length such as transverse floor beams, when compared to AASHTO Type 3, 3-S2 and 3-3 legal loads and HS20 design load. Therefore, SHVs, i.e., SU4, SU5, SU6 and SU7 or NRL, are to be included in rating and posting analyses in accordance with Article 6A.2.3 and Article 6B.9.2 of the 1st Edition of the MBE (Article 6B.7.2 of the 2nd Edition of the MBE), unless one of the following two conditions is met:

Condition A: The State verifies that State laws preclude SHV use; or

Condition B: The State has its own rating vehicle models for legal loads and verifies that the State legal load models envelope the ***applicable*** AASHTO SHV loading models specified in Appendix D6A and Figure 6B.9.2-2 of the 1st Edition of the MBE (Figure 6B.7.2-2 of the 2nd Edition of the MBE), and the State legal load models have been included in rating/posting analyses of all bridges. The SHV types, e.g. six- or seven-axle SHVs, precluded by State laws need not be considered.

The SHV load models apply to Allowable Stress Rating, Load Factor Rating, and Load and Resistance Factor Rating in accordance with Section 6A and 6B of the MBE.

The FHWA recognizes that there are bridges in the inventory that have not been rated for SHVs and that it is not feasible to include SHVs in the ratings for the entire inventory at once. FHWA is establishing the following timelines for rating bridges for SHVs, if neither Condition A or B is met:

Group 1: Bridges with the shortest span not greater than 200 feet should be re-rated after their next NBIS inspection, but no later than December 31, 2017, that were last rated by:

a) either Allowable Stress Rating (ASR) or Load Factor Rating (LFR) method and have an operating rating for the AASHTO Routine Commercial Vehicle either Type 3, Type 3S2, or Type 3-3 less than 33 tons (English), 47 tons (English), or 52 tons (English) respectively; or
b) Load and Resistance Factor Rating (LRFR) method and have a legal load rating factor for the AASHTO Routine Commercial Vehicle, either Type 3, Type 3S2 or Type 3-3, less than 1.3.

Group 2: Rate those bridges not in Group 1 no later than December 31, 2022.

For either group, if a re-rating is warranted due to changes of structural condition, loadings, or configuration, or other requirements, the re-rating should include SHVs.

The selection of load rating method should comply with FHWA's Policy Memorandum *Bridge Load Ratings for the National Bridge Inventory*, dated October 30, 2006.

A State may utilize an alternative approach in lieu of the above to address the load rating for SHVs for bridges in their inventory; however, the approach must be reviewed and formally accepted by FHWA.

The timeline presented above will be incorporated into the review of Metric 13 under the National Bridge Inspection Program (NBIP); specifically, it is expected that all bridges meeting Group 1 criteria be load rated for SHVs by the end of 2017. Please work with your State to assist them in developing appropriate actions to meet those timelines. If your State is currently developing or implementing a Plan of Corrective Actions (PCA) for load rating bridges, the PCA should be reviewed and modified as necessary to take into account the rating of SHVs for those bridges and these timelines.

We request that you share this memorandum with your State or Federal agency partner. All questions that cannot be resolved at the Division Office level should be directed to Lubin Gao at lubin.gao@dot.gov or at 202-366-4604.

8.2 Appendix B - List of Bridges with Controlling Ohio Legal and SHV RFs

			Ohio Legal Loads		SHV		
Number	Bridge ID	Span Length (ft.)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Truck & Location	Ratio
1	1400517	15	1.589	4F1- 50%	1.500	SU4-7- 50%	1.06
2	0304239	17	1.216	4F1- 50%	1.124	SU6 & SU7- 50%	1.08
3	1402706	17	1.682	4F1- 50%	1.555	SU6 & SU7- 50%	1.08
4	1402765	17	1.720	4F1- 50%	1.591	SU6 & SU7- 50%	1.08
5	1101269	18.83	1.426	4F1- 50%	1.271	SU6 & SU7- 50%	1.12
6	1400541	19	1.411	4F1- 50%	1.254	SU6 & SU7- 50%	1.13
7	0402338	20	2.838	4F1- 50%	2.483	SU6 & SU7- 50%	1.14
8	1403842	20	1.583	4F1- 50%	1.385	SU6 & SU7- 50%	1.14
9	1600249	20.33	3.49	4F1- 50%	3.040	SU6 & SU7- 50%	1.15
10	0201618	21	2.239	4F1- 50%	1.933	SU6 & SU7- 50%	1.16
11	0505110	21	3.461	4F1- 50%	2.988	SU6 & SU7- 50%	1.16
12	0102016	21.75	1.356	4F1- 50%	1.160	SU6 & SU7- 50%	1.17
13	2701839	22	1.562	4F1- 50%	1.334	SU6 & SU7- 50%	1.17
14	1403605	23	1.648	4F1- 50%	1.393	SU6- 50%	1.18
15	2101416	24	1.676	4F1- 50%	1.404	SU6 & SU7- 50%	1.19
16	0700940	24	2.449	4F1- 50%	2.051	SU6 & SU7- 50%	1.19
17	0902357	26	2.706	4F1- 50%	2.200	SU7- 50%	1.23
18	1100793	26.63	4.137	4F1- 50%	3.335	SU7- 50%	1.24
19	8305013	28	1.747	4F1- 50%	1.386	SU7- 50%	1.26
20	0103845	29	1.742	4F1- 50%	1.384	SU7- 50%	1.26
21	2101505	29	1.732	4F1- 50%	1.376	SU7- 50%	1.26
22	0301906	29	2.607	4F1- 50%	2.072	SU7- 50%	1.26
23	0203041	29	3.033	4F1- 50%	2.410	SU7- 50%	1.26
24	2600196	31	2.283	4F1- 50%	1.814	SU7- 50%	1.26
25	1402498	31.5	1.657	4F1- 50%	1.321	SU7- 50%	1.25
26	0300098	32	2.176	4F1- 50%	1.736	SU7- 50%	1.25
27	1802194	35	1.988	4F1- 50%	1.591	SU7- 50%	1.25
28	1802623	35.5	4.270	4F1- 50%	3.419	SU7- 50%	1.25
29	0902322	38	4.435	4F1- 50%	3.528	SU7- 50%	1.26
30	2600722	39	2.700	4F1- 50%	2.150	SU7- 50%	1.26

8.2.1 Concrete Slab Simple (111)

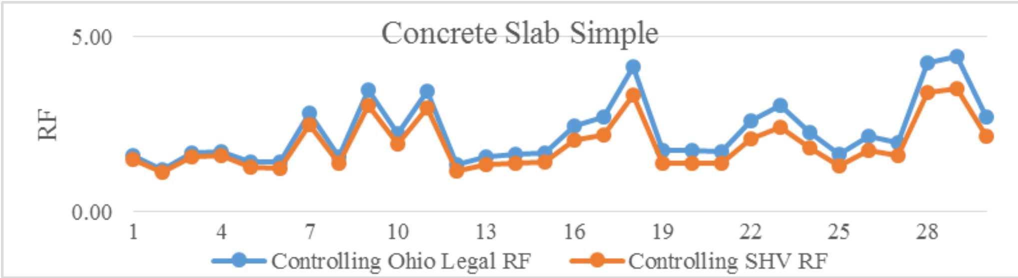

Fig. 23 Comparison of Controlling Ohio Legal RF and SHV RF vs. Controlling Span (ft.)

8.2.2 Concrete Slab Continuous (112)

			Ohio Legal Loads		SHV		Ohio Legal Loads
Serial No	Bridge ID	Span Length (ft)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Truck & Location	Ratio
1	1802461	38-47.5-40	1.429	5C1- S1 (100%)	1.505	SU7- S2 (50%)	0.95
2	0101052	35-42.5-35	1.162	5C1- S1 (100%)	1.148	SU7- S2 (50%)	1.01
3	0200158	18.5-22.5-18.5	1.890	5C1- S2 (34.4%)	1.706	SU6- S1 (40%)	1.11
4	0101087	32-40-32	1.189	5C1- S1 (100%)	1.115	SU7- S2 (50%)	1.07
5	0600180	16.5-20-16.5	1.992	5C1- S3 (60%)	1.820	SU6- S2 (100%)	1.09
6	0200123	18.5-22.5-18.5	1.890	5C1- S2 (34.4%)	1.724	SU6- S1 (40%)	1.10
7	0200158	18.5-22.5-18.6	1.890	5C1- S2 (34.4%)	1.724	SU6- S1 (40%)	1.10
8	0400445	32-39-32	1.900	5C1- S2 (100%)	1.730	SU7- S3 (60%)	1.10
9	0500445	32-39-32	1.900	5C1- S2 (100%)	1.730	SU7- S3 (60%)	1.10
10	0700339	34 spans, max span 33	1.737	5C1- S3 (100%)	1.577	SU7- S1 (100%)	1.10
11	0600156	20.5-25-20.5	1.277	4F1- S3 (60%)	1.117	SU7- S1 (100%)	1.14
12	4800095	20-25-20	1.783	4F1- S2 (50%)	1.548	SU7- S2 (50%)	1.15
13	0300039	33-40-33	1.334	5C1- S2 (100%)	1.155	SU7- S3 (60%)	1.15
14	4800559	21.5-26-21.5	2.841	4F1- S1 (54%)	2.446	SU7- S1 (54%)	1.16

ASSESSMENT OF BRIDGES OF SPECIALIZED HAULING VEHICLE REQUIREMENT

			Ohio Legal Loads		SHV		Ohio Legal Loads
Serial No	Bridge ID	Span Length (ft)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Truck & Location	Ratio
15	0301205	40-50-40	1.940	5C1-S2 (100%)	1.669	SU7- S2 (50%)	1.16
16	2100363	22-27.5-22	1.686	4F1- S2 (50%)	1.437	SU7- S2 (50%)	1.17
17	1600281	23.5-28.75-23.5	2.605	N/A	2.204	N/A	1.18
18	0400718	34-42-34	1.907	5C1- S1 (100%)	1.601	SU7- S1 (68.2%)	1.19
19	0401145	24-30-24	1.863	4F1- S2 (50%)	1.564	SU7- S2 (50%)	1.19
20	0401234	24-30-24	1.863	4F1- S2 (50%)	1.564	SU7- S2 (50%)	1.19
21	0900362	24-30-24	1.901		1.585		1.20
22	0900753	25-30-25	2.411	4F1- S1 (40%)	1.998	SU7- S1 (40%)	1.21
23	0100544	30-37.5-30	1.735	4F1- S1 (55.3%)	1.407	SU7- S1 (55.3%)	1.23
24	4800133	28-40-28	2.159	4F1- S2 (50%)	1.733	SU7- S2 (50%)	1.25
25	0901113	22.29-22.29	1.840	4F1- S1 (100%)	1.469	SU7- S1 (100%)	1.25
26	0200336	20.5-22-20.5	1.726	4F1- S2 (100%)	1.376	SU7- S1 (100%)	1.25
27	2100215	36.5-46-36.5	2.173	5C1- S2 (100%)	1.725	SU7- S2 (50%)	1.26
28	2100274	36.5-46-36.6	2.173	5C1- S2 (100%)	1.725	SU7- S2 (50%)	1.26
29	1600583	36-45-36	2.239	4F1- S2 (50%)	1.763	SU7- S2 (50%)	1.27
30	0301140	40-50-41	2.097	4F1- S2 (50%)	1.633	SU7- S2 (50%)	1.28
31	1600559	44-55-44	2.057	4F1- S3 (60%)	1.599	SU7- S2 (50%)	1.29
32	0500887	38-47.5-38	1.647	4F1- S1 (73.7%)	1.245	SU7-S1 (73.7%)	1.32
33	0500895	38-47.5-39	1.699	4F1- S3 (26.3%)	1.284	SU7- S3 (26.3%)	1.32
34	1804863	32-45-32	2.593	4F1- S2 (50%)	2.043	SU7- S2 (50%)	1.27

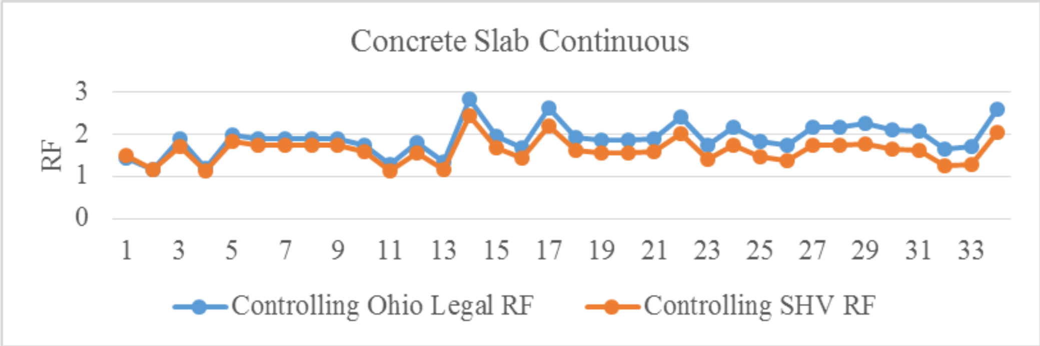

Fig. 24 Comparison of Controlling Ohio Legal RF and SHV RF vs. Controlling Span (ft.)

8.2.3 PS I-Beam Simple/Continuous (221/222)

			Ohio Legal Loads		SHV		
No	Bridge ID	Span Length (ft.)	Controlling RF	Controlling Truck & Location	Controllin g RF	Controlling Location & Truck	Ratio
1	8303754	39.3-47.6-39.3	2.697	4F1- S2 (0%)-IG	2.215	SU7- S2 (100%)-IG	1.22
2	8303665	39.3-47.6-39.4	2.339	4F1- S2 (0%)-IG	1.921	SU7- S2 (0%)-IG	1.22
3	8303428	39.2-47.6-39.2	2.007	4F1- S2 (0%)-IG	1.646	SU7- S2 (100%)-IG	1.22
4	8303398	39.2-47.6-39.3	2.007	4F1- S2 (100%)-IG	1.646	SU7- S2 (100%)-IG	1.22
5	1832476	56	1.952	4F1- (50%)-IG	1.468	SU7- (50%)-IG	1.33
6	1205293	64	2.991	4F1- (50%)-IG	2.222	SU7- (50%)-IG	1.35
7	1205307	64	2.991	4F1- (50%)-IG	2.222	SU7- (50%)-IG	1.35
8	1402277	67.5	3.263	4F1- (50%)-IG	2.415	SU7- (50%)-IG	1.35
9	1402269	67.5	3.263	4F1- (50%)-IG	2.415	SU7- (50%)-IG	1.35
10	8304092	70	2.462	4F1- (39.9%)-IG	1.933	SU6- (39.9%)-IG	1.27
11	7102429	76	3.309	5C1- (60%)-IG	2.722	SU7- (90%)-IG	1.22
12	7102410	76	3.309	5C1- (60%)-IG	2.722	SU7- (90%)-IG	1.22

			Ohio Legal Loads		SHV		
No	Bridge ID	Span Length (ft.)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Location & Truck	Ratio
13	1301969	78	2.395	5C1- (0%)-IG	2.026	SU7- (0%)-IG	1.18
14	6802656	84	2.559	4F1- (70%)-EG	2.085	SU6- (39.9%)-EG	1.23
15	5200733	87	3.042	5C1- (98.2%)-IG	2.364	SU7- (50%)-IG	1.29
16	1402234	91.5	2.91	5C1- (100%)-IG	2.558	SU7- (100%)-IG	1.14
17	1402242	91.5	2.689	5C1- (100%)-IG	2.364	SU7- (100%)-IG	1.14
18	0400947	94-128-128-94	2.291	4F1- S1 (50%)-IG	1.75	SU7- S1 (50%)-IG	1.31
19	2331403	94	2.821	5C1- (2.7%)-IG	2.494	SU7- (70%)-IG	1.13
20	1301918	96	2.781	5C1- (50%)-IG	2.144	SU7- (50%)-IG	1.30
21	7105444	105.7	2.785	5C1- (97.6%)-IG	2.516	SU7- (97.6%)-IG	1.11
22	0500593	110-135-110	2.823	5C1- S1 (100%)-IG	2.427	SU7- S1 (50%)-IG	1.16
23	6800238	114.8	1.62	5C1- (30%)-IG	1.3656	SU7- (30%)-IG	1.19
24	0901822	116	3.344	5C1- (0%)-IG	2.995	SU7- (39.5%)-IG	1.12
25	1402161	117.6	3.372	5C1- (0%)-IG	3.001	SU7- (30%)-IG	1.12
26	1402188	117.6	3.372	5C1- (0%)-IG	3.001	SU7- (30%)-IG	1.12
27	7605412	120	2.646	5C1- (70%)-IG	2.241	SU7- (70%)-IG	1.18
28	6802591	125	2.67	5C1- (98.8%)-IG	2.47	SU7- (98.8%)-IG	1.08
29	5708338	128.25	4.13	5C1-(30%)- NB-IG	3.543	SU7-(30%)- NB-IG	1.17
30	7306040	148	2.65	5C1- (30%)-EG	2.326	SU7- (30%)-EG	1.14

			Ohio Legal Loads		SHV		
No	Bridge ID	Span Length (ft.)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Location & Truck	Ratio
31	2000520	86.5-86.5	3.758	5C1- S1 (50%)-IG	2.769	SU7- S1 (50%)-IG	1.36

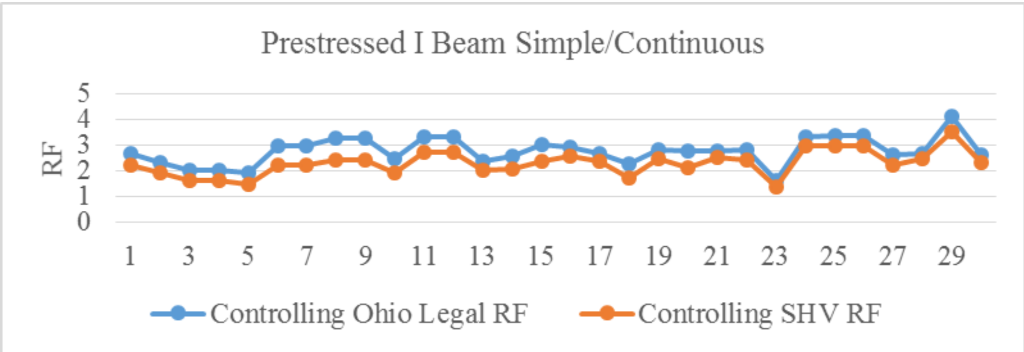

Fig. 25 Comparison of Controlling Ohio Legal RF and SHV RF vs. Controlling Span (ft.)

8.2.4 PS Concrete Box Beam- Simple/Continuous (231/232)

			Ohio Legal Loads		SHV		
No	Bridge ID	Span Length (ft.)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Location & Truck	Ratio
1	8505470	25	2.576	4F1-(70%)-IG	2.365	SU5-(40%)-IG	1.09
2	6403735	30	2.277	4F1-(60%)-IG	1.842	SU7-(50%)-IG	1.24
3	8505535	30	2.035	4F1-(30%)-EG	1.811	SU5-(30%)-EG	1.12
4	6403409	31.5	2.807	4F1-(50%)-IG	2.238	SU7-(50%)-IG	1.25
5	2590271	35-35-35	2.694	4F1-(50%)-IG	2.156	SU7-(50%)-IG	1.25
6	8803714	35	1.708	4F1- S1 (50%)-IG	1.463	SU7- S1 (50%)-IG	1.17
7	6402410	35	2.251	4F1-(50%)-IG	1.801	SU7-(50%)-IG	1.25
8	8102805	38.6	2.315	IG- 50%, 4F1	1.829	SU7-(50%)-IG	1.27
9	2803461	39.67-39.67-39.67	2.643	4F1-(0%)-IG	2.216	SU7-(50%)-IG	1.19
10	2803496	39.67-39.67-39.69	2.643	4F1-(0%)-IG	2.216	SU7-(50%)-IG	1.19

			Ohio Legal Loads		SHV		
No	Bridge ID	Span	Controlling RF	Controlling	Controlli	Controlling	Ratio
11	6402534	40	2.42	4F1-(50%)-IG	1.9	SU7-(50%)-IG	1.27
12	7807678	28.25-40.5-28.25	1.694	4F1- S2 (30%)-IG	1.489	SU5- S2 (25.3%)-IG	1.14
13	6403212	41.5	2.184	4F1-(30%)-IG	1.704	SU7-(50%)-IG	1.28
14	8505020	42	2.141	4F1-(50%)-IG	1.668	SU7-(50%)-IG	1.28
15	8505446	43	2.115	4F1-(60%)-IG	1.655	SU7-(50%)-IG	1.28
16	5710375	45	2.688	4F1-(50%)-IG	2.073	SU7-(50%)-IG	1.30
17	7807694	48.7	3.517	4F1-(50%)-IG	2.684	SU7-(50%)-IG	1.31
18	2801582	49-49-49	2.914	4F1-(100%)-IG	2.223	SU7-(50%)-IG	1.31
19	2801604	49-49-50	2.914	4F1-(100%)-IG	2.223	SU7-(50%)-IG	1.31
20	8505659	50	2.302	4F1-(50%)-IG	1.751	SU7-(50%)-IG	1.31
21	6402666	52	1.958	4F1-(50%)-IG	1.483	SU7-(50%)-IG	1.32
22	7807813	55	1.776	4F1-(50%)-IG	1.338	SU7-(50%)-IG	1.33
23	5703220	58	2.549	4F1-(50%)-IG	1.913	SU7-(50%)-IG	1.33
24	8505578	60	2.01	4F1-(50%)-G2&G3	1.501	SU7-(50%)-G2&G3	1.34
25	8802351	60	2.082	4F1-(50%)-IG	1.555	SU7-(50%)-IG	1.34
26	4305728	61.5	2.295	4F1-(50%)-IG	1.71	SU7-(50%)-IG	1.34
27	8102953	62	2.345	4F1-(50%)-IG	1.747	SU7-(50%)-IG	1.34
28	8102953	62	2.345	4F1-(50%)-IG	1.747	SU7-(50%)-IG	1.34
29	8506523	65	1.903	4F1-(50%)-IG	1.412	SU7-(50%)-IG	1.35
30	4303164	66	2.098	4F1-(50%)-IG	1.555	SU7-(50%)-IG	1.35
31	8751633	70	2.371	4F1-(50%)-IG	1.75	SU7-(50%)-IG	1.35

			Ohio Legal Loads		SHV		
No	Bridge ID	Span	Controlling RF	Controlling	Controlli	Controlling	Ratio
32	8505942	76	1.942	4F1-(50%)-IG	1.425	SU7-(50%)-IG	1.36
33	6402445	80	2.165	4F1-(50%)-IG	1.584	SU7-(50%)-IG	1.37

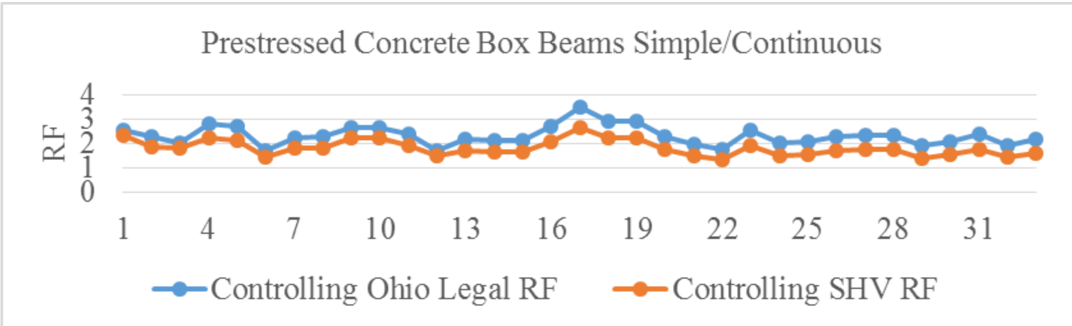

Fig. 26 Comparison of Controlling Ohio Legal RF and SHV RF vs. Controlling Span (ft.)

8.2.5 Steel - Simple (321)

			Ohio Legal Loads		SHV		
No	Bridge ID	Span Length (ft.)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Location & Truck	Ratio
1	2135183	22.67	3.047	4F1-(50%)-EG	2.583	SU7-(50%)-EG	1.18
2	1957406	26.104	1.66	4F1-(60%)-EG	1.347	SU7-(50%)-EG	1.23
3	4602315	26.14	1.257	4F1-(50%)-EG	1.02	SU7-(50%)-EG	1.23
4	2135574	27.875	3.021	4F1-(40%)-EG	2.401	SU7-(50%)-EG	1.26
5	2340127	28	2.31	4F1-(60%)-G2	1.84	SU7-(50%)-G2	1.26
6	1956876	28.27	1.863	4F1-(40%)-EG	1.484	SU7-(50%)-EG	1.26
7	1934368	29.28	1.329	4F1-(40%)-EG	1.058	SU7-(50%)-EG	1.26
8	6039251	32	1.98	4F1-(50%)-G2	1.58	SU7-(50%)-G2	1.25
9	1933434	34	1.665	4F1-(50%)-EG	1.331	SU7-(50%)-EG	1.25
10	6035647	35	2.012	4F1-(55.7%)-EG	1.622	SU7-(50%)-EG	1.24

			Ohio Legal Loads		SHV		
No	Bridge	Span	Controlling	Controlling	Controlli	Controlling	Ratio
11	1930001	35.03	2.122	4F1-(50%)-IG	1.698	SU7-(50%)-IG	1.25
12	2342146	38	1.406	4F1-(50%)-IG	1.114	SU7-(50%)-IG	1.26
13	0738484	40	2.28	4F1-(50%)-G2	1.811	SU7-(50%)-G2	1.26
14	6030203	40	1.967	4F1-(45.7%)-EG	1.554	SU7-(50%)-EG	1.27
15	2333368	40	2.018	4F1-(50%)-EG	1.585	SU7-(50%)-EG	1.27
16	2735327	45	2.06	4F1-(50%)-EG	1.588	SU7-(50%)-EG	1.30
17	5930987	50	1.565	4F1-(50%)-EG	1.194	SU7-(50%)-EG	1.31
18	0734527	52.55	2.031	4F1-(50%)-EG	1.537	SU7-(50%)-EG	1.32
19	4537940	59	2.144	4F1-(50%)-EG	1.604	SU7-(50%)-EG	1.34
20	2336731	60	2.176	4F1-(47.1%)-EG	1.628	SU7-(50%)-EG	1.34
21	2738938	65	2.255	4F1-(50%)-EG	1.673	SU7-(50%)-EG	1.35
22	6038239	70	2.103	4F1-(50%)-EG	1.552	SU7-(50%)-EG	1.36
23	1832808	80	3.512	5C1-(10%)-G2	2.934	SU7-(10%)-G2	1.20
24	6037488	85	2.195	5C1-(52.2%)-EG	1.626	SU7-(50%)-EG	1.35
25	7930836	87	2.575	5C1-(50%)-G2	2.2	SU7-(50%)-G2	1.17
26	7032536	87	2.649	5C1-(50%)-G2	1.956	SU7-(50%)-G2	1.35
27	1834088	87.5	4.512	5C1-(50%)-G2	3.348	SU7-(50%)-G2	1.35
28	5736102	121.5	3.606	5C1-(17.1%)-IG	3.212	SU7-(50%)-IG	1.12
29	1832816	130	2.01	5C1-(10%)-G2	1.875	SU7-(51%)-G2	1.07
30	0936952	154	3.375	5C1-(100%)-IG	3.206	SU7-(100%)-IG	1.05

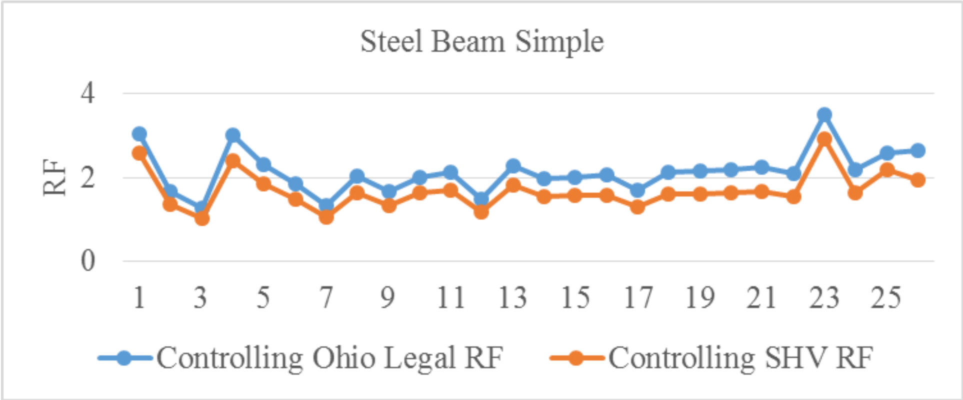

Fig. 27 Comparison of Controlling Ohio Legal RF and SHV RF vs. Controlling Span (ft.)

8.2.6 Steel - Continuous (322)

			Ohio Legal Loads		SHV		
N0	Bridge ID	Span Length (ft.)	Controlling RF	Controlling Truck & Location	Controlling RF	Controlling Location & Truck	Ratio
1	8003300	40-50-40	1.831	5C1- S2 (100%)-IG	1.965	SU7- S2 (100%)-IG	0.93
2	4001206	40-58-58-40	1.53	5C1- S4 (0%)-IG	1.481	SU7- S3 (50%)-IG	1.03
3	4803183	177-191	2.755	5C1- S2 (60%)-IG	2.49	SU7- S2 (60%)-IG	1.11
4	5903424	32-40-32	1.639	5C1- S2 (100%)-IG	1.427	SU7- S2 (50%)-IG	1.15
5	0403008	49-73-73-49	2.486	5C1- S3 (100%)-IG	2.153	SU7- S1- (85.7%)-IG	1.15
6	3402797	68-85-68	3.68	5C1- S1 (100%)-IG	3.179	SU7- S1 (40%)-IG	1.16
7	6002463	52.5-87.5-87.5-52.5	5.116	5C1- S3 (100%)-IG	4.201	SU7- S3 (100%)-IG	1.22
8	4003187	44-55-44	1.701	4F1- S3 (60%)-IG	1.351	SU7- S3 (60%)-IG	1.26
9	6503217	48-60-48	1.633	4F1- S3 (60%)-IG	1.281	SU7- S3 (60%)-IG	1.27
10	1812580	70.5-116-70.5	2.1	5C1-N/A	1.64	SU7-N/A	1.28
11	4800907	29.5-45.5-53.5-30	2.652	4F1- S3 (50%)-IG	2.058	SU7- S3 (50%)-IG	1.29
12	0800813	62-77.5-77.5-77.5-62	2.648	5C1- S1 (92.9%)-IG	2.041	SU7- S1 (92.9%)-IG	1.30

			Ohio Legal Loads		SHV		
N0	Bridge	Span	Controlling	Controlling	Controlling	Controlling	Ratio
13	2103516	56-70-56	1.742	4F1- S3 (60%)-IG	1.34	SU7- S1 (40%)-IG	1.30
14	3006212	49-70-70-57	1.536	4F1- S4 (60%)-IG	1.18	SU7- S4 (60%)-IG	1.30
15	2901714	57-82-82-57	1.701	4F1- S4 (60%)-IG	1.306	SU7- S4 (60%)-IG	1.30
16	2901803	57-82-82-58	1.701	4F1- S4 (60%)-IG	1.306	SU7- S4 (60%)-IG	1.30
17	3005887	60-87-87-60	1.683	4F1- S4 (60%)-IG	1.286	SU7- S4 (60%)-IG	1.31
18	2503786	60-86-86-60	1.771	4F1- S1 (40%)-IG	1.353	SU7- S1 (40%)-IG	1.31
19	3005887	60-87-87-60	1.683	4F1- S4 (60%)-IG	1.286	SU7- S4 (60%)-IG	1.31
20	4902734	62-89-89-62	1.77	4F1- S1 (40%)-IG	1.346	SU7- S1 (40%)-IG	1.32
21	4504054	64-80-80-64	1.43	4F1- S1 (40%)-IG	1.084	SU7- S1 (40%)-IG	1.32
22	0704628	64-80-80-80-64	1.887	4F1- (40%)-EG	1.43	SU7- (60%)-EG	1.32
23	1305476	58-83-83-58	1.72	4F1- S4 (60%)-IG	1.298	SU7- S2 (50%)-IG	1.33
24	3107957	42-70-70-42	1.801	4F1- S2 (50%)-IG	1.358	SU7- S2 (50%)-IG	1.33
25	4903390	72-90-72	2.528	4F1- S2 (40%)-IG	1.895	SU7- S1- (40%)-IG	1.33
26	3001741	58-83-83-58	1.503	4F1- S1 (40%)-IG	1.126	SU7- S2 (50%)-IG	1.33
27	0403601	51-82-82-51	1.437	4F1- S2 (50%)-IG	1.075	SU7- S2 (50%)-IG	1.34
28	0403636	51-82-82-51	1.437	4F1- S2 (50%)-IG	1.075	SU7- S2 (50%)-IG	1.34
29	4904176	74.5-106.5-106.5-74.5	1.781	IG-S4 (60%), 4F1	1.331	SU7- S4 (60%)-IG	1.34
30	3002047	57-81.5-81.5-57	1.42	4F1- S3 (40%)-IG	1.059	SU7- S3 (50%)-IG	1.34

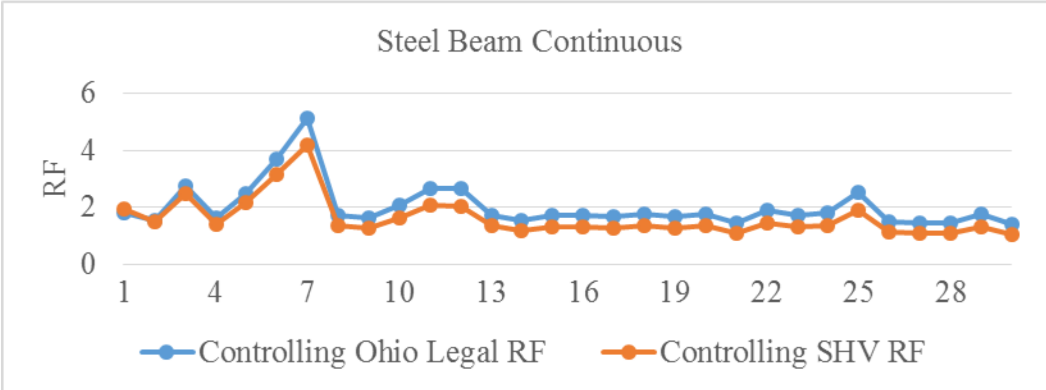

Fig. 28 Comparison of Controlling Ohio Legal RF and SHV RF vs. Controlling Span (ft.)

8.3 Appendix C - Simple Span

8.3.1 MathCAD Calculation Sheet

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CLIENT: Ohio Department of Transportation (ODOT)

PROJECT: Assessment of the Load Rating of Bridge with RF ≥ 1.35
to meet Special Hauling Vehicle requirements

CALCULATION BY: Shariful Islam, Graduate Student, Department of Civil Engineering

CHECKED BY: Dr. Douglas Nims, Professor, Department of Civil Engineering

Insitutuion: University of Toledo, Toledo, OH-43606

OBJECTIVE: LL Force Effect Comparison between Ohio Legal Loads and AASHTO SHVs

Simple Span Bridge from 10ft to 200 ft with 5 ft increment

Length, $L := 10, 15 .. 200$

Maximum Moment due to Trcuk

$$M_{HS20}(L) := \begin{cases} (8\cdot L) & \text{if } 0 < L \le 23.9 \\ \left(16\cdot L + \frac{784}{L} - 224\right) & \text{if } 23.9 < L \le 33.8 \\ \left(18\cdot L + \frac{392}{L} - 280\right) & \text{if } 33.8 < L \le 144.81 \\ \left(0.08\cdot L^2 + 4.5\cdot L\right) & \text{if } L > 144.81 \end{cases}$$

$$M_{2F1}(L) := \begin{cases} (5\cdot L) & \text{if } 0 < L \le 18.165 \\ \left(7.5\cdot L + \frac{250}{3\cdot L} - 50\right) & \text{otherwise} \end{cases}$$

$$M_{3F1}(L) := \begin{cases} (4.25\cdot L) & \text{if } 0 < L \le 8 \\ (8.5\cdot L - 34) & \text{if } 8 < L \le 19.952 \\ \left(11.5\cdot L + \frac{14.6957}{L} - 94\right) & \text{otherwise} \end{cases}$$

$$M_{4F1}(L) := \begin{cases} (3.5\cdot L) & \text{if } 0 < L \le 8 \\ (10.5\cdot L - 56) & \text{if } 8 < L \le 26.347 \\ \left(13.5\cdot L + \frac{130.667}{L} - 140\right) & \text{otherwis} \end{cases}$$

$$M_{5C1}(L) := \begin{cases} (4.25\cdot L) & \text{if } 0 < L \le 8 \\ (8.5\cdot L - 34) & \text{if } 8 < L \le 23.556 \\ \left(11.5\cdot L + \frac{31.3913}{L} - 106\right) & \text{if } 23.556 < L \le 64.656 \\ \left(20\cdot L + \frac{2322.0125}{L} - 691\right) & \text{otherwise} \end{cases}$$

$$M_{SU4}(L) := \begin{cases} (4.25\cdot L) & \text{if } 0 < L \le 6.8284 \\ \left(8.5\cdot L + \frac{34}{L} - 34\right) & \text{if } 6.8284 < L \le 9.398 \\ \left(10.5\cdot L + \frac{7.714}{L} - 50\right) & \text{if } 9.398 < L \le 27.103 \\ \left(13.5\cdot L + \frac{80.667}{L} - 134\right) & \text{otherwise} \end{cases}$$

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$$M_{SU5}(L) := \begin{cases} (4.25 \cdot L) & \text{if } 0 < L \le 6.8284 \\ \left(8.5 \cdot L + \frac{34}{L} - 34\right) & \text{if } 6.8284 < L \le 9.398 \\ \left(10.5 \cdot L + \frac{7.7143}{L} - 50\right) & \text{if } 9.398 < L \le 16.117 \\ \left(12.5 \cdot L + \frac{3.92}{L} - 82\right) & \text{if } 16.117 < L \le 33.661 \\ \left(15.5 \cdot L + \frac{240.06452}{L} - 190\right) & \text{otherwise} \end{cases}$$

$$M_{SU6}(L) := \begin{cases} (4.25 \cdot L) & \text{if } 0 < L \le 6.8284 \\ \left(8.5 \cdot L + \frac{34}{L} - 34\right) & \text{if } 6.8284 < L \le 9.398 \\ \left(10.5 \cdot L + \frac{7.7143}{L} - 50\right) & \text{if } 9.398 < L \le 14.546 \\ \left(12.5 \cdot L + \frac{50}{L} - 82\right) & \text{if } 14.546 < L \le 17.284 \\ \left(14.5 \cdot L + \frac{5.582}{L} - 114\right) & \text{if } 17.284 < L \le 35.01 \\ \left(17.375 \cdot L + \frac{105.183468}{L} - 217.5\right) & \text{otherwise} \end{cases}$$

$$M_{SU7}(L) := \begin{cases} (4.25 \cdot L) & \text{if } 0 < L \le 6.8284 \\ \left(8.5 \cdot L + \frac{34}{L} - 34\right) & \text{if } 6.8284 < L \le 9.398 \\ \left(10.5 \cdot L + \frac{7.7143}{L} - 50\right) & \text{if } 9.398 < L \le 14.546 \\ \left(12.5 \cdot L + \frac{50}{L} - 82\right) & \text{if } 14.546 < L \le 17.284 \\ \left(14.5 \cdot L + \frac{5.5862}{L} - 114\right) & \text{if } 17.284 < L \le 22.667 \\ \left(16.5 \cdot L + \frac{66}{L} - 162\right) & \text{if } 22.667 < L \le 36.456 \\ \left(19.375 \cdot L + \frac{18.145125}{L} - 265.5\right) & \text{otherwise} \end{cases}$$

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$$M_{OH.C}(L) := \max\left(M_{2F1}(L), M_{3F1}(L), M_{4F1}(L), M_{5C1}(L)\right)$$

$$M_{SHV.C}(L) := \max\left(M_{SU4}(L), M_{SU5}(L), M_{SU6}(L), M_{SU7}(L)\right)$$

L =	M_{2F1}(L	M_{3F1}(L	M_{4F1}(L	M_{5C1}(L)	$M_{OH.C}$(L)	M_{SU4}(L)	M_{SU5}(L)	M_{SU6}(L)	M_{SU7}(I	$M_{SHV.C}$(L
10	50	51	49	51	51	55.8	55.8	55.8	55.8	55.8
15	75	93.5	101.5	93.5	101.5	108	108	108.8	108.8	108.8
20	104.2	136.7	154	136	154	160.4	168.2	176.3	176.3	176.3
25	140.8	194.1	206.5	182.8	206.5	212.8	230.7	248.7	253.1	253.1
30	177.8	251.5	269.4	240	269.4	273.7	293.1	321.2	335.2	335.2
35	214.9	308.9	336.2	297.4	336.2	340.8	359.4	393.7	417.4	417.4
40	252.1	366.4	403.3	354.8	403.3	408	436	480.1	510	510
45	289.4	423.8	470.4	412.2	470.4	475.3	512.8	566.7	606.8	606.8
50	326.7	481.3	537.6	469.6	537.6	542.6	589.8	653.4	703.6	703.6
55	364	538.8	604.9	527.1	604.9	610	666.9	740	800.5	800.5
60	401.4	596.2	672.2	584.5	672.2	677.3	744	826.8	897.3	897.3
65	438.8	653.7	739.5	644.7	739.5	744.7	821.2	913.5	994.2	994.2
70	476.2	711.2	806.9	742.2	806.9	812.2	898.4	1000.3	1091	1091
75	513.6	768.7	874.2	840	874.2	879.6	975.7	1087	1187.9	1187.9
80	551	826.2	941.6	938	941.6	947	1053	1173.8	1284.7	1284.7
85	588.5	883.7	1009	1036.3	1036.3	1014.4	1130.3	1260.6	1381.6	1381.6
90	625.9	941.2	1076.5	1134.8	1134.8	1081.9	1207.7	1347.4	1478.5	1478.5
95	663.4	998.7	1143.9	1233.4	1233.4	1149.3	1285	1434.2	1575.3	1575.3
100	700.8	1056.1	1211.3	1332.2	1332.2	1216.8	1362.4	1521.1	1672.2	1672.2
105	738.3	1113.6	1278.7	1431.1	1431.1	1284.3	1439.8	1607.9	1769	1769
110	775.8	1171.1	1346.2	1530.1	1530.1	1351.7	1517.2	1694.7	1865.9	1865.9
115	813.2	1228.6	1413.6	1629.2	1629.2	1419.2	1594.6	1781.5	1962.8	1962.8
120	850.7	1286.1	1481.1	1728.4	1728.4	1486.7	1672	1868.4	2059.7	2059.7
125	888.2	1343.6	1548.5	1827.6	1827.6	1554.1	1749.4	1955.2	2156.5	2156.5
130	925.6	1401.1	1616	1926.9	1926.9	1621.6	1826.8	2042.1	2253.4	2253.4
135	963.1	1458.6	1683.5	2026.2	2026.2	1689.1	1904.3	2128.9	2350.3	2350.3
140	1000.6	1516.1	1750.9	2125.6	2125.6	1756.6	1981.7	2215.8	2447.1	2447.1
145	1038.1	1573.6	1818.4	2225	2225	1824.1	2059.2	2302.6	2544	2544
150	1075.6	1631.1	1885.9	2324.5	2324.5	1891.5	2136.6	2389.5	2640.9	2640.9
155	1113	1688.6	1953.3	2424	2424	1959	2214	2476.3	2737.7	2737.7
160	1150.5	1746.1	2020.8	2523.5	2523.5	2026.5	2291.5	2563.2	2834.6	2834.6
165	1188	1803.6	2088.3	2623.1	2623.1	2094	2369	2650	2931.5	2931.5
170	1225.5	1861.1	2155.8	2722.7	2722.7	2161.5	2446.4	2736.9	3028.4	3028.4
175	1263	1918.6	2223.2	2822.3	2822.3	2229	2523.9	2823.7	3125.2	3125.2
180	1300.5	1976.1	2290.7	2921.9	2921.9	2296.4	2601.3	2910.6	3222.1	3222.1
185	1338	2033.6	2358.2	3021.6	3021.6	2363.9	2678.8	2997.4	3319	3319
190	1375.4	2091.1	2425.7	3121.2	3121.2	2431.4	2756.3	3084.3	3415.8	3415.8
195	1412.9	2148.6	2493.2	3220.9	3220.9	2498.9	2833.7	3171.2	3512.7	3512.7
200	1450.4	2206.1	2560.7	3320.6	3320.6	2566.4	2911.2	3258	3609.6	3609.6

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- Assume, unit stiffness

Ratio between Controlling Ohio Legal RF to controlling SHV RF-

$$R_M(L) := \frac{M_{SHV.C}(L)}{M_{OH.C}(L)} \qquad y := 1.35, 1.35 .. 1.35$$

L =	$R_M(L)$ =
10	1.09
15	1.07
20	1.14
25	1.23
30	1.24
35	1.24
40	1.26
45	1.29
50	1.31
55	1.32
60	1.33
65	1.34
70	1.35
75	1.36
80	1.36
85	1.33
90	1.3
95	1.28
100	1.26
105	1.24
110	1.22
115	1.2
120	1.19
125	1.18
130	1.17
135	1.16
140	1.15
145	1.14
150	1.14
155	1.13
160	1.12
165	1.12
170	1.11
175	1.11
180	1.1
185	1.1
190	1.09
195	1.09
200	1.09

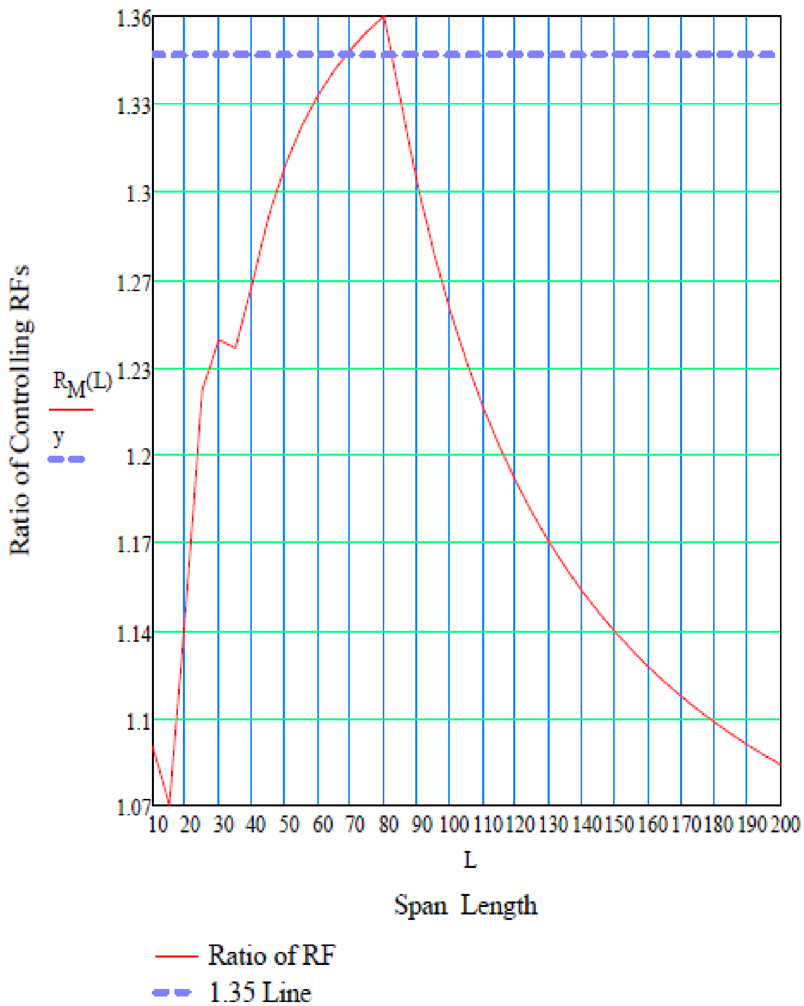

Figure- Ratio of Controlling RF between Ohio Legal Load and SHV for Moment

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Maximum Shear due to Truck

$$V_{HS20}(L) := \begin{cases} 32 & \text{if } 0 < L \le 14 \\ \left(64 - \frac{448}{L}\right) & \text{if } 14 < L \le 28 \\ \left(72 - \frac{672}{L}\right) & \text{if } 28 < L \le 142.28 \\ (26 + 0.32 \cdot L) & \text{otherwise} \end{cases}$$

$$V_{2F1}(L) := \begin{cases} (20) & \text{if } 0 < L \le 10 \\ \left(30 - \frac{100}{L}\right) & \text{otherwise} \end{cases}$$

$$V_{3F1}(L) := \begin{cases} (17) & \text{if } 0 < L \le 4 \\ \left(34 - \frac{68}{L}\right) & \text{if } 4 < L \le 14 \\ \left(46 - \frac{236}{L}\right) & \text{otherwise} \end{cases}$$

$$V_{4F1}(L) := \begin{cases} (14) & \text{if } 0 < L \le 4 \\ \left(28 - \frac{56}{L}\right) & \text{if } 4 < L \le 8 \\ \left(42 - \frac{168}{L}\right) & \text{if } 8 < L \le 18 \\ \left(54 - \frac{384}{L}\right) & \text{otherwise} \end{cases}$$

$$V_{5C1}(L) := \begin{cases} (17) & \text{if } 0 < L \le 4 \\ \left(34 - \frac{68}{L}\right) & \text{if } 4 < L \le 16 \\ \left(46 - \frac{260}{L}\right) & \text{if } 16 < L \le 48.45 \\ \left(68 - \frac{1326}{L}\right) & \text{if } 48.45 < L \le 51 \\ \left(80 - \frac{1938}{L}\right) & \text{otherwise} \end{cases}$$

$$V_{SU4}(L) := \begin{cases} (17) & \text{if } 0 < L \le 4 \\ \left(34 - \frac{68}{L}\right) & \text{if } 4 < L \le 8 \\ \left(42 - \frac{132}{L}\right) & \text{if } 8 < L \le 18 \\ \left(54 - \frac{348}{L}\right) & \text{otherwise} \end{cases}$$

$$V_{SU5}(L) := \begin{cases} (17) & \text{if } 0 < L \le 4 \\ \left(34 - \frac{68}{L}\right) & \text{if } 4 < L \le 8 \\ \left(42 - \frac{132}{L}\right) & \text{if } 8 < L \le 12 \\ \left(50 - \frac{228}{L}\right) & \text{if } 12 < L \le 22 \\ \left(62 - \frac{492}{L}\right) & \text{otherwise} \end{cases}$$

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$$V_{SU6}(L) := \begin{cases} (17) & \text{if } 0 < L \le 4 \\ \left(34 - \frac{68}{L}\right) & \text{if } 4 < L \le 8 \\ \left(42 - \frac{132}{L}\right) & \text{if } 8 < L \le 12 \\ \left(50 - \frac{228}{L}\right) & \text{if } 12 < L \le 22 \\ \left(58 - \frac{428}{L}\right) & \text{if } 22 < L \le 26 \\ \left(69.5 - \frac{727}{L}\right) & \text{otherwise} \end{cases}$$

$$V_{SU7}(L) := \begin{cases} (17) & \text{if } 0 < L \le 4 \\ \left(34 - \frac{68}{L}\right) & \text{if } 4 < L \le 8 \\ \left(42 - \frac{132}{L}\right) & \text{if } 8 < L \le 12 \\ \left(50 - \frac{228}{L}\right) & \text{if } 12 < L \le 22 \\ \left(58 - \frac{428}{L}\right) & \text{if } 22 < L \le 29 \\ \left(66 - \frac{660}{L}\right) & \text{if } 29 < L \le 30 \\ \left(77.5 - \frac{1005}{L}\right) & \text{otherwise} \end{cases}$$

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$$V_{OH.C}(L) := \max\left(V_{2F1}(L), V_{3F1}(L), V_{4F1}(L), V_{5C1}(L)\right)$$

$$V_{SHV.C}(L) := \max\left(V_{SU4}(L), V_{SU5}(L), V_{SU6}(L), V_{SU7}(L)\right)$$

L =	$V_{2F1}(L)$	$V_{3F1}(L)$	$V_{4F1}(L)$	$V_{5C1}(L)$	$V_{OH.C}(L) =$	$V_{SU4}(L)$	$V_{SU5}(L)$	$V_{SU6}(L)$	$V_{SU7}(L)$	$V_{SHV.C}(L) =$
10	20	27.2	25.2	27.2	27.2	28.8	28.8	28.8	28.8	28.8
15	23.3	30.3	30.8	29.5	30.8	33.2	34.8	34.8	34.8	34.8
20	25	34.2	34.8	33	34.8	36.6	38.6	38.6	38.6	38.6
25	26	36.6	38.6	35.6	38.6	40.1	42.3	40.9	40.9	42.3
30	26.7	38.1	41.2	37.3	41.2	42.4	45.6	45.3	44	45.6
35	27.1	39.3	43	38.6	43	44.1	47.9	48.7	48.8	48.8
40	27.5	40.1	44.4	39.5	44.4	45.3	49.7	51.3	52.4	52.4
45	27.8	40.8	45.5	40.2	45.5	46.3	51.1	53.3	55.2	55.2
50	28	41.3	46.3	41.5	46.3	47	52.2	55	57.4	57.4
55	28.2	41.7	47	44.8	47	47.7	53.1	56.3	59.2	59.2
60	28.3	42.1	47.6	47.7	47.7	48.2	53.8	57.4	60.8	60.8
65	28.5	42.4	48.1	50.2	50.2	48.6	54.4	58.3	62	62
70	28.6	42.6	48.5	52.3	52.3	49	55	59.1	63.1	63.1
75	28.7	42.9	48.9	54.2	54.2	49.4	55.4	59.8	64.1	64.1
80	28.8	43	49.2	55.8	55.8	49.6	55.9	60.4	64.9	64.9
85	28.8	43.2	49.5	57.2	57.2	49.9	56.2	60.9	65.7	65.7
90	28.9	43.4	49.7	58.5	58.5	50.1	56.5	61.4	66.3	66.3
95	28.9	43.5	50	59.6	59.6	50.3	56.8	61.8	66.9	66.9
100	29	43.6	50.2	60.6	60.6	50.5	57.1	62.2	67.5	67.5
105	29	43.8	50.3	61.5	61.5	50.7	57.3	62.6	67.9	67.9
110	29.1	43.9	50.5	62.4	62.4	50.8	57.5	62.9	68.4	68.4
115	29.1	43.9	50.7	63.1	63.1	51	57.7	63.2	68.8	68.8
120	29.2	44	50.8	63.9	63.9	51.1	57.9	63.4	69.1	69.1
125	29.2	44.1	50.9	64.5	64.5	51.2	58.1	63.7	69.5	69.5
130	29.2	44.2	51	65.1	65.1	51.3	58.2	63.9	69.8	69.8
135	29.3	44.3	51.2	65.6	65.6	51.4	58.4	64.1	70.1	70.1
140	29.3	44.3	51.3	66.2	66.2	51.5	58.5	64.3	70.3	70.3
145	29.3	44.4	51.4	66.6	66.6	51.6	58.6	64.5	70.6	70.6
150	29.3	44.4	51.4	67.1	67.1	51.7	58.7	64.7	70.8	70.8
155	29.4	44.5	51.5	67.5	67.5	51.8	58.8	64.8	71	71
160	29.4	44.5	51.6	67.9	67.9	51.8	58.9	65	71.2	71.2
165	29.4	44.6	51.7	68.3	68.3	51.9	59	65.1	71.4	71.4
170	29.4	44.6	51.7	68.6	68.6	52	59.1	65.2	71.6	71.6
175	29.4	44.7	51.8	68.9	68.9	52	59.2	65.3	71.8	71.8
180	29.4	44.7	51.9	69.2	69.2	52.1	59.3	65.5	71.9	71.9
185	29.5	44.7	51.9	69.5	69.5	52.1	59.3	65.6	72.1	72.1
190	29.5	44.8	52	69.8	69.8	52.2	59.4	65.7	72.2	72.2
195	29.5	44.8	52	70.1	70.1	52.2	59.5	65.8	72.3	72.3
200	29.5	44.8	52.1	70.3	70.3	52.3	59.5	65.9	72.5	72.5

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- Assume, Unit Stiffness

Ratio of Controlling Ohio Legal RF to Controlling SHV RF-

$$R_V(L) := \frac{V_{SHV.C}(L)}{V_{OH.C}(L)} \qquad y := 1.35, 1.35..1.35$$

L =	$R_V(L)$ =
10	1.06
15	1.13
20	1.11
25	1.1
30	1.11
35	1.13
40	1.18
45	1.21
50	1.24
55	1.26
60	1.27
65	1.24
70	1.21
75	1.18
80	1.16
85	1.15
90	1.13
95	1.12
100	1.11
105	1.1
110	1.1
115	1.09
120	1.08
125	1.08
130	1.07
135	1.07
140	1.06
145	1.06
150	1.06
155	1.05
160	1.05
165	1.05
170	1.04
175	1.04
180	1.04
185	1.04
190	1.03
195	1.03
200	1.03

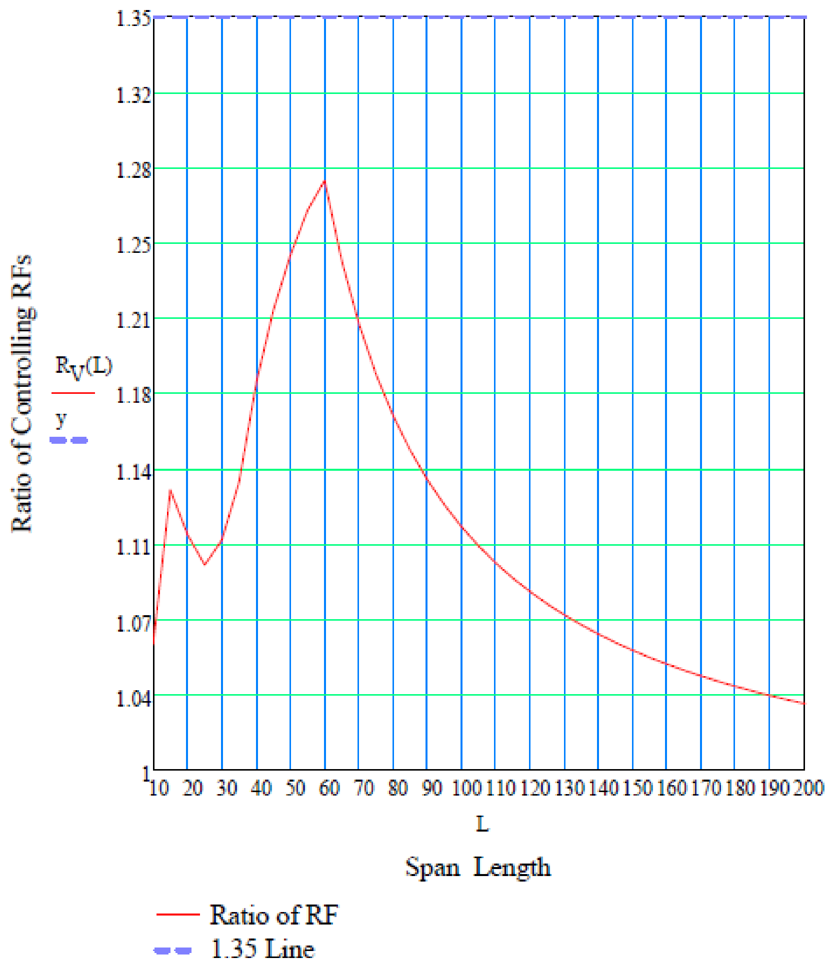

Figure- Ratio of Controlling Ohio RF to Controlling SHV RF for Shear

8.3.2 Controlling Truck Position for Max Moment on Critical Span (80 ft.)

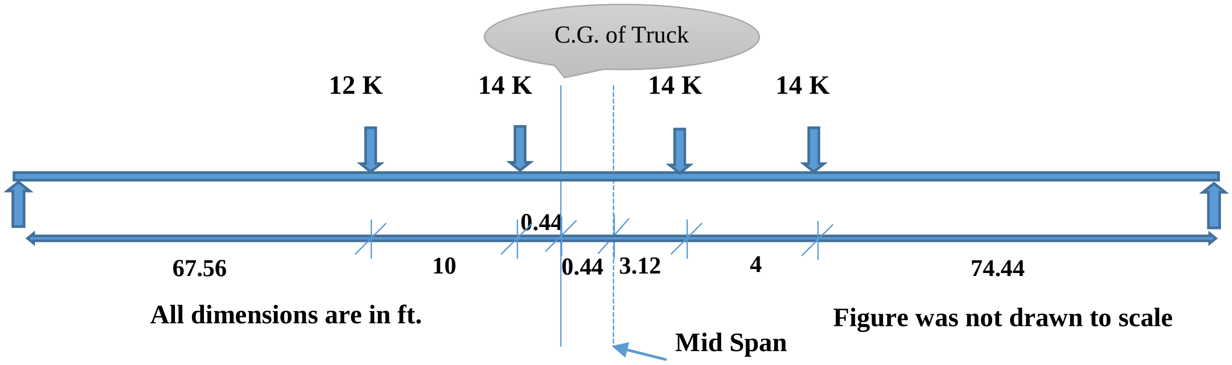

Fig. 29 Controlling Ohio Legal Load- 4F1 Truck

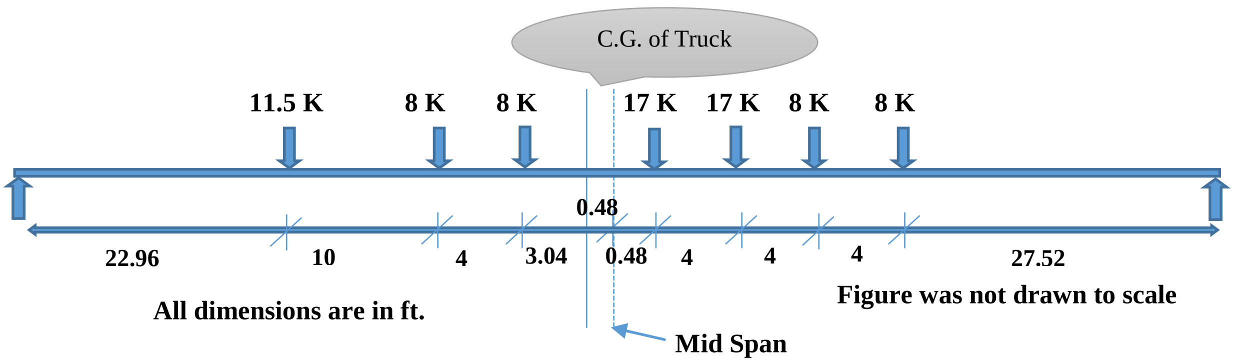

Fig. 30 Controlling AASHTO SHV- SU7 Truck

8.3.3 Controlling Truck Position for Max Shear on Critical Span (60 ft.)

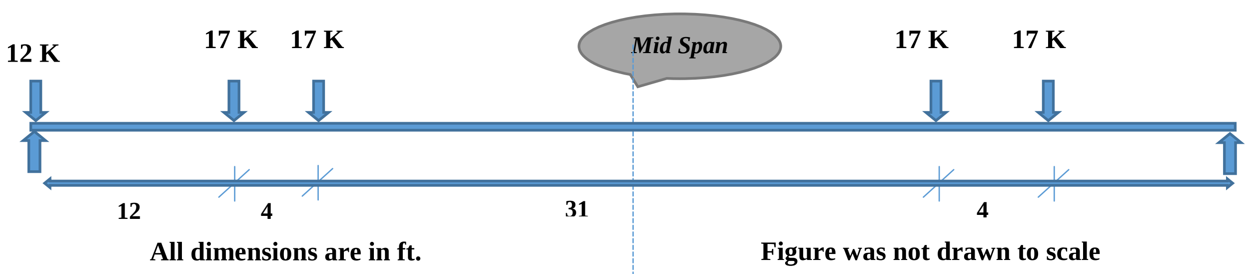

Fig. 31 Controlling Ohio Legal Truck- 5C1 Truck

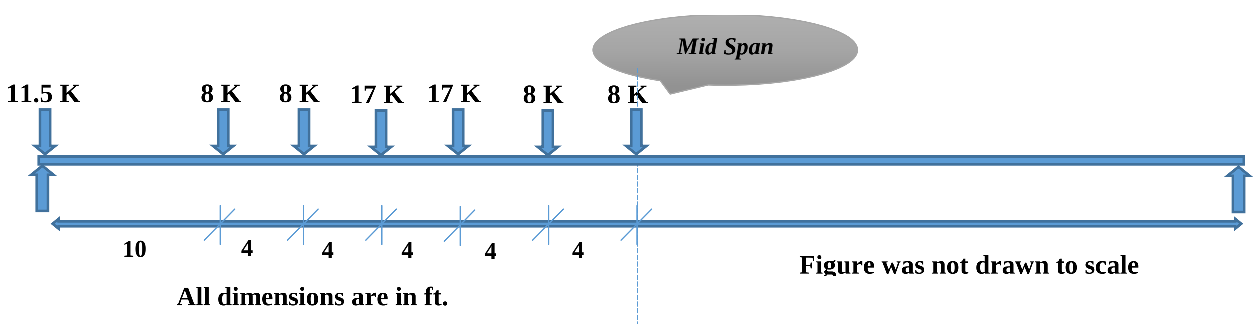

Fig. 32 Controlling AASHTO SHV- SU7 Truck

8.4 Appendix D - Multi-Span (Two Span)

8.4.1 C - Program

```
#include <stdio.h>
#include <stdlib.h>
float
r1[10000],r2[10000],v[10000],ilm[10000][10000],ilv[10000][10000],m[10000],ilmp[10000][10000],ilvp
[10000][10000];
int main()
{
    float length1,length2,reference,s[350],p[350],mmax,sumspacing=0,vmaxP,vmaxN,step;
    int n,count,count1,count2,i,j,mesh,temp;
    printf("Total no of Axles:");
    scanf("%d",&n);
    for(count=1;count<=n;count++)
       {
        printf("Axle Load %d:",count);
        scanf("%f",&p[count]);
        }
       for(count=1;count<n;count++)
       {
        printf("Load Spacing %d:",count);
        scanf("%f",&s[count]);
        sumspacing=sumspacing+s[count];
       }
        printf("Length of First Span:");
        scanf("%f",&length1);
        printf("Length of Second Span:");
        scanf("%f",&length2);
        reference=length2;
    while (length1<=200)
     {
     while(length2<=200)
        {
            float length=length1+length2;
            mesh=1000;
            count1=0;
        while(count1<=mesh)
          {
            step=length/mesh;
            count2=0;
            while(count2<=mesh)
              {
                if(step*count2<=length1)
                  {
                    r1[count2]=((step*count2)*(step*count2)*(step*count2)-
step*count2*(2*length1*length2+3*length1*length1)+

2*length1*length1*(length1+length2))/(2*length1*length1*(length1+length2));
                    r2[count2]=(-(step*count2)*(step*count2)*(step*count2)+

step*count2*(2*length1*length2+length1*length1))/(2*length1*length1*(length2));
                  }

               else if (step*count2>=length1&&step*count2<=length)
                  {
                    r1[count2]=(-(step*count2-length1-length2)*(step*count2-length1-
length2)*(step*count2-length1-length2)*
                            (length1/length2)+length1*length2*(step*count2-length1-
length2))/(2*length1*length1*(length1+length2));
                    r2[count2]=((step*count2-length1-length2)*(step*count2*step*count2-

2*(length1+length2)*step*count2+length1*length1))/(2*length2*length2*length1);
                  }
               if(count1*step>=count2*step&&step*count1<length1)
                    {
                     ilm[count1][count2]=r1[count2]*step*count1-(step*count1-step*count2);
                     ilv[count1][count2]=r1[count2]-1;
                    }
```

```
              else if(count1*step<count2*step&&step*count1<length1)
                  {
                    ilm[count1][count2]=r1[count2]*step*count1;
                    ilv[count1][count2]=r1[count2];
                  }
             else if(count1*step>=count2*step&&step*count1>=length1)
                 {
                     ilm[count1][count2]=r1[count2]*step*count1-(step*count1-
step*count2)+r2[count2]*(step*count1-length1);
                     ilv[count1][count2]=r1[count2]-1+r2[count2];
                 }
             else if(count1*step<count2*step&&step*count1>=length1)
                 {
                     ilm[count1][count2]=r1[count2]*step*count1+r2[count2]*(step*count1-
length1);
                     ilv[count1][count2]=r1[count2]+r2[count2];
                 }
                   count2=count2+1;
           }
             count1=count1+1;
        }
        count1=0;
        count2=0;
        count=n;
        mmax=0;
        s[count]=0;
         while(count1<=mesh)
           {
             count2=0;
             while(count2<=mesh+sumspacing/step)
                {
                  count=n;
                  ilmp[count1][count2]=0;
                  ilvp[count1][count2]=0;
                  temp=0;
                  while(count>0)
                     {
                       temp=temp+s[count];
                         if(step*count2-temp<0)
                          {
                            break;
                          }
                         else if((step*count2-temp)>length)
                          {
                            count=count-1;
                            continue;
                          }
                        int value=temp/step;
                        ilmp[count1][count2]=ilmp[count1][count2]+(ilm[count1][count2-
value])*p[count];
                        ilvp[count1][count2]=ilvp[count1][count2]+(ilv[count1][count2-
value]*p[count]);
                        count=count-1;
                     }
                   count2=count2+1;
                }
                  count1=count1+1;
           }
       float mmaxP=0;
       float mmaxN=0;
       vmaxP=0;
       vmaxN=0;
       float c1,c2,c3,c4,c5,c6,c7,c8;
       for(count1=0;count1<=mesh;count1++)
         {
           for(count2=0;count2<=mesh+sumspacing/step;count2++)
           {
               if(ilmp[count1][count2]>mmaxP)
               {
                 mmaxP=ilmp[count1][count2];
```

```
                    c1=count1;
                    c2=count2;
                  }
                  if(ilmp[count1][count2]<mmaxN)
                  {
                    mmaxN=ilmp[count1][count2];
                    c3=count1;
                    c4=count2;
                  }
                  if(ilvp[count1][count2]>vmaxP)
                  {
                    vmaxP=ilvp[count1][count2];
                    c5=count1;
                    c6=count2;
                  }
                 if(ilvp[count1][count2]<vmaxN)
                 {
                    vmaxN=ilvp[count1][count2];
                    c7=count1;
                    c8=count2;
                 }
            }
          }
            printf("\n%f,%f,%f,%f",mmaxP,mmaxN,vmaxP,vmaxN);
            length2=length2+5;
        }
          length2=reference;
          length1=length1+5;
      }
       return 0;
}
```

8.4.2 Controlling Truck Position for Max +VE Moment on Critical Span (80 ft. – 55 ft.)

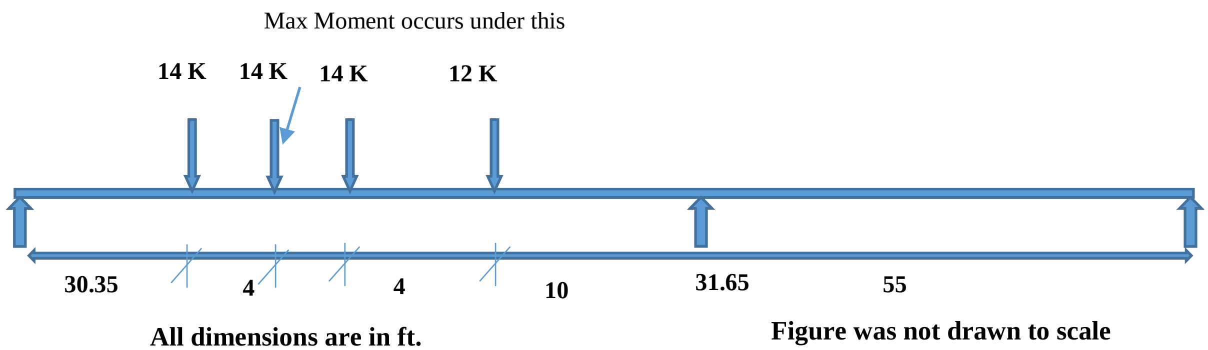

Fig. 33 Controlling Ohio Legal Truck- 4F1 Truck

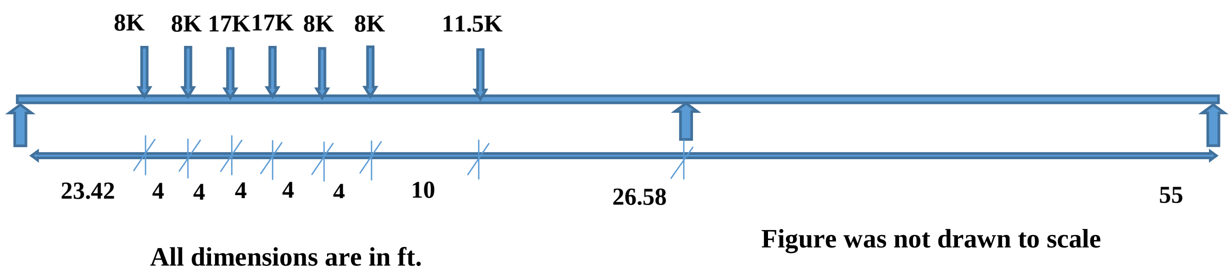

Fig. 34 Controlling AASHTO SHV- SU7 Truck

8.4.3 Controlling Truck Position for Max -VE Moment on Critical Span (30 ft. – 20 ft.)

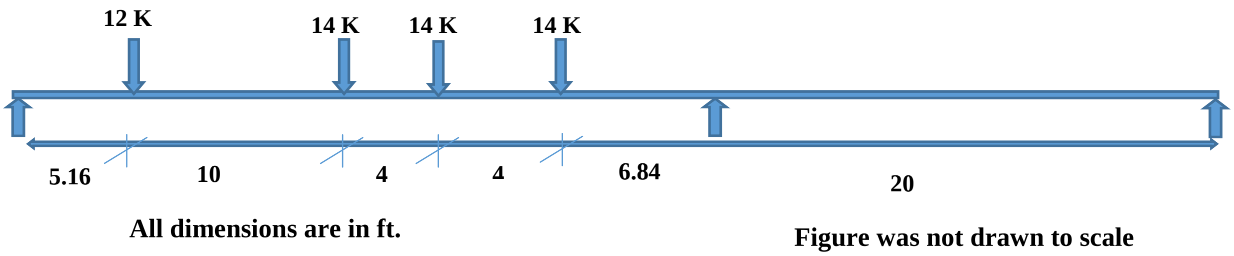

Fig. 35 Controlling Ohio Legal Truck- 4F1 Truck

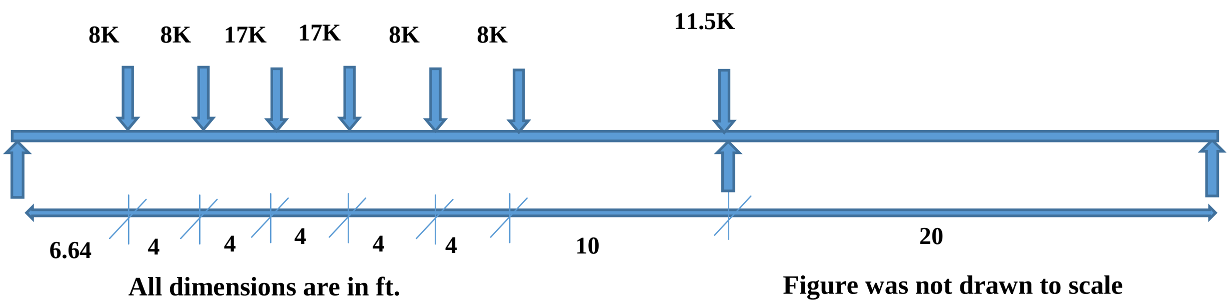

Fig. 36 Controlling AASHTO SHV- SU7 Truck

8.4.4 Controlling Truck Position for Max +VE Shear on Critical Span (55 ft. – 55 ft.)

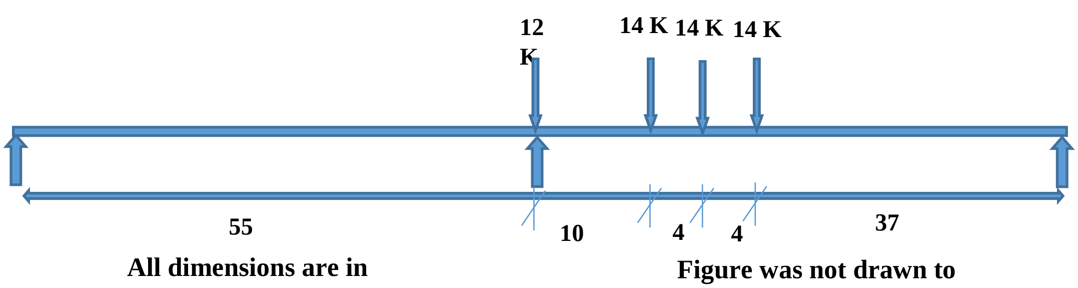

Fig. 37 Controlling Ohio Legal Truck- 4F1 Truck

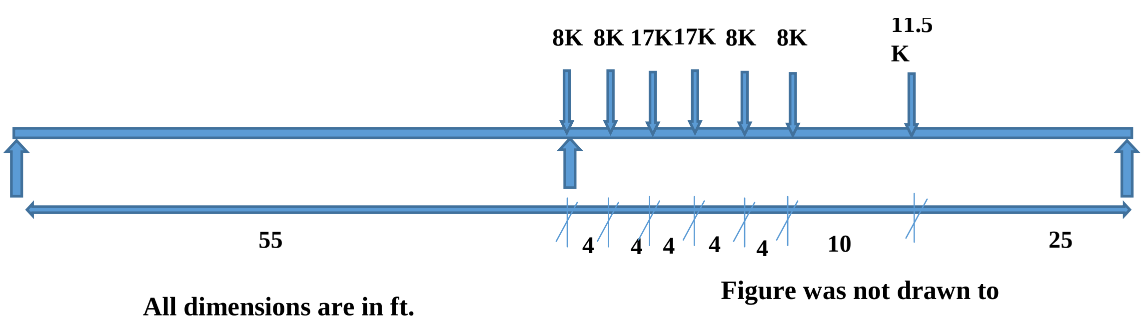

Fig. 38 Controlling AASHTO SHV- SU7 Truck