JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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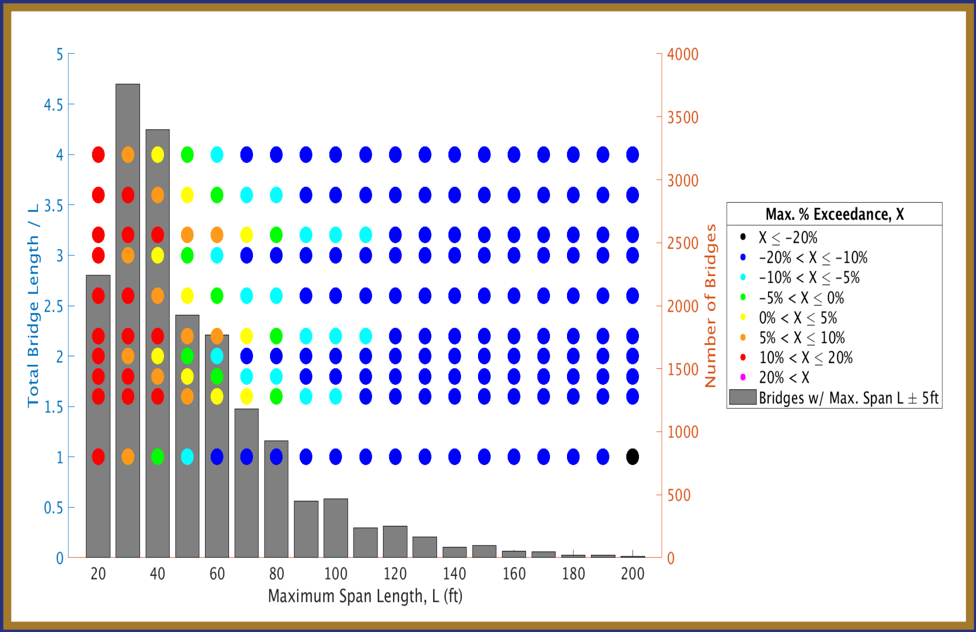
Legal and Permit Loads Evaluation for Indiana Bridges



Chris Kusiak, Mark D. Bowman, Arun Prakash

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AUTHORS

Chris Kusiak
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Mark D. Bowman, PhD
Professor of Civil Engineering
Lyles School of Civil Engineering
(765) 494-2220
bowmanmd@purdue.edu
Corresponding Author

Arun Prakash
Associate Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University

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16. Abstract

According to federal law, routine commercial vehicles must adhere to certain limits on their load configuration in order to operate legally on interstate highways. However, states may allow for heavier or different load configurations provided that bridges on the state and county highway system are load rated and, if necessary, posted with vehicles that appropriately represent these loads. The state of Indiana allows several classes of vehicles to operate with loads that exceed federal limits, and, presently, several LFD design loads are used to represent these exceptions as state legal loads. This study evaluates the MBE rating loads for their ability to encompass Indiana's exception vehicles and recommends a set of state rating loads which can replace the current state legal loads and, combined with the MBE rating loads, satisfactorily encompass the load effects due to these exceptions. Comparing moment and shear envelopes on a representative set of bridges, the MBE rating vehicles were found to be insufficient for representing Indiana's exception vehicles. Three new rating loads are proposed which encompass the exception vehicles efficiently and represent realistic legal loads. Conversely, acceptable HS-20 rating factors are also provided as an alternative to the adoption of these new vehicles. These rating factors, all 1.0 or greater, can ensure a similar level of safety by requiring a specific amount of excess capacity for the HS-20 design load.

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EXECUTIVE SUMMARY

Introduction

According to federal law, routine commercial vehicles must adhere to the Federal Bridge Formula (FBF) as well as a 20-kip axle weight limit, a 34-kip tandem axle weight limit, and an 80-kip gross vehicle weight limit in order to operate legally on interstate highways. However, states may allow for heavier or different load configurations provided that bridges on the state and county highway system are load rated with vehicles that appropriately represent such loads and are posted if necessary. The rating vehicles currently used in Indiana include those required by the Federal Highway Administration (FHWA) (namely, those recommended by the American Association of State Highway and Transportation Officials (AASHTO) in the *Manual for Bridge Evaluation* (MBE)), which are calibrated to encompass loads that conform to federal limits. However, the state of Indiana allows several classes of vehicles to operate with loads that exceed federal limits, and, as such, the H-20, HS-20, and alternate military design load serve as state legal loads and are meant to encompass these exception vehicles.

This study was commissioned in order to evaluate the removal of the design vehicles from the list of Indiana's rating vehicles. This would require an evaluation of the remaining MBE rating loads for their ability to encompass Indiana's exception vehicles and, if they cannot, to recommend a set of additional state rating loads that do encompass the exceptions. In order to achieve this objective, each type of exception vehicle was researched extensively, and a set of representative vehicles was developed for each. A beam-line analysis was conducted on a set of representative bridges and the moment and shear envelopes for the exception vehicles were compared to those of the rating vehicles.

The exception vehicles used in this analysis include garbage trucks and vehicles carrying farm or lumber commodities. Another class of exception vehicle allowed by the Indiana Code, emergency response vehicles, was not included in this study since they were considered to be adequately addressed by the rating vehicles introduced by the FAST Act. Additionally, the Indiana Code features a "grandfather law," which can apply to any vehicle, regardless of purpose, as long as it meets certain weight limits which were in place before the introduction of the FBF. This law allows certain vehicles which would otherwise be illegal according to federal limits.

Findings

The results show that the current MBE rating vehicles alone are insufficient for encompassing the exception vehicles operating in Indiana, with several of the exception vehicles producing moments that were about 30% greater than the corresponding moments generated by the MBE rating vehicles. A set of three additional rating loads are proposed which encompass the state exception vehicles on every bridge in the representative set of bridges. The proposed new rating loads were designed to both resemble realistic vehicles or realistic combinations of vehicles and to encompass the exception vehicles as efficiently as possible, minimizing the number of bridges that would need to be posted as a result of adopting these loads as rating and posting loads.

An additional analysis was conducted to provide for an alternative, phased approach. For this phased approach, instead of conducting the load-rating of each bridge again with the proposed new rating loads, a simpler method based on the current bridge rating factors was developed. Since Indiana bridges are currently rated for the HS-20 loading, a series of multipliers for this load are developed, such that the HS-20 scaled by these multipliers would encompass, within tolerance, the exception vehicles on every representative bridge considered in this study.

Recommendations

The primary focus of the study was to examine possible new legal loads that could envelope the load effects of exception vehicles in Indiana if the design vehicles were removed from the current list of Indiana legal loads. It was found that three new proposed legal loads could successfully envelope the exception vehicles. The study examined the severity of the loading, but it was beyond the scope of the study to examine the frequency of the exception vehicle loadings and suitable load factors that should be used together with those loadings. Consequently, an additional study is recommended to examine the frequency of the exception vehicle loadings and establish a suitable loading factor for use together with the new proposed legal loads.

It is recommended that the three loads developed for the purpose of encompassing Indiana's exception vehicles be considered for future adoption as state legal loads to improve the safety of bridges on the state and county highway systems once the new additional study better defines the appropriate loading factor to be used with those new legal loadings. Alternatively, if a small exceedance of load effects is deemed acceptable, several possible alterations, which consist of the same loadings but with reduced weights, are also presented and could be implemented in the future instead.

Moreover, an alternative bridge load rating method was found to also envelope the load effects of the exception vehicles by using the current rating factor for the HS-20 loading. For this alternative method, the current rating factors for the HS-20 on each bridge are compared with the multipliers proposed herein. Bridges with HS-20 rating factors less than the proposed multipliers may then be screened for further analysis involving the proposed legal loads, whereas bridges with rating factors larger than the corresponding multiplier would be deemed safe. Hence, this alternative approach can also be considered for possible future implementation on all bridges in the state and is considered an acceptable substitute for the adopting the legal loads proposed herein.

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1. MOTIVATION FOR THE STUDY

The Indiana Code allows certain vehicles to exceed the federal weight limits for typical commercial traffic, and, in order to represent these vehicles for load rating and posting, several LFD design vehicles have been adopted as state legal loads (INDOT, 2019). However, it is unknown to what degree the current bridge rating and posting loads used by INDOT represent the exception vehicles, and, in fact, it is believed to be too conservative to use these design vehicles as state legal loads. In order to ensure that bridges determined to be safe by INDOT's bridge rating program will in fact be able to safely withstand the exception loads and to produce more reasonable state legal loads, a comparison between the rating loads and the exception loads must be made. This study provides this comparative analysis between the rating loads recommended in the AASHTO MBE and the state exception loads, and, as a result of this analysis, supplemental bridge rating loads are proposed which will allow bridges to be evaluated for their ability to carry these exception vehicles.

2. DESCRIPTION OF ANALYSIS

2.1 Set of Bridges Considered

An important question in evaluating the safety of Indiana's bridges is which bridges are to be considered when comparing the states' rating loads to its exception vehicles. Rather than focus on the details of specific bridges, a representative suite of bridges was instead constructed. The criterion for evaluating the current rating vehicles then became the degree to which an exception vehicle would cause higher stresses than the rating and posting vehicles on any one of those bridge structures. The suite of bridges was constructed to include a wide range of span lengths and a number of multi-span configurations. It covered span lengths from 20 ft to 200 ft, in 10-ft increments. This span range was used since the AASHTO LRFD specifications apply over this range (AASHTO, 2017) and most INDOT bridges are within this range. The number of spans and the ratios between different spans (aspect ratios) were varied as follows:

1. One span (20′, 30′, …200′; 19 bridges total)
2. Two spans ($3 \times 19 = 57$ bridges)
   a. Two equal spans
   b. Two unequal spans with an aspect ratio of 60%
   c. Two unequal spans with an aspect ratio of 80%
3. Three spans ($3 \times 19 = 57$ bridges)
   a. Three equal spans
   b. Unequal interior and exterior spans with an aspect ratio of 60%

$$\left(\frac{\text{exterior span}}{\text{interior span}} = 0.6\right)$$

   c. Unequal interior and exterior spans with an aspect ratio of 80%

$$\left(\frac{\text{exterior span}}{\text{interior span}} = 0.8\right)$$

4. Four Spans ($3 \times 19 = 57$ bridges)
   a. Four equal spans
   b. Unequal interior and exterior spans with an aspect ratio of 60%

$$\left(\frac{\text{exterior span}}{\text{interior span}} = 0.6\right)$$

   c. Unequal interior and exterior spans with an aspect ratio of 80%

$$\left(\frac{\text{exterior span}}{\text{interior span}} = 0.8\right)$$

This variation in span ranges produced 190 bridge span configurations in total.

For the most part, each structure in this suite was to be considered of equal importance; however, the actual distribution of Indiana's bridges by maximum span length is shown in Figure 2.1 (FHWA, 2016). Each bin of the histogram in Figure 2.1 contains bridges with spans ± 5 ft of the listed values of L. The exception to this was the last bin, which only contained bridges with maximum span lengths between 195 ft and 200 ft. This figure depicts 17,101 highway bridges after removing culverts, railroad bridges, pedestrian bridges, bridges with maximum spans shorter than 15 ft, and bridges with maximum spans greater than 200 ft.

As Figure 2.1 shows, Indiana's bridges are not uniformly distributed according to maximum span length. Bridges with maximum span lengths of about 30 to 40 ft are the most common, and by a significant margin at that. While there could be merits to prioritizing these bridges in ensuring that the state's legal vehicles are sufficiently encompassed by rating vehicles, instead, because bridges with a wide variety of span lengths have a significant representation in Indiana's inventory, it was ultimately decided that the goal of the project would be to ensure a uniform minimum level of safety for all bridges in the proposed analysis suite.

2.2 The Set of Rating Vehicles, Load Factors, and Impact Factors Considered

The set of rating vehicles to be used in the analyses consisted of the mandatory AASHTO rating vehicles (as defined in the *Manual for Bridge Evaluation–MBE* (AASHTO, 2018)), or more specifically, all of the AASHTO rating vehicles except the Notional Rating Load (NRL), which is an alternative to the manual's four single-unit vehicles. The FAST Act vehicles (Hartmann, 2016), which are also mandatory rating vehicles, were not included in this analysis either since

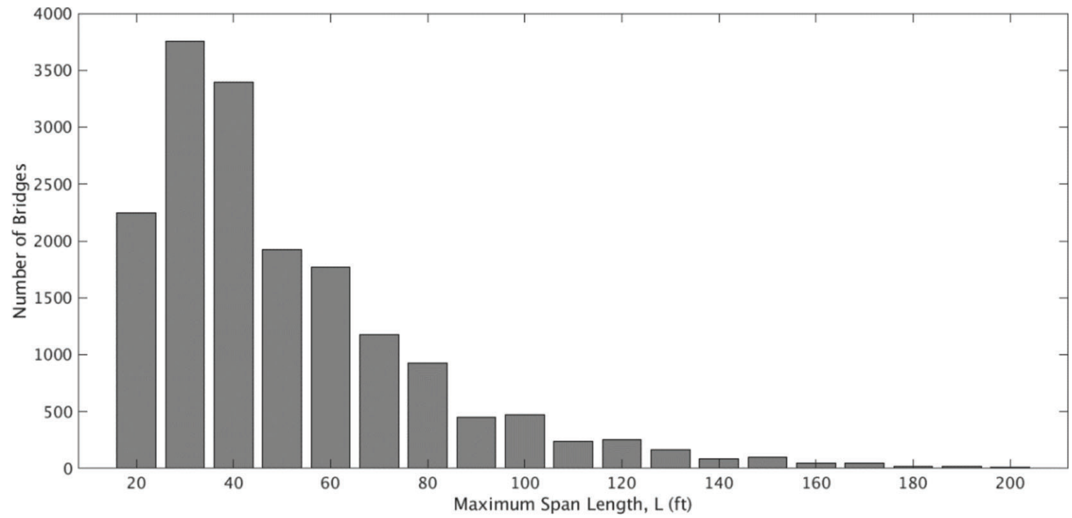

Figure 2.1 Histogram of Indiana's bridge inventory, sorted by maximum span length, L.

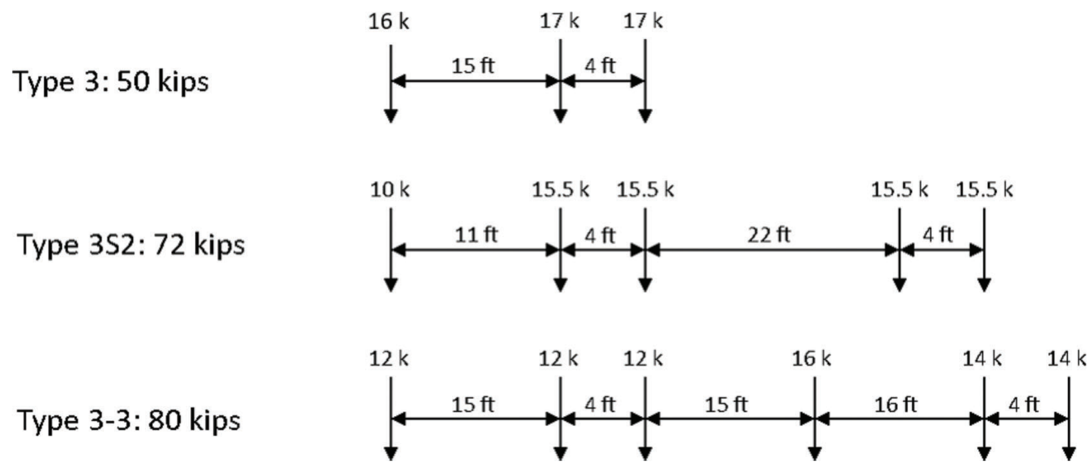

Figure 2.2 AASHTO Type 3 MBE rating loads.

the exception vehicles to be investigated did not include any emergency vehicles. This remaining set of MBE vehicles will be referred to in the text as the Reduced Indiana Rating Vehicles (RIRVs). These vehicles represent the baseline requirements for bridge load rating vehicles, and any additional vehicles should supplement these so as to encompass any exceptions to the FBF. The details of the RIRVs are shown in Figures 2.2, 2.3, and 2.4. The current Indiana Rating Vehicles, or CIRVs, consist of the RIRVs and the H-20, HS-20, and alternate military design loads; they also include the NRL and the EV loadings, but for the reasons stated above, those loadings were not to be included in analysis.

Impact and load factors were used in accordance with the current AASHTO and Indiana rating requirements. According to *INDOT's Indiana Bridge Inspection Manual*, bridges owned or maintained by the state shall be rated according to the LRFR method, regardless of the design methodology (INDOT, 2019). As such, the load factor used for both the legal exception vehicles and the IRVs was the 1.45 prescribed for routine commercial traffic using the LRFR method (AASHTO, 2018). This load factor for routine commercial traffic can actually vary, but for an analysis involving only routine traffic, the load factors for the AASHTO rating vehicles and any other vehicles will always be the same, making the actual value of the load factor immaterial. Nevertheless, since 1.45 is the load factor assigned to bridges with an unknown amount of traffic, it was considered an appropriate choice should it become necessary to make an accounting of the magnitude of the stresses caused by the exception vehicles. As further specified in the MBE, a dynamic impact factor of 1.33 was applied to all axle loads (but not distributed loads) since there are no provisions in Indiana law requiring exception vehicles to operate under a speed reduction.

Figures 2.2, 2.3, and 2.4 provide the specifics on each of the RIRVs.

It should be noted that it is assumed herein that the exception vehicles qualify as routine commercial

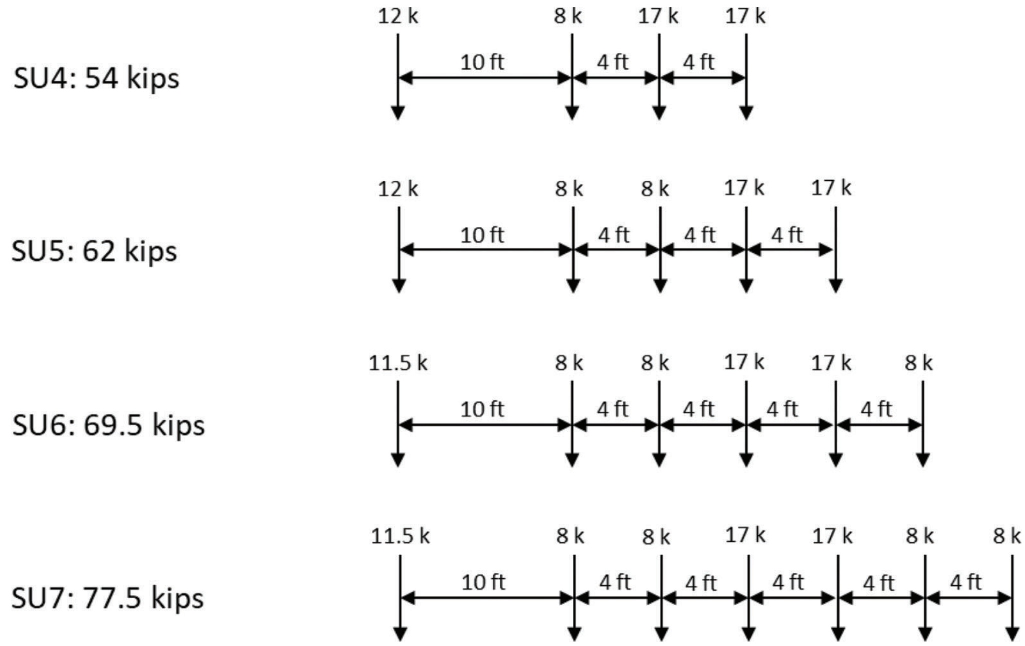

Figure 2.3 AASHTO MBE SHV rating loads.

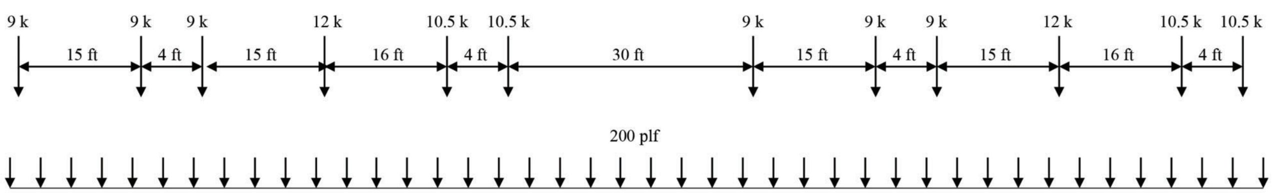

Figure 2.4 AASHTO MBE lane-type load.

traffic. It is possible that these exception vehicles only account for a relatively small amount of truck traffic, which, because the magnitude of a load factor depends on how common the loads are, could result in these vehicles requiring a lower load factor than the rating and posting vehicles. The approach taken in this project is, therefore, conservative and a more in-depth analysis of the prevalence of these vehicles in order to determine more appropriate load factors would be required to obtain more accurate results.

2.3 Comparison of Legal Exception Vehicles with the Rating Loads

Using the previously defined set of bridges, the load effects of the exception vehicles were compared to those of the RIRVs. An in-house computer program was written such that each exception vehicle configuration could be analyzed and checked against the RIRVs on the entire set of 190 bridges. Moment and shear envelopes were determined for each load by first developing the moment and shear influence lines at tenth points for each of the 190 bridges. Next, the effect of loading each bridge with a particular vehicle was calculated to obtain the corresponding moment and shear envelopes for the entire set of bridges. This analysis treated each bridge as a beam, and no accounting for lateral load distribution was made. Furthermore, all spans were considered to have equal and uniform material and cross-sectional properties, with the stiffness of each of the spans being defined only relative to each other on the basis of their lengths.

The moment and shear envelopes of each of the RIRVs were then compiled into an “envelope of envelopes.” The term “envelope of envelopes” refers to a single envelope that encompasses the moment or shear envelopes of all the vehicles in a group (in this case the RIRVs). Finally, moment and shear envelopes from every exception vehicle were calculated as well and compared to the rating vehicles’ “envelopes of envelopes.” This approach does not directly involve the capacity of the bridge and functions only as a means of determining the quality of a rating factor determined using the RIRVs.

As an example, a graphical comparison of a fictitious exception vehicle’s moment envelope and the RIRVs’ moment envelope of envelopes is provided for a bridge with two equal spans of 60 ft each (Figure 2.5). The graph presents a case where the negative bending moment produced by the exception

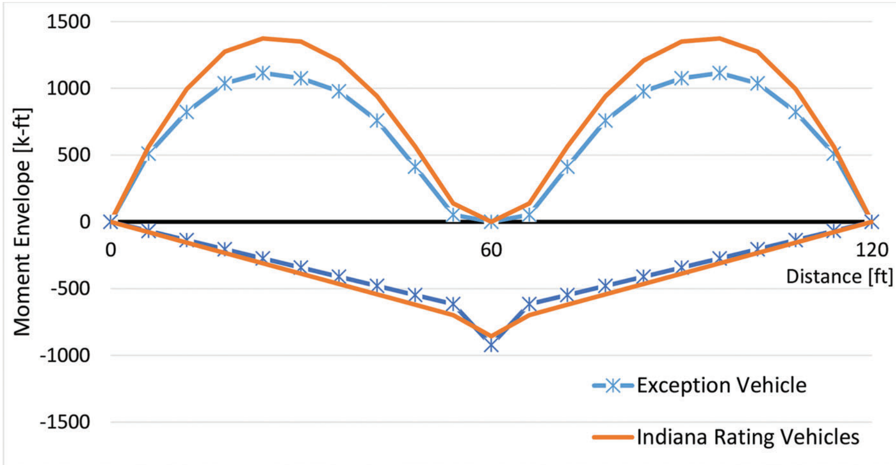

Figure 2.5 Sample comparison of an exception vehicle's moment envelope and the RIRVs' moment "envelope of envelopes" for a bridge with two equal spans of 60 ft.

vehicle exceeds the negative moments caused by the RIRVs. In this case, assuming that no exceedances of the RIRVs are tolerable, the exception load would not be acceptable unless a more refined analysis accounting for lateral load distribution and bridge capacity found that it was permissible. Alternatively, additional vehicles may be added to the set of RIRVs to prevent the exceedance.

3. LEGAL LOADS

3.1 Legal Load Overview

Routine commercial traffic in Indiana must normally adhere to the greater of two limits, either the Federal Bridge Formula (FBF), or Indiana's own "grandfather" law. The analyses in this report were conducted on groups of vehicles which, provided that they perform a certain function, are allowed exceptions by the Indiana Code and which violated either the FBF, the grandfather law, or both. One of these groups, garbage trucks, were analyzed because they are allowed particularly heavy axle loads. Another two groups, which included vehicles carrying lumber or agricultural products, respectively, were of particular concern due to their exception laws which allow for particularly heavy gross vehicle weights (GVWs). Additionally, the current CIRVs were designed to address the vehicles encompassed by the Bridge Formula, but their effectiveness in encompassing the load effects of grandfathered vehicles was unknown. Several examples of legal grandfathered vehicles were included in this study and were also compared to the rating and posting vehicles. Lastly, although the law as interpreted by the investigators states that construction vehicles do not receive exceptions when operating on open roads, it was believed from previous work (SPR-3910) that ready-mix concrete trucks may be operating beyond legal limits and that type of vehicle was consequently analyzed as well. As a whole, the set of exception vehicles analyzed in this study are referred to as the state operating vehicles (SOVs).

3.1.1 The Federal Bridge Formula

Congress enacted the Federal Bridge Formula in 1975 to limit the weight-to-length ratio of a vehicle when crossing an interstate highway bridge (USDOT, 2015). Theoretically, a vehicle configuration that does not comply with the formula can be made to do so by either by introducing additional axles or by increasing the distance between axles. The formula is listed in Equation 3.1.

$$W = 500 \times \left[\frac{L \times N}{N-1} + 12 \times N + 36\right] \qquad \text{(Eq. 3.1)}$$

where W = the acceptable gross weight on any group of two or more consecutive axles, rounded to the nearest 500 pounds, L = the distance in feet between the outer axles of any group of two or more consecutive axles, and N = the number of axles in the group under consideration.

In addition to the formula itself, federal law requires single axle weights to be limited to 20,000 pounds, and tandem axles (i.e., two axles spaced no more than 96 inches apart) to be limited to a combined 34,000 pounds. Furthermore, the gross vehicle weight (GVW) is limited to 80,000 pounds (US DOT, 2006).

3.1.2 Indiana's Grandfather Law

Indiana's grandfather law is comprised of a limit for gross vehicle weight and a set of limits for the weights of individual axles. These limits (listed in section IC 9-20-4-1(c) (2019) of the Indiana Code) are as follows: GVW must be less than or equal to 73,280 pounds, single axles are limited to 18,000 pounds, and each axle in a tandem is limited to 16,000 pounds (Indiana General Assembly, 2019). There is additionally a limit on wheel weights, which was not accounted for since it would be irrelevant to the simplified analysis conducted in this study. It should be noted that this law is relevant to this analysis in spite of the fact that all weight limits are less than the federal limits because, unlike the federal limit, there is no formula in the grandfather law which dictates legal distances between axles. Therefore, any vehicle that conforms to these axle and gross vehicle weight limits is legal in Indiana, regardless of how close together the axles are spaced.

3.2 Legal Load Data Sources and Models

3.2.1 Modeling Garbage Trucks

According to the Indiana Code (specifically, Section IC 9-20-11-2 (2019)), garbage trucks are allowed single axle loads of up to 24,000 pounds and tandems loads of up to a combined 42,000 pounds, except on interstate highways where the grandfather and FBF are enforced instead. The only other restriction of possible relevance to this work was that the trucks must also conform to the FBF and grandfather law while unladen. Initially, garbage trucks were modeled by using these limits as the axle weights of theorical garbage trucks, forming an upper bound for the load effect envelopes. All garbage trucks considered in this study were two- or three-axle single-unit vehicles, although tractor-trailer combinations can also be eligible for the above exceptions under certain conditions.

Desiring a more realistic analysis, data were acquired from the websites of garbage truck manufacturers in order to make a better estimate of real axle weights. It was believed to be realistic that garbage trucks would approach or exceed the special axle weights they are allowed on the rear, load-bearing axles. On the other hand, it was thought unrealistic that the steering axle would also attain the maximum legal limit and manufacturer data were referenced to specifically address this inconsistency. The final estimate was based on only two- and three-axle trucks where the rear axles were rated to carry at least 24,000 pounds or 42,000 pounds, respectively. Rated weights, where referenced in this work, refer to the maximum safe weight an axle can carry, as specified by manufacturers. The rated weights of the rear single or tandem axles were scaled down to the legal limit (or up, where measurements of the empty truck's weight were available) and the front axle was scaled proportionally. The average front axle weights for two-axle and three-axle garbage trucks were then determined separately and were assumed to reasonably model the front axle weights of any such garbage truck. The resulting configurations, which consisted of these axle weights and a range of possible axle spacings, are shown in Figure 3.1. The dimensions shown in this figure spanned the range of spacings which were available for two- and three-axle garbage trucks, across all manufacturers. More details on the garbage trucks used for this estimate can be found in Appendix A in Figure A.1 and Figure A.2.

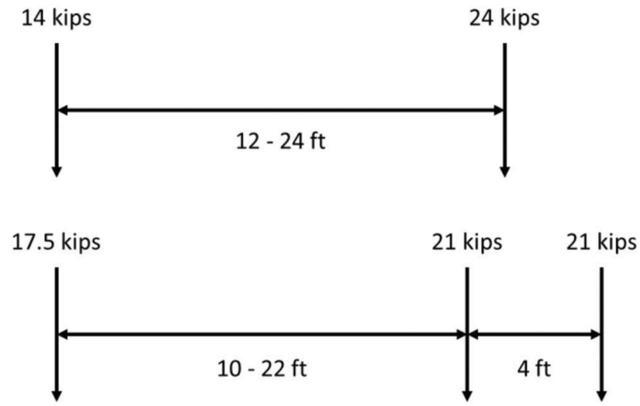

Figure 3.1 Garbage truck configurations used in analysis.

3.2.2 Modeling Farm Commodity Vehicles

According to the Indiana Code (IC 9-20-4-2, 2019) weight limits do not apply to vehicles that transport:

> …farm commodities from the place of production to the first point of delivery where the commodities are weighed and title to the commodities is transferred if the weight of the vehicle with load or combination of vehicles with load does not exceed the gross weight limit by more than ten percent (10%).

This exception does not apply on interstate highways or on posted bridges.

Based on the number of assumptions made in analyzing farm commodities in SPR-3913, this class of exception vehicle was to be reexamined with greater detail so that an analysis of more realistic vehicle configurations would be possible. A survey of the manufacturers of grain trailers and truck-tractors was undertaken in order to find information on the axle configurations of combinations of these vehicles as well as measurements or estimates of their empty loads and load capacities. For the tractors, typical weights and axle-spacings were found and two variants were combined with each trailer. The trailers analyzed in this study were specialized models, with hoppers equipped for unloading grain.

In determining the axle weights of the farm commodity SOVs it was assumed that the operator of a grain tractor-trailer combination would follow Indiana law to the letter. In other words, it was assumed that they would load their trailers with as much as possible, but not so much that they would violate the federal GVW limit by more than 10%. That GVW limit was either that set by the application of the federal bridge formula, or at most the 80,000 lb upper bound. Furthermore, it was assumed that this 10% exception applied not only to the federal GVW limit, but also the alternate limit set by Indiana's grandfather law. This assumption was based on the investigators' interpretation of the Indiana Code, although it is unknown if this is how this law is commonly put into practice. Pertaining to farm commodity vehicles, exceedance of individual axle weight limits is not mentioned in the

Code and it was assumed that by this omission any axle weights were allowable, as long as the GVW did not exceed either the FBF or grandfather law by more than 10%. However, by using the above methodology to generate realistic axle weights none of the configurations exceeded axle weight limits by more than 10% as long as the GVWs weren't exceeded by more than 10%.

The initial distribution of weight was derived from the spatial distribution of the axles, i.e., it was determined by assuming the group of axles at the front of the semi-trailer (the tandem at the back of the tractor) received the weight associated with a certain tributary length, and the group at the back, usually a tandem or tridem, received the remaining weight, with the tributary lengths being adjoined at the midpoint between these two axle groups. It was further assumed that all axles on the same suspension carried an equal portion of the weight carried by that group of axles. The maximum legal weight, according to either the FBF or grandfather law, was determined to the nearest 100 pounds, and the appropriate 10% increase was applied according to the same distribution of weight. The resulting truck configurations are listed in Appendix A in Table A.2, with the corresponding FBF or grandfather weights (no 10% GVW exception) listed in Table A.1.

Efforts were made to obtain data regarding grain trailer loads commonly used in Indiana. Five-axle tractor trailers hauling grain are regularly observed throughout Indiana at certain times of the year. The photograph in Figure 3.2 depicts one such trailer. An Indiana farming association was contacted to see if records from local elevators could be obtained. Such efforts, however, were not successful in yielding any actual grain trailer loads.

While the analyses in the remainder of this report pertain to the preceding definition of farm commodities, an interview with state police indicated that there is, in fact, very little oversight of the loads that farmers transport during harvest. As such, it is possible that any load which a farm commodity vehicle may physically be able to carry may in fact be in operation on Indiana roads, regardless of any law. A further analysis was conducted, assuming that each grain trailer in our inventory would be carrying, at full capacity, a particularly dense farm product. In this case, it was soybeans. The grain trailers in the inventory had their capacities reported in cubic feet, both for the trailer loaded to its *level* capacity, i.e., loaded to the very top of the trailer, as well as for a *heaped* capacity, which meant it would be loaded with an extra 8 or 10 inches of product above the height of the trailer walls. Since the definition of a heaped load varied from source to source, it was decided that a level load would be used for a demonstration of the types of loads which might possibly be carried on Indiana's roads.

Realizing that these configurations often resulted in axle weights that exceeded the rated axle limits of these vehicles, a further refinement was considered, where it was assumed that farmers would be aware of rated axle limits and would not knowingly exceed those limits. However, since the axle ratings are most likely reported with a certain factor of safety, it may be possible to carry these loads without causing obvious damage to the vehicle and actual practice may entail that Indiana farmers transport their product with a fully loaded trailer regardless of the weight of the load. Conversely, it should still be kept in mind that the higher capacity trailers may only ever be loaded with lower density products and real loads may yet adhere to the Indiana Code, or at least the stated load capacity of the transport vehicles.

Nevertheless, a limited analysis of these theoretical loads was conducted, and it was found that when loaded to axle capacity some grain trucks produced moments that were more than 1.6 times larger than the RIRV moment envelopes. Furthermore, with the trucks loaded to full volumetric capacity some produced moments greater than those of the MBE rating loads by a factor of over 2.3. The full volumetric load, which was still significantly less than the possible heaped load, even exceeded the design load by over 30% on some bridges. It should be noted that all comparisons between the RIRVs and these theoretical illegal SOVs was conducted only at critical design points on each bridge in the analysis suite. Due to the highly speculative nature of these particular analyses no recommendations are made on the basis their results. This discussion is included to bring attention to this issue as a possible topic for future investigation.

Figure 3.2 Typical 5-axle semi-tractor-trailer truck seen transporting grain in Indiana.

3.2.3 Modeling Lumber Commodities

According to the Indiana Code (IC 9-20-4-2, 2019) weight limits do not apply to vehicles that transport: "…logs, wood chips, bark, and sawdust if the weight of the vehicle with load does not exceed either: (A) the gross weight limit; or (B) the axle weight limit; by more than ten percent (10%)."

For the purposes of this study, only vehicles transporting logs were considered. This exception also does not apply on interstate highways or on posted bridges.

Similar to the approach for vehicles transporting agricultural commodities, resources provided by manufacturers were used to produce axle configurations for analysis. The analysis was further focused on logging trailers, which were specifically designed to transport freshly cut logs. An identical methodology to that used for farm commodities was used here to determine the axle weights of a number of reasonable lumber truck configurations. The only difference in the application of these two exceptions was that axle weights were also limited to exceeding the standard limits by no more than 10%, rather than only the GVW. This meant, for example, if a certain configuration attained its maximum, non-exception weight according to the FBF, no tandem could exceed a weight of 37,400 pounds, but if instead the grandfather law allowed for a larger weight, no axle in a tandem could exceed 17,600 pounds. In practice this did not affect the final configurations; just as no farm commodity vehicle exceeded the axle limits by 10%, the comparable lumber loads did not do so while staying at or below 110% of the GVW limit. The axle configurations of the final legal and exception loads are included in the Appendix, in Table A.3 and Table A.4.

There was no reason to assume that these vehicles would, like agricultural commodity vehicles, carry arbitrarily heavy loads, limited only by the number of logs that the trailer could hold. However, for the sake of completeness a similar analysis could be carried out to define an upper bound to these loads. To do so, the packing efficiency of the logs in the space provided by the trailer would have to be estimated, and the weights of native tree species would have to be determined. An in-depth analysis of this topic, as with the topic of overloaded agricultural commodities, was considered beyond the scope of this project, but this discussion is included to once again highlight the lack of direct observations involved in this study, as well as the accompanying uncertainty in the actual practices of exception vehicle operators.

3.2.4 Ready-Mix Truck Data

According to the Indiana Code (IC 9-20-2-1, 2019), vehicles are exempt from weight laws:

1. while engaged in the construction of highways; and
2. when the movement of the vehicle is confined wholly to highways or roads or sections of highways or roads that are under construction and not yet open to unlimited public use.

Therefore, these vehicles should not be in violation of state and federal laws when operating on open roads. Nevertheless, based on previous analysis of ready-mix trucks, reasonable configurations for those types of vehicles were produced and further analyzed here.

Two sources were used to determine the configurations of front-end discharge concrete mixer trucks used in Indiana. One was the Terex Advance website, accessed in 2016, and the other was a Terex mixer operator's manual from 2006. Terex Advance, based in Fort Wayne Indiana, is one of the nation's largest manufacturers of front-end discharge mixers, which are not particularly prevalent nationally, though they are the primary type of mixer truck used in Indiana. Presently, Terex provides scant details on its website as to the specifications of its trucks, which is why data on older models were used. The 2006 owner's manual contained the most complete information, including the empty weight, inter-axle spacings and the weight distribution of a loaded truck. The 2016 data consisted mostly of some of the spacings and all of the axle ratings. The ratings were assumed to correspond with the loaded weight distribution and the empty weights were estimated taking the increased (relative to 2006) empty weight of one new model, all that was available, and then accordingly scaling all the older model weights. The final weight used for analysis was the sum of the empty load and a normal weight concrete load of 8 cubic yards. Based on interviews with concrete industry experts, this was believed to the be the standard maximum load. Greater volume loads were possible for all of the models considered, but current practice is reputedly to not fill the mixer to full capacity in order to prevent spillage. About half of the resulting configurations, from 2006 and 2016 alike, were found to violate either the federal bridge formula or the grandfather law.

An additional analysis, motivated by the observations of the investigators, was performed for a weight distribution when the all the "tag" and "pusher" axles were raised, leaving all load supported by the front axle and the primary tandem. This distribution of weight was determined by assuming that the listed (2006) or estimated (2016) axle loads represented a valid equilibrium condition and that they could therefore be used to calculate the mixer trucks' centers of mass. This center of mass was assumed to be identical when the axles were raised and the weight distribution on the remaining axles was determined accordingly.

The motivation for this analysis was the anecdotal observation that mixer trucks often operate with their drum spinning and therefore presumably carrying a load of concrete, with some or all of their liftable axles raised. This practice, assuming a standard load of 8 cubic yards, could result in extremely heavy axle loads on a very short vehicle, well in excess of the loads allowed by federal or state law. Furthermore, these

TABLE 3.1
Legal Ready-Mix Truck Configurations According to FBF or Grandfather Law (8 yd^3 Normal Weight Concrete)

Model	Data	Axle Weights (kips) and Axle Spacings (ft)							GVW (kips)
2006 FD5000	Weights	16.9	12.2	12.2	12.2	12.2	—	—	62.3
	Spacings	10.2	4.08	4.33	4.25	—	—	—	
2006 FDB5000	Weights	16.7	12.1	12.1	12.1	12.1	—	—	61.6
	Spacings	9.2	4.08	4.33	4.25	—	—	—	
2006 FDB6000	Weights	17.0	3.8	3.8	16.1	16.1	9.47	—	70.0
	Spacings	7.1	3.50	3.92	4.33	7.75	—	—	
2006 FDB7000	Weights	17.5	5.9	5.9	11.6	11.6	7.02	9.21	78.4
	Spacings	7.1	3.50	3.92	4.33	3.92	8.83	—	
2016 FD6000	Weights	15.6	7.48	7.48	15.6	15.6	8.98	—	69.3
	Spacings	8.58	4.17	4.17	4.50	4.17	—	—	
2016 FDB6000	Weights	15.2	7.25	7.25	15.2	15.2	8.70	—	68.7
	Spacings	5.92	4.50	4.50	4.50	10.5	—	—	
2016 FDB7000	Weights	14.0	6.69	6.69	14.0	14.0	8.03	8.03	71.5
	Spacings	5.50	4.50	4.50	4.50	4.50	10.3	—	

configurations would also cause an exceedance of the rated axle weights on the vehicle, though as mentioned in the discussion of overloaded grain trailers, there are likely sizable factors of safety built into those figures. The graveness of these scenarios may imply that, in practice, concrete mixer truck operators are not actually carrying a full load while the liftable axles are raised. However, it is unknown whether this is the case and the observation that these trucks do operate under load while engaging fewer than their full complement of axles remains.

Making any sort of judgment on the presumption of illegal practices and vehicles used by ready-mix concrete truck operators would be inappropriate at this time, given the lack of actual data, and, furthermore, would be beyond the scope of this project. With that in mind, only the configurations which were found to be legal were compared with the RIRVs, in order to further evaluate their effectiveness in representing vehicles safely encompassed by the bridge formula or Indiana's grandfather law.

The legal and grandfathered ready-mix trucks used in analysis are listed in Table 3.1. The remaining configurations, which were estimated to carry illegal loads, are listed in the appendices (Table A.5) along with all of the other illegal configurations where the liftable axles are not used (Table A.6).

4. ANALYSIS RESULTS FOR LEGAL LOADS

In this section the analysis results for each class of legal exception vehicle are presented in the form of charts, with color-coded points representing the amount of exceedance caused by the SOVs. The amount of exceedance was calculated as a percentage of the magnitude of the RIRV envelope, and only at critical points. In this analysis the critical points were at the piers or abutments for shear, at 40% or 50% of the span length from a support for positive moment, and at the piers for negative moment. Each point in each chart represents one of the 190 members of the suite of analysis bridges, plotted with their maximum span length on the abscissa and their total length normalized by their maximum span length on the left ordinate. On the second vertical axis is the number of bridges with each value of L, the maximum span length. The advantage of presenting the results in this way is that it allows easy visualization of the type and dimensions of bridges where the largest exceedances occur and how many bridges in the inventory are likely to be impacted by that exceedance.

4.1 Results for Ready-Mix Trucks

Figures 4.1, 4.2, and 4.3 show the amount of shear, positive moment, and negative moment exceedance caused by the legal ready-mix trucks, respectively. Referring to each figure's legend, note that all exceedance values were negative, meaning that the SOV values were less than the RIRV values at every critical point on all of the bridges. As would be expected, the RIRVs encompassed the vehicles which adhere to the federal bridge formula and more interestingly, also those vehicles that violated that formula and only retained a legal status under the grandfather law.

4.2 Results for Garbage Trucks

The results for garbage trucks, shown in Figures 4.4, 4.5, and 4.6, were more dire than those for ready-mix trucks. In this case significant exceedances occurred, especially for bridges with shorter maximum spans. The main issue appeared to be shear exceedances on bridges with 20-, 30-, and 40-ft maximum span lengths, where exceedances were regularly in excess of 10% of the shears caused by the RIRVs. Exceedances were somewhat similar in magnitude for positive moment, though with only the very shortest span bridges being affected that strongly. On the other hand, negative moment exceedances were all found to be less than 10%

and no negative moment exceedances occurred on any bridges with a maximum span length greater than 20 ft.

These results were attributed to the heavy tandem on each of the three-axle garbage trucks, which allowed for high, yet concentrated loads, something which the MBE vehicles would not be able to replicate. Based on this analysis it was determined that new vehicles need to be proposed which could represent these loads. It is proposed that such a vehicle or vehicles would need to include a very heavy single axle or a closely spaced heavy axle group, similar to the tandem on the garbage trucks, in order to encompass this class of exception vehicle.

4.3 Results for Lumber Commodity Vehicles

As shown in Figure 4.7 the lumber commodity vehicles also caused significant exceedances when compared to the RIRVs' shear envelope. However, instead of exclusively causing exceedances on the shortest of spans, these vehicles caused exceedances on most of the longest structures in the analysis suite. With regards to positive moment, the results shown in Figure 4.8 indicate that lumber trucks caused exceedances greater than 10% on one structure only. Moreover, other than a small handful of additional instances with significantly lesser exceedances, this class of SOV was encompassed for positive moment. Comparing the shear and positive moment exceedances of these SOVs with the previous group, lumber trucks would seem to be the less critical load case compared to the suite of garbage trucks. In spite of the fact that the lumber trucks caused their largest shear exceedances on a completely different set of bridges, up until this point, encompassing the SOVs would appear to be a rather simple task.

However, the real issue for concern with lumber trucks was revealed to be exceedances on certain multi-span bridges when making a comparison for negative moment. Over a set of fairly common bridges, those with maximum spans of 50 ft to 60 ft, exceedances grew larger than 20%, an alarming result for a series of vehicles that only exceeded typical state GVW and axle limits by 10%. This would imply that the MBE cannot encompass typical lumber trucks, even when they are not given any special exceptions. As before, the MBE loads, principally the lane-type load, comfortably encompassed everything on bridges with maximum spans of 80 ft or more.

4.4 Results for Farm Commodity Vehicles

The results for farm commodities as shown in Figures 4.10, 4.11, and 4.12 were quite similar to the results observed for lumber commodities. Starting again with shear, farm commodity SOVs exceeded the RIRVs on certain bridges with 20-ft spans, but most of this group's exceedances were on long span bridges. In this case the exceedances were far more widespread, with span lengths as short as 140 ft seeing exceedances greater than 5%. For positive moment envelopes, the exceedances were of a similar magnitude to those of the lumber commodities, but somewhat more widespread. Lastly, negative moment exceedances were similarly severe when compared to the lumber commodities, with the most notable difference being the additional exceedance greater than 20% on a bridge with a 40-ft span (Figure 4.9). Clearly the negative moment exceedances are a significant problem for both lumber and farm commodities, with their magnitude again indicating that the MBE vehicles may not be sufficient for encompassing all vehicles covered by the FBF.

4.5 Summary of Results

A summary of the exceedances caused by each group of SOVs is included in Table 4.1, showing numerical values for the amount of exceedance. Again, exceedances are measured as a percentage of the RIRV's envelope. In this table red (positive) values correspond to an exceedance, and black (negative) values correspond to an excess. The values reported are the maximum values for each load effect at critical points on any span, i.e., the worst-case scenarios. In other words, if a value is red then that is the largest exceedance on any bridge in the analysis suite and exceedances will be less than that elsewhere. If a value is black, then naturally the SOVs are encompassed on all bridges and the value listed is the point where they come closest to exceeding the IRVs.

As can be seen from this table, and which was obscured in the plots, the MBE vehicles actually only very narrowly encompass all of the legal ready-mix trucks, but as was shown in the plots they do encompass all of them. Other additional details seen only here are that the garbage trucks are actually fairly close to 20% exceedance in some places, and that the grain trailers do in fact cause slightly larger exceedances for each load effect when compared to the logging trucks. Lastly, not only do the lumber and farm commodities exceed the RIRVs by more than 20%, the farm commodities can exceed by as much as nearly 30%. For a set of loads that are considered to be routine traffic these exceedances appear to be unacceptable and new loads are proposed which are designed to encompass these SOVs.

4.6 Development of Alternate Loads for the RIRVs

In addition to needing to encompass the load effects produced by the SOVs, any proposed additions to the RIRVs needed to satisfy several constraints imposed by INDOT. First, any proposed rating vehicle should weigh less than 80,000 pounds. Second, any exceedances should be encompassed with no more than three additional vehicles if possible. Lastly, a self-imposed limitation was that any new vehicle should be reasonably realistic and should itself be legal under Indiana law. Furthermore, rather than just simply encompassing

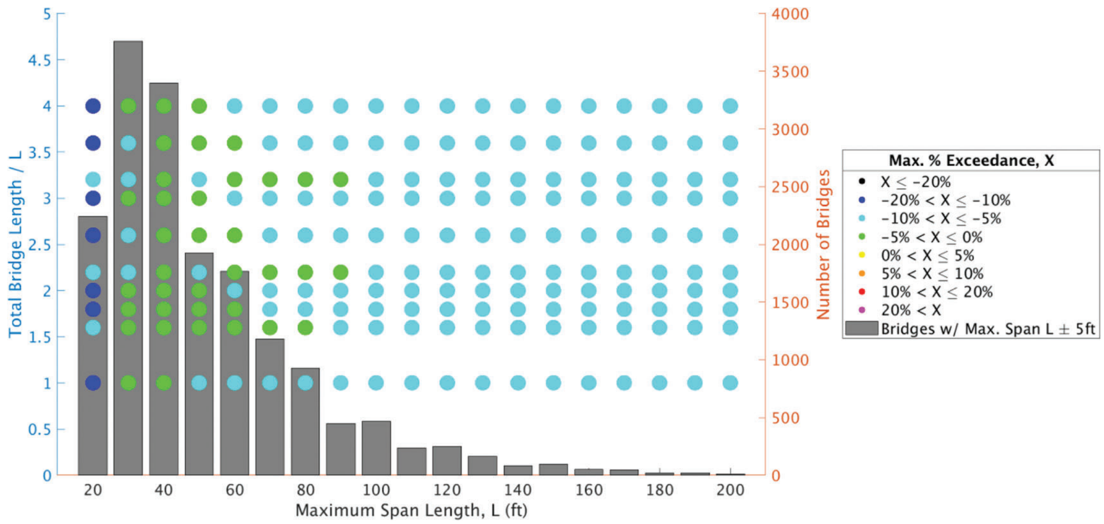

Figure 4.1 Color-coded depiction of the maximum percentage of shear exceedance by legal ready-mix trucks.

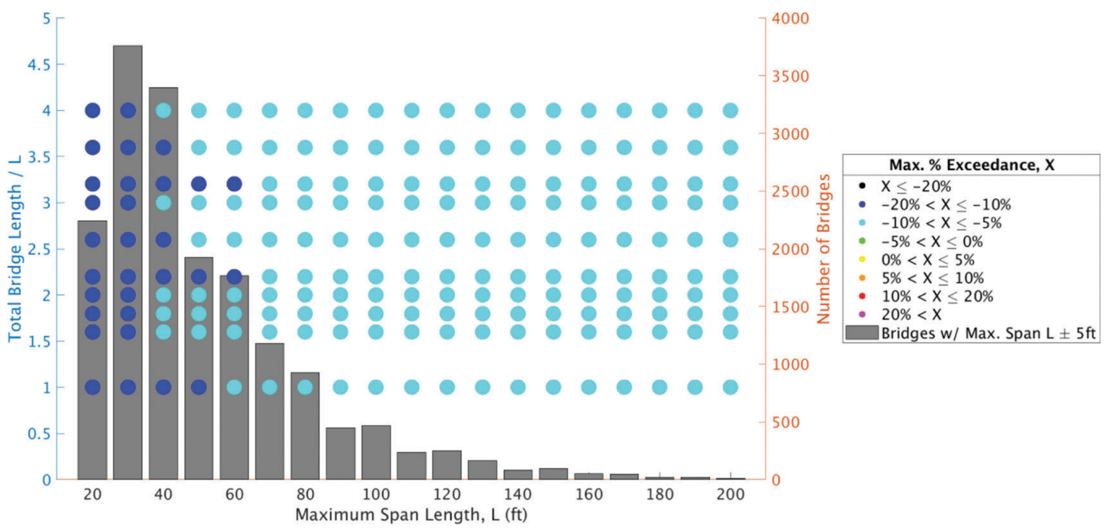

Figure 4.2 Color-coded depiction of the maximum percentage of positive moment exceedance by legal ready-mix trucks.

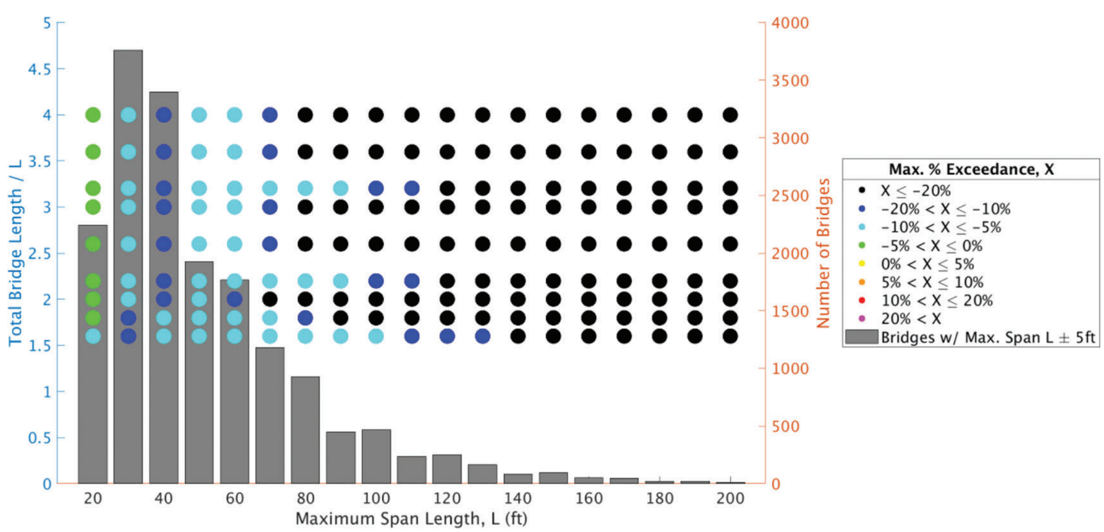

Figure 4.3 Color-coded depiction of the maximum percentage of negative moment exceedance by legal ready-mix trucks.

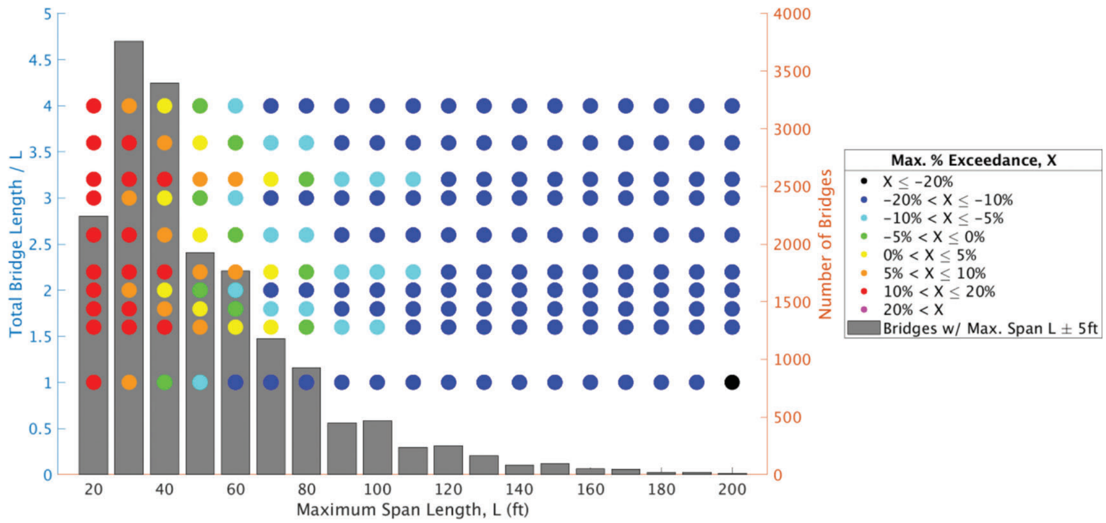

Figure 4.4 Color-coded depiction of the maximum percentage of shear exceedance by garbage trucks.

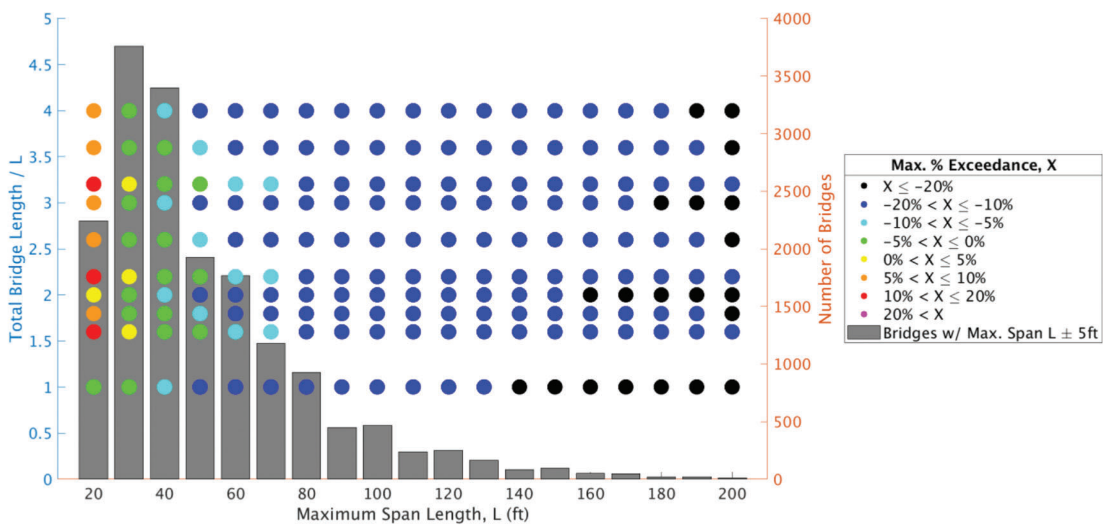

Figure 4.5 Color-coded depiction of the maximum percentage of positive moment exceedance by garbage trucks.

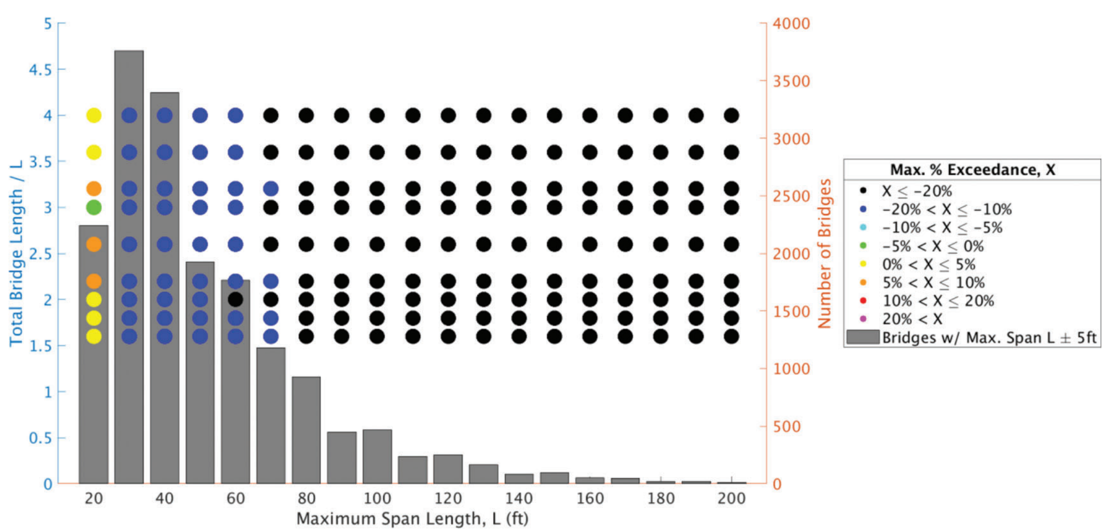

Figure 4.6 Color-coded depiction of the maximum percentage of negative moment exceedance by garbage trucks.

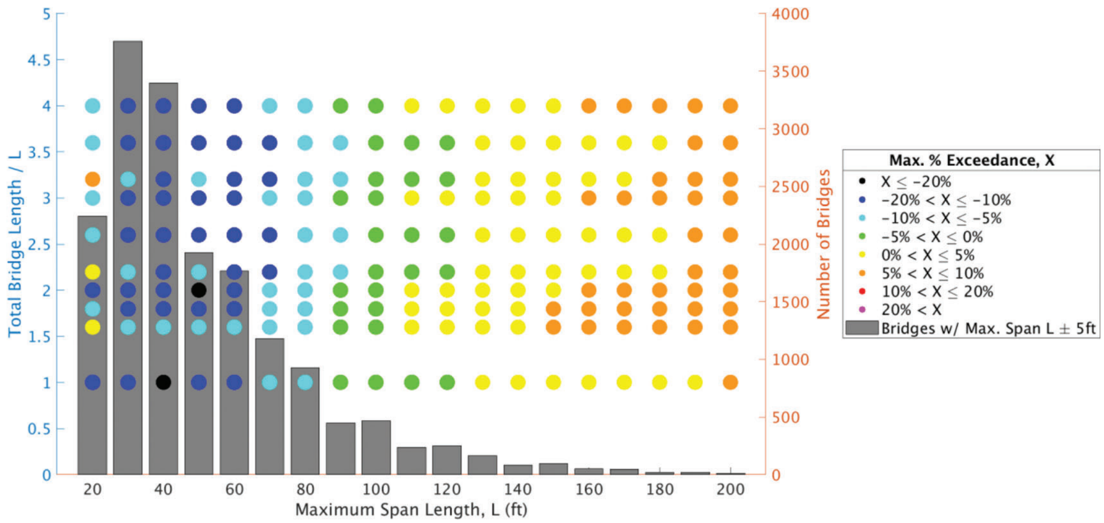

Figure 4.7 Color-coded depiction of the maximum percentage of shear exceedance by lumber commodity vehicles.

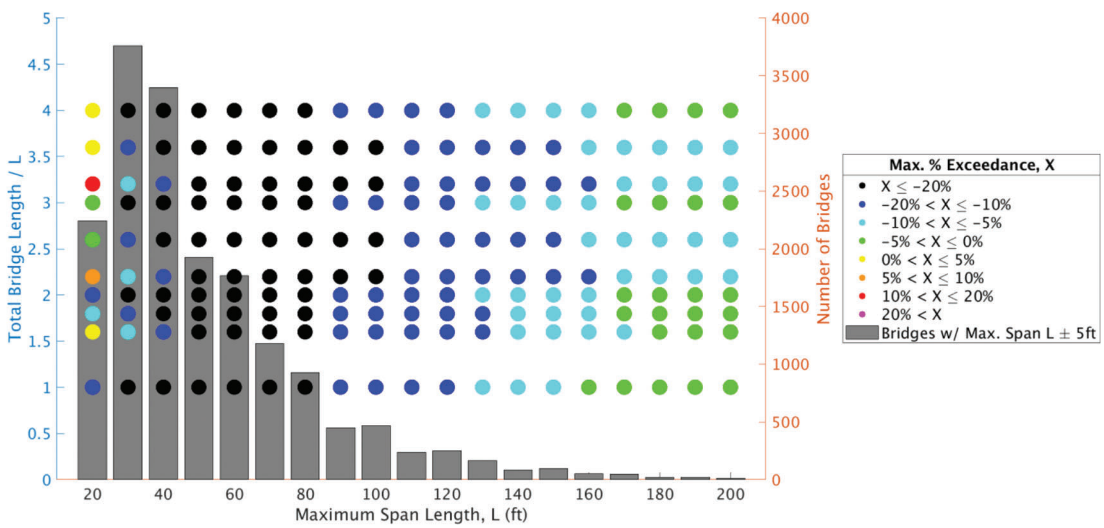

Figure 4.8 Color-coded depiction of the maximum percentage of positive moment exceedance by lumber commodity vehicles.

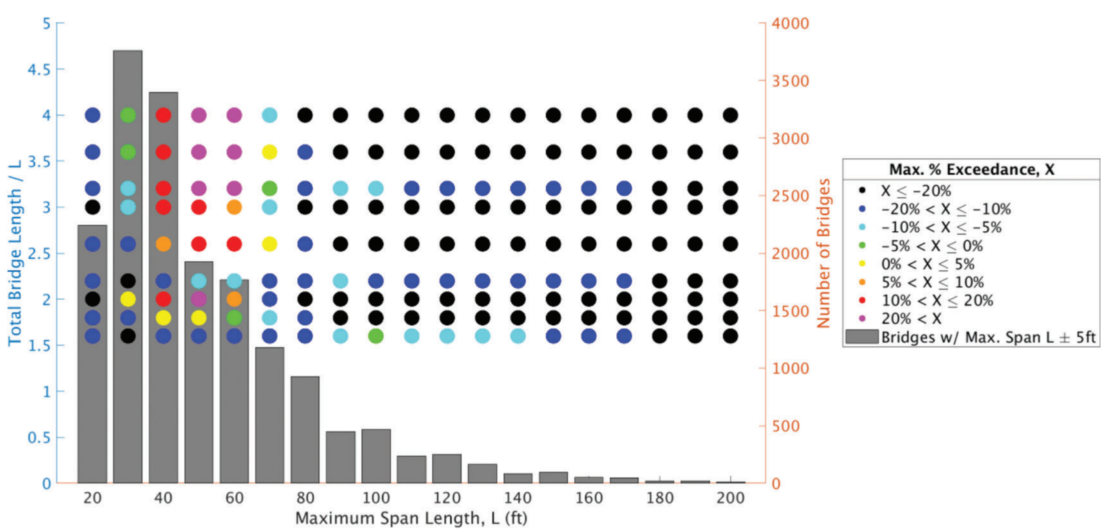

Figure 4.9 Color-coded depiction of the maximum percentage of negative moment exceedance by lumber commodity vehicles.

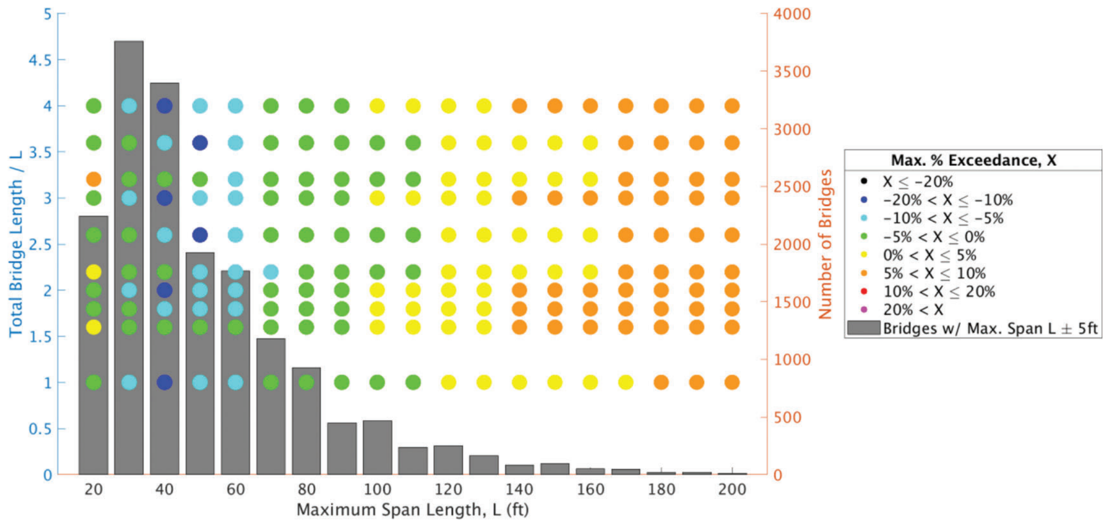

Figure 4.10 Color-coded depiction of the maximum percentage of shear exceedance caused by farm commodity vehicles.

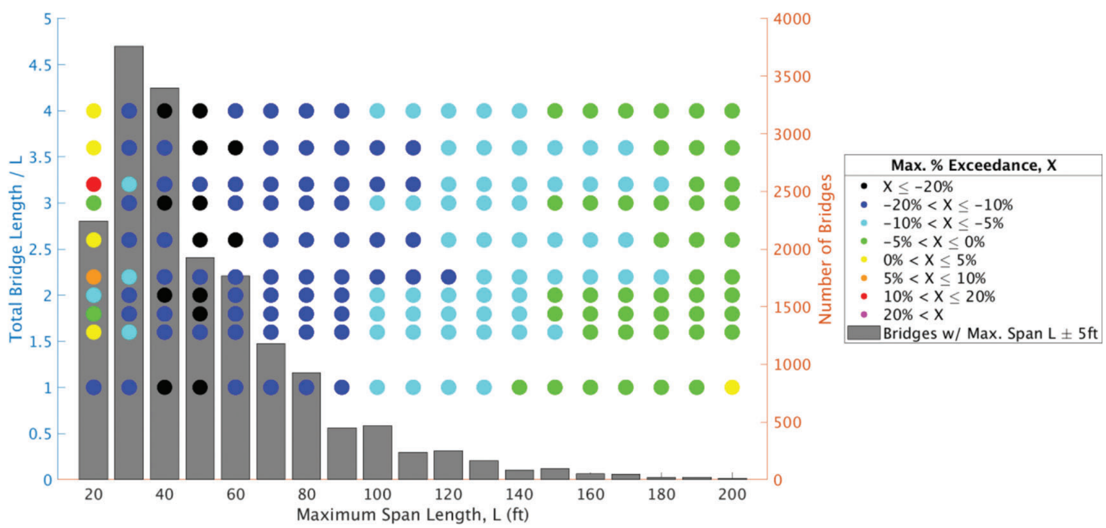

Figure 4.11 Color-coded depiction of the maximum percentage of positive moment exceedance caused by farm commodity vehicles.

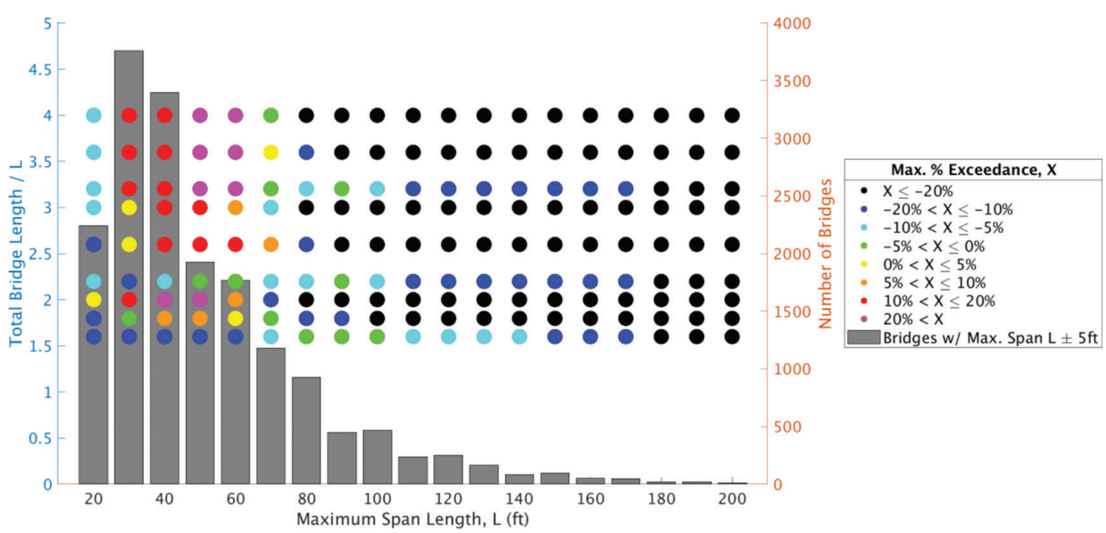

Figure 4.12 Color-coded depiction of the maximum percentage of negative moment exceedance caused by farm commodity vehicles.

TABLE 4.1
Percentage Exceedances of the MBE Rating Vehicles by the SOVs

Load Effect	Ready-Mix	Garbage Trucks	Lumber Commodities	Farm Commodities
Shear	-3.0	15	8	8.7
Positive Moment	-8.6	17	13	14
Negative Moment	-0.63	7.3	25	27

all SOV loads it was desired to do so as efficiently as possible so as to prevent as many bridges as possible from being posted, while still ensuring they would be able to safely carry any of the SOVs. This meant minimizing the amount of "excess exceedance," or how much the new RIRVs (NIRVs) exceed the SOVs. The methodology for achieving these goals was often trial and error, with some loads tailor-made to encompass certain load effects on certain bridges via an examination of the influence lines of the corresponding beam approximation.

Working under these constraints, the primary issue that needed to be addressed in encompassing the exception vehicles was the negative moments caused by the 88,000-pound logging trailers and grain trailers. To address these issues, it was necessary to design a rating load that could produce comparable moments on the same bridges, while also adhering to an 80,000-pound GVW limit. One way to handle this issue was to create a two-vehicle load, similar to the lane-type load in the MBE. Like that load, it could be applied for negative moment only, so its adoption into the RIRVs would not cause additional bridge posting due to shear or positive moment. Additionally, the two vehicles could each independently adhere to the 80,000-pound limit.

Several iterations for the two-truck case were attempted using different spacings between the two vehicles and different arrangements of axle weights for the vehicles themselves. It was found that using alternate spacings between the two vehicles in the MBE lane-type load was not sufficient for eliminating the negative moment exceedances. For bridge spans in the range of interest it was determined that a similar weight over a shorter distance would be necessary to produce the optimal negative moment while adhering to the stipulations for new rating vehicles. It was found that a particularly short and fairly heavy truck, a variant of the SU7 which would be legal under the grandfather law, could accomplish this goal, but only when combined with a lane load and spaced 20 ft apart.

Having established a workable remedy to the negative moment exceedances caused by the logging and agricultural commodities, the next step taken in the project was to propose a load that could encompass the shear exceedances on long bridges. It was theorized that given the length of the structures in question a lane load would be a particularly efficient load for encompassing shear on long structures. It was subsequently found that the same 200-plf load used in the MBE lane-type load when combined with a fairly heavy vehicle, such as the HS-20 truck, would efficiently eliminate shear exceedance on all long span bridges. Rather than actually use the HS-20 truck, a more realistic configuration was proposed where the 32-kip axle loads were split into two tandems with 16 kips on each axle.

Another advantage to using a load similar to the HS-20 was its ability to complement the two-truck load on certain spans. The MBE vehicles encompass the SOVs by a wide margin on long span bridges when it comes to negative moment. Ideally, this situation should not be exacerbated, and any additional loads should not contribute more "black dots" to the exceedance charts. This was not the case in the initial version of the new two-truck load, and it was determined steps had to be taken to reduce the magnitude of this load. It was subsequently found that if the lane load was removed from the new proposed two-truck case and the axle weights were reduced by 20%, some minor exceedances will begin to occur on bridges with maximum spans of 30 ft, with more significant exceedances on 20-ft spans. Leaving the exceedances on 20-ft spans to presumably be encompassed by the same load which would encompass the shear caused by garbage trucks, a particular spacing between the two tandems in the HS-20-based vehicle was adopted to maximize the negative moment it generated on 30-ft span bridges. By minimizing all other spacings and increasing the front axle weight, a configuration was produced which allowed all remaining exceedances on 30-ft span bridges to be encompassed. Furthermore, following the grandfather law, this vehicle was still legal. The resulting HS-20-like vehicle is currently dubbed NIRV-2 and is shown in Figure 4.14. The final, reduced version of the two identical trucks in the new two-truck load is called NIRV-3 and is shown in Figure 4.15.

Initially, there was some difficulty in identifying a load which could encompass all garbage trucks while still satisfying all of the above criteria. Ultimately, something of a notional load was adopted: a vehicle with the same inter-axle spacings as the shortest of the three axle garbage trucks, but with 24 kips loaded on the front axle. This load, which was able to encompass all remaining exceedances for shear, positive moment, and negative moment is not considered realistic given the currently available data. All previous observations of the weight distribution of garbage trucks does not support the existence of such a heavy front axle, and, indeed, none of the three-axle garbage trucks found to be produced by manufacturers had front axles rated to carry more than 20,000 pounds. Nevertheless, this vehicle was still considered feasible in that it is legal under Indiana law. This vehicle has been named NIRV-1 and is shown in Figure 4.13.

The charts showing the exceedances of the RIRVs together with the three NIRVs over the SOVs are depicted in Figures 4.16, 4.17, and 4.18. As the figures show, there is no exceedance of the combined RIRVs and NIRVs by the SOVs. Referring to the plots for shear and positive moment in particular, the NIRVs are successful in meeting the objectives of the project. These plots show few new blue points and for most of the bridges for which there were originally exceedances their points are now plotted as green, indicating the NIRVs encompass the SOVs on those bridges by less than 5%, guaranteeing safety with regards to encompassing the SOVs while also minimizing the number of new bridge postings.

With regards to negative moment the resulting NIRVs were not quite as efficient. Although great pains were taken to try and reduce exceedances here in particular and to do so efficiently, several new black points were added to the plot as well as many dark blue ones. It is presently difficult to imagine how this result may be improved without increasing the number of new rating vehicles, especially since the current NIRVs were largely developed with negative moment in mind and still so inefficiently envelope the SOVs in negative moment. Ironically, the NIRVs seemed to effortlessly encompass shear and positive moment exceedances using effectively only two new loads. This is considered to be a symptom of the sharp gradation in the negative

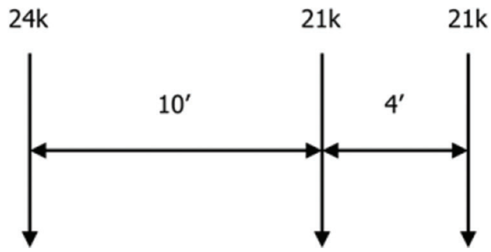

Figure 4.13 NIRV-1–GVW = 66 k.

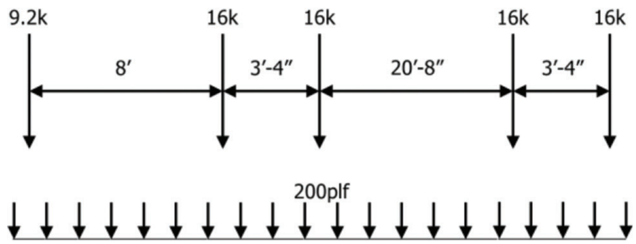

Figure 4.14 NIRV-2–GVW = 73.2 k.

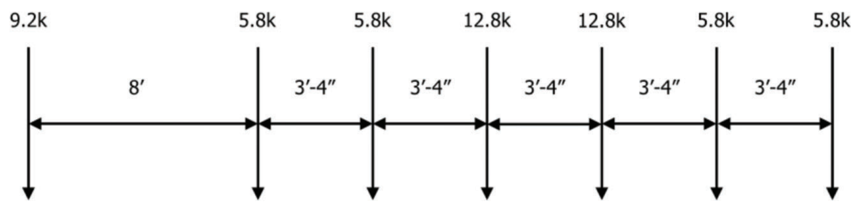

Figure 4.15 NIRV-3–GVW = 58 k (only one truck shown; use two trucks spaced 20′ apart).

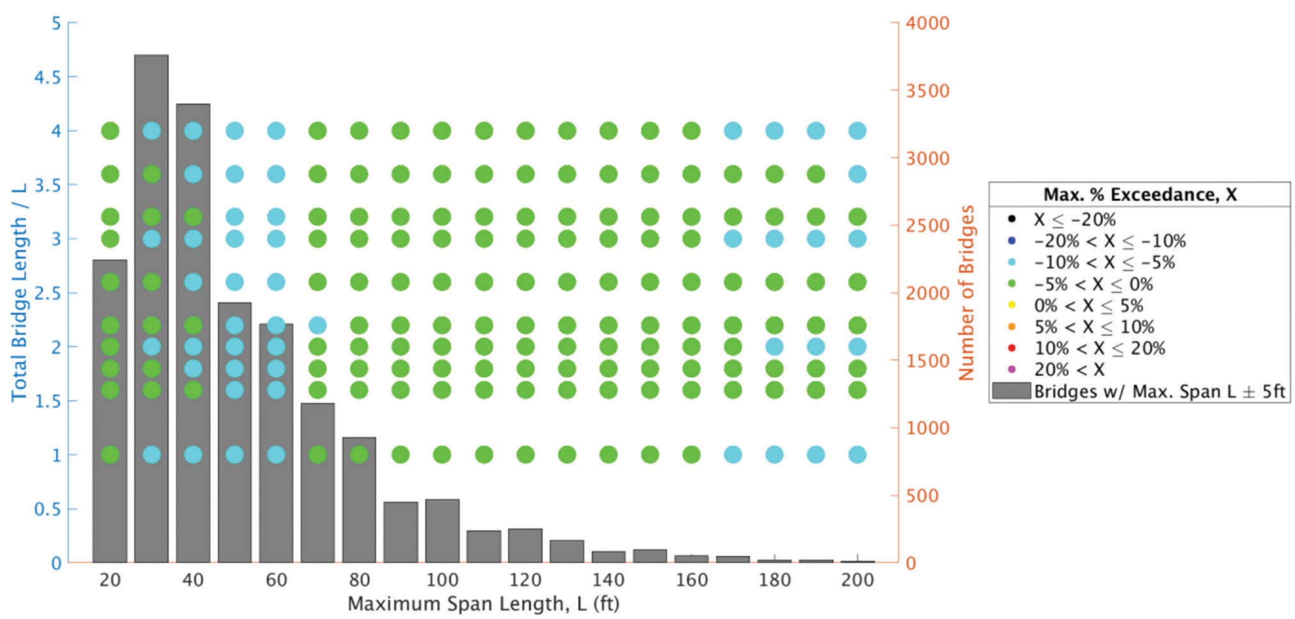

Figure 4.16 Depiction of maximum shear exceedance on every bridge in the suite if the proposed NIRVs are adopted.

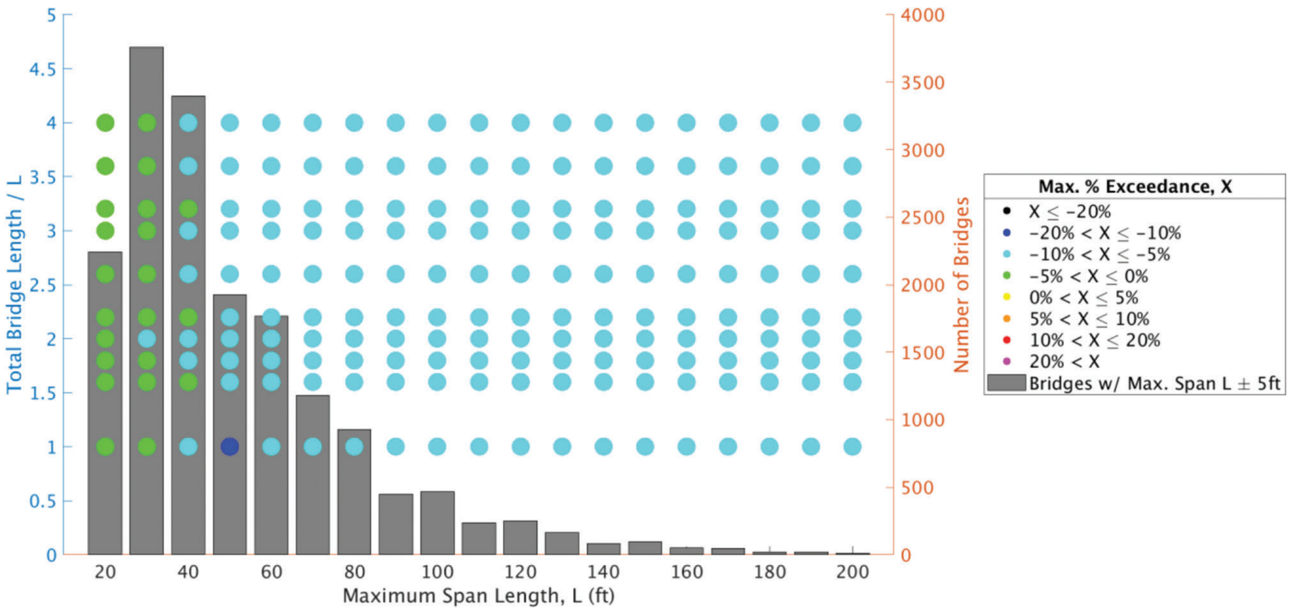

Figure 4.17 Depiction of maximum positive moment exceedance on every bridge in the suite if the proposed NIRVs are adopted.

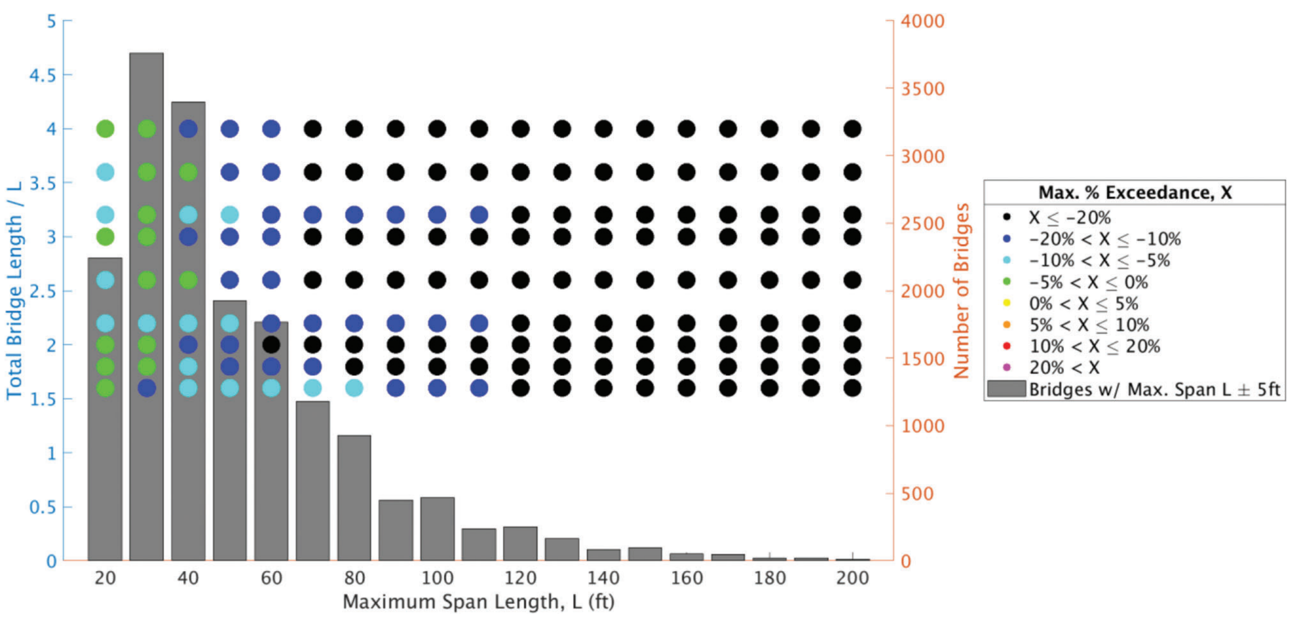

Figure 4.18 Depiction of maximum negative moment exceedance on every bridge in the suite if the proposed NIRVs are adopted.

moment envelope of the commodity vehicles, i.e., in developing a single load which can encompass the large exceedances caused by farm and lumber commodities on some bridges. The resulting load will likely also cause unnecessarily large moments on other, similar bridges where the commodity vehicles themselves nevertheless produce much smaller moments.

In evaluating the NIRV-2 with the two-truck case specified in section 6A.4.4.2.1a of the MBE (AASHTO, 2018) only the truck was considered, i.e., the lane load shown in Figure 4.14 was not included in addition to the one required in the MBE. For NIRV-3 (developed for two trucks 20 ft apart) only two trucks were used, spaced 30 ft apart, rather than a combination of 4 trucks with two pairs spaced 30 ft apart.

4.7 Simplified Analysis for Immediate Implementation

As mentioned previously, the state of Indiana already has a set of legal loads, listed in INDOT's *Indiana Bridge Inspection Manual*, which are used to represent the SOVs. This set of posting vehicles includes

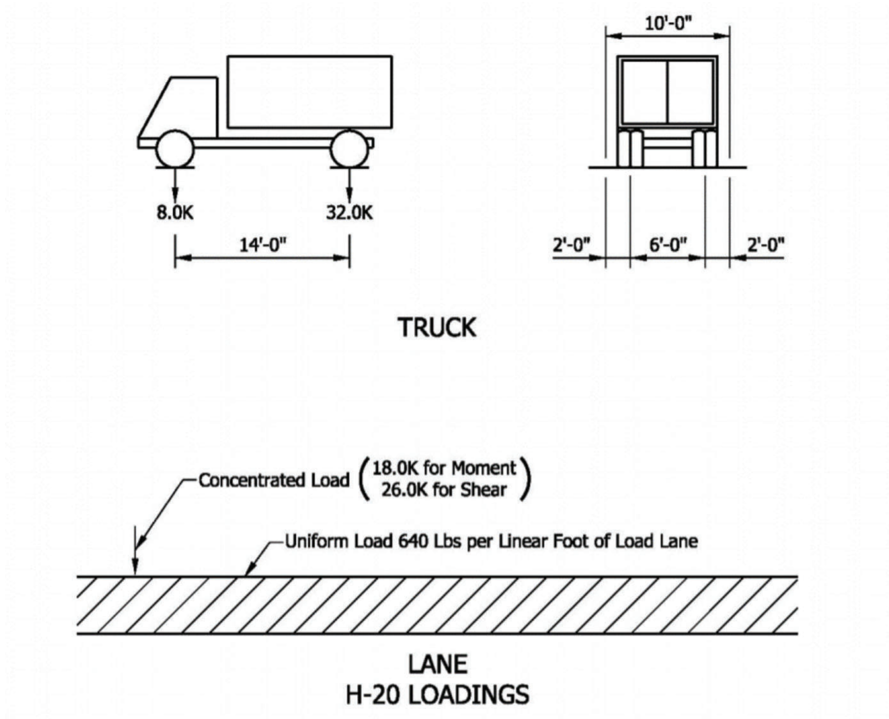

Figure 4.19 H-20 loads (INDOT, 2019).

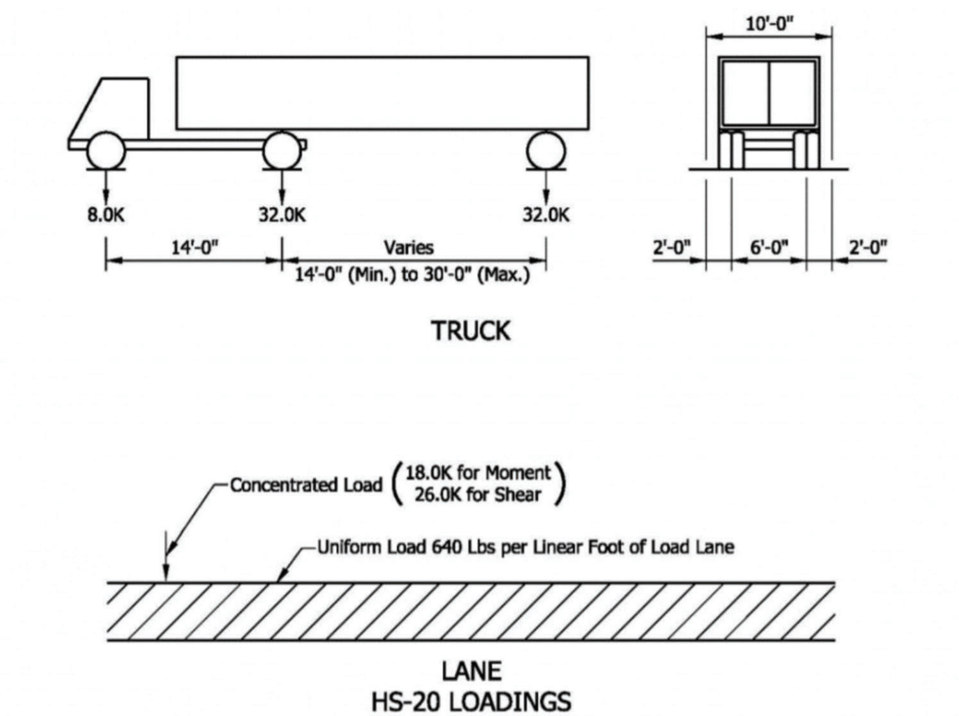

Figure 4.20 HS-20 loads (INDOT, 2019).

not only the MBE loads, but the H-20, HS-20 and alternate military loads from the AASHTO Standard Specifications for Highway Bridges, shown in Figures 4.19, 4.20, and 4.21. Rather than immediately requiring bridge owners to re-evaluate all of their bridges using whichever new NIRVs INDOT may decide to adopt, it possible to quickly evaluate the safety of their bridges relative to the state legal loads they have already analyzed instead. Therefore, further analyses were conducted where the inspection manual vehicles, in combination with the MBE vehicles, were compared to the SOVs. To use the previously introduced terminology, these were the vehicles referred to as the CIRVs.

The *Indiana Bridge Inspection Manual* states that these additional rating vehicles should be used with routine commercial traffic load factors, though unlike at the state level, bridges at the county level may be rated for LRFR or LFR (INDOT, 2019). For this analysis it was concluded that using only LRFR to compare the CIRVs to the SOVs would be a conservative approach. This was because identical load factors would be used for both the CIRVs and SOVs regardless of whether the LFR or LRFR methods are used, so the actual value would not matter. However, there was one other difference between LRFR and LFR (or at least only one at the level at which this analysis was conducted) and that was the impact factor. In LRFR the impact factor is fixed at 1.33, while in LFR the impact factor varies depending on a vehicle's position on a bridge, but it is capped at 1.3 (AASHTO, 2002). As such, since the CIRVs contained several lane loads, to which the impact factor is not applied, and the SOVs contain none, it was clear that the analysis

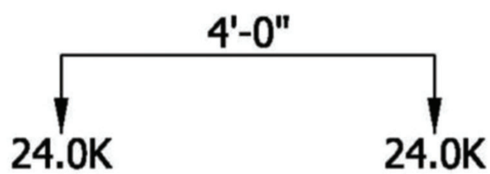

Figure 4.21 Alternate military load (INDOT, 2019).

method which would give the most conservative results would be the one with the largest impact factor—LRFR.

Having compared the CIRVs and the SOVs using LRFR load and impact factors, it was found that this larger set of CIRVs could not encompass the SOVs, as shown in Figures 4.22, 4.23, and 4.24. Given this result, the preferred recourse, at INDOT's request, was to increase the magnitude of all HS-20 loads and re-evaluate the results. The goal of this approach was to determine an amplification factor on the HS-20 envelope which would allow it to encompass all of the SOVs. Then, given a successful factor of, for example, 1.2, it could be said that all bridges with an HS-20 rating factor greater than or equal than 1.2 would not have to be re-evaluated, greatly simplifying the way in which bridges can be rated for their ability to safely carry the SOVs. One more detail to this approach was that it was predetermined that an exceedance within 5% of the CIRVs' envelope would be acceptable and therefore the target of this part of the project was to find and amplification factor on the HS-20 which would reduce all exceedances to a value of 5% or less. The way this was achieved was to incrementally increase the amplification factor of the HS-20, starting at 1.05, then 1.1, and so forth.

According to the results shown in Figure 4.23, the CIRVs already achieve the necessary benchmark when it comes to positive moment. As shown in Figure 4.25, shear exceedances are brought in line with an HS-20 amplification of 10%. On the other hand, in order to encompass the SOVs' negative moment envelope only a 5% increase was required, as seen in Figure 4.26. For reference, the shear exceedances with the HS-20 increased by only 5% are shown in Figure B.1 in Appendix B.

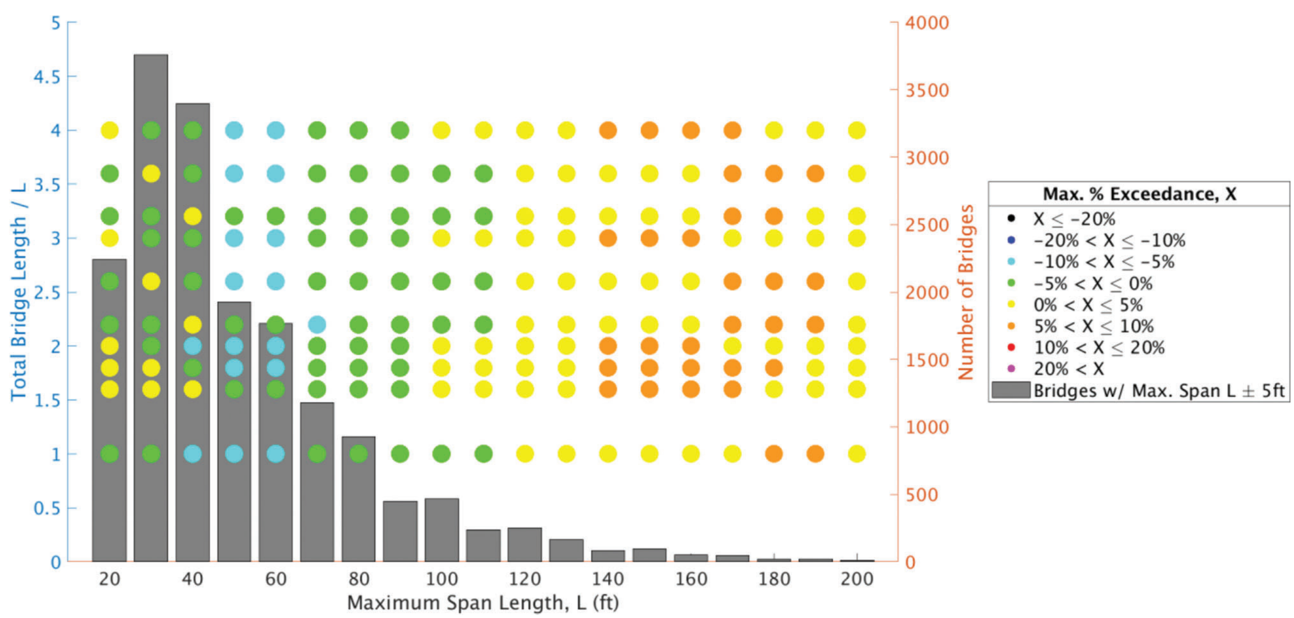

Figure 4.22 Shear envelope comparison of CIRVs to the SOVs.

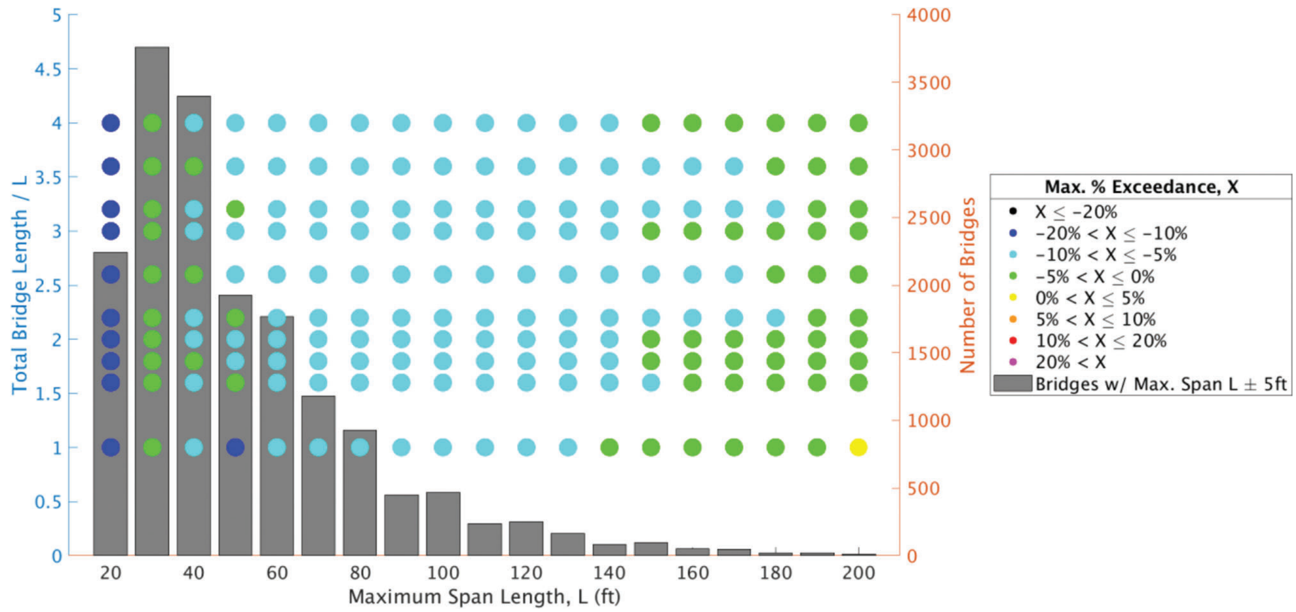

Figure 4.23 Positive moment envelope comparison of CIRVs to the SOVs.

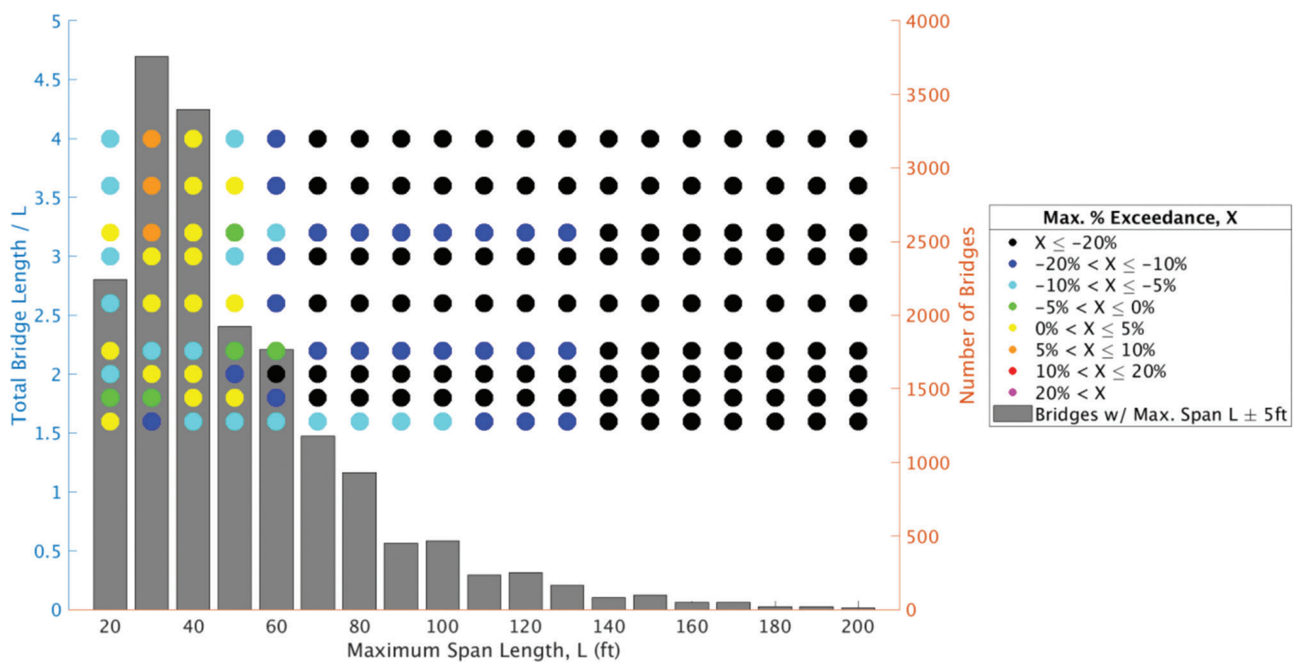

Figure 4.24 Negative moment envelope comparison of CIRVs to the SOVs.

While this approach does result in CIRVs that encompass the SOVs within a certain acceptable tolerance, it should be noted that, in contrast to the performance of the NIRVs, this approach is very inefficient. For example, the unmodified CIRV loads may not quite encompass the negative moments of the SOVs on bridges with maximum spans of 50 ft or shorter, but they encompass longer bridges with an excess of up to 48% (the maximum excess associated with the black dots in Figure 4.24). The NIRVs and RIRVs together encompass the SOV negative moments with an excess of only up to 39%, which also happens to be identical to the excess caused by the RIRVs themselves. If applied incorrectly, the results of this approach could further exacerbate this issue and result in a large and unnecessary number of new bridge postings. Therefore, some finesse is required in deciding how to best utilize the results of this analysis.

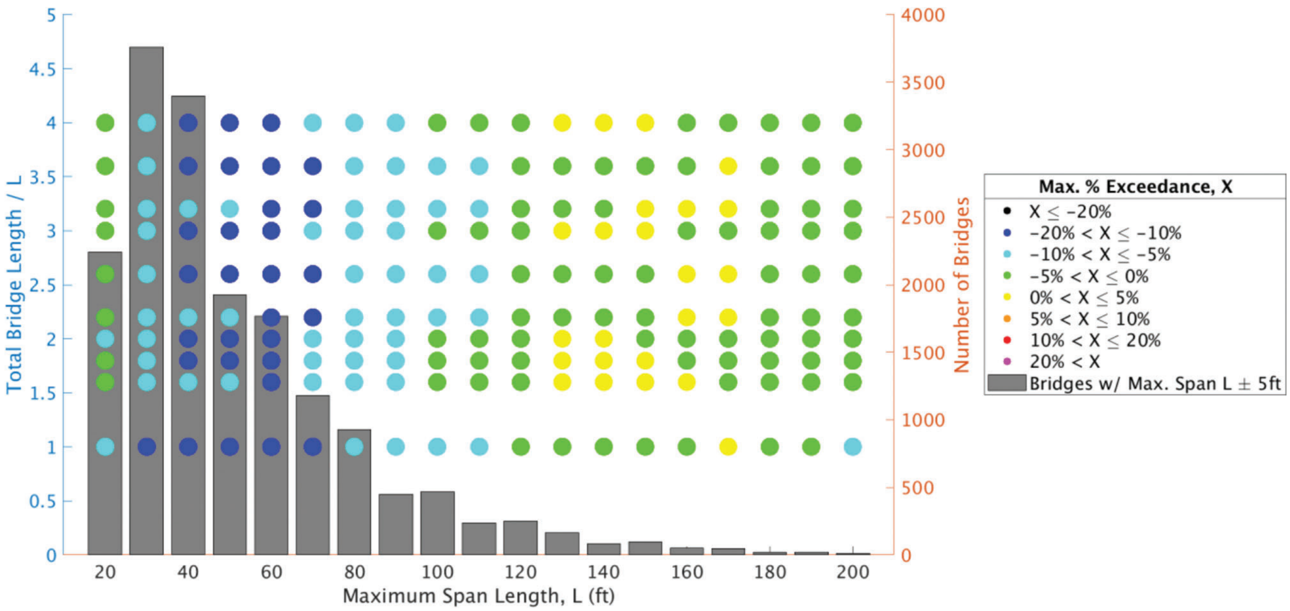

Figure 4.25 Shear envelope comparison between the SOVs and the CIRVs with the HS-20 increased by 10%.

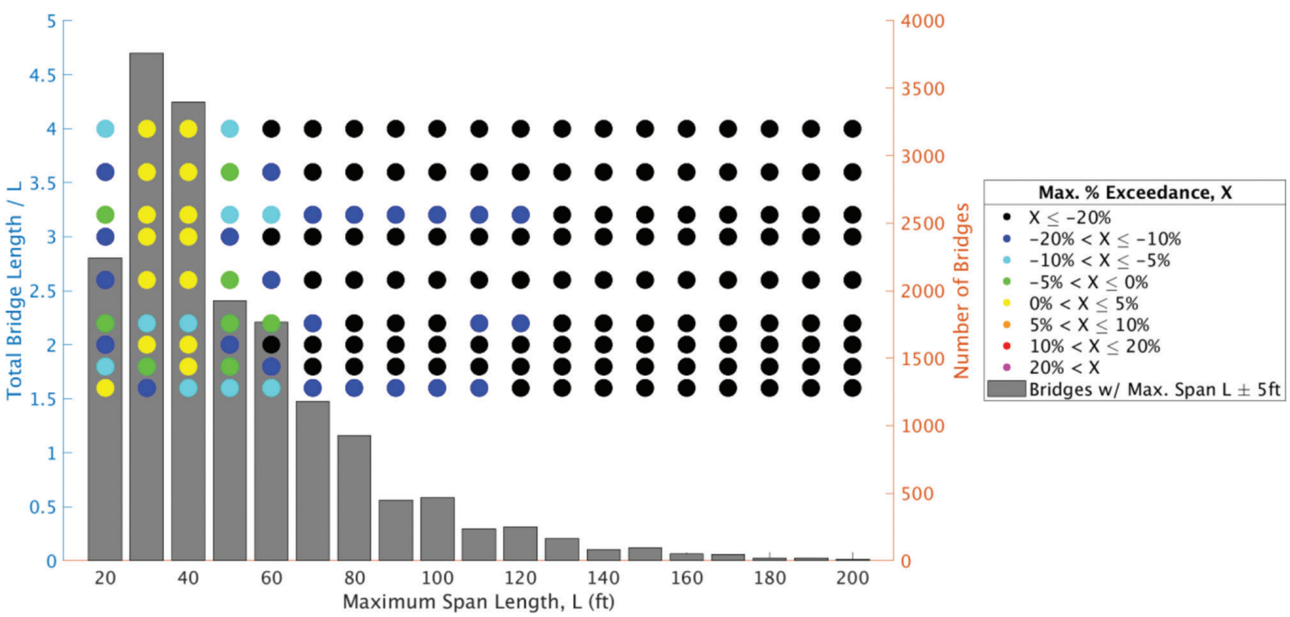

Figure 4.26 Negative moment envelope comparison between the SOVs and the CIRVs with the HS-20 increased by 5%.

5. RECOMMENDATIONS

The proposed new IRVs, a combination of the RIRVs and NIRVs to be henceforth referred to as the proposed Indiana rating vehicles (PIRVs), completely encompasses SOV exceedances on the suite of bridges considered in this work. However, if it is so desired, a slightly reduced version of the NIRV loads proposed herein would reduce excessive surpluses over the SOVs while allowing minor exceedances of their load effects on a few representative bridges. The amount of exceedance that may be considered, if any, is left to the discretion of the project owner, but for reference a series of alternative weights are presented here to be compared against the full loads. It should be noted that the full loads proposed in this report are not guaranteed to encompass the state's SOVs on all bridges in the state inventory, only on the bridges considered here in an approximate analysis. The loads proposed in section 4.6 are recommended with the assumption that any other bridges in the inventory are sufficiently similar to the bridges in the limited suite used here that any exceedances which may occur on the real bridges will be small. It is also assumed that if exceedances on the suite of 190 bridges are capped at some other value, say at 5% of the PIRV envelope for example, then there may be real bridges in the inventory where exceedances will still be above 5%, though presumably not by much.

Figures 5.1, 5.2, and 5.3 demonstrate a set of reduced axle weights which correspond to a new set of PIRVs which allow up to 5% exceedance by the SOV envelopes. The details of the resulting exceedances are shown in Figures 5.4, 5.5, and 5.6.

Figures 5.7, 5.8, and 5.9 show even further reduced weights for the NIRVs, allowing for exceedances of up to 10% on the suite of analysis bridges. The types of bridges where these exceedances occur can be observed in Figures 5.10, 5.11, and 5.12.

If allowing either a 5% or 10% exceedance is deemed acceptable, then the loading shown in Figures 5.1, 5.2, and 5.3 (Loading A) or Figures 5.7, 5.8, and 5.9 (Loading B) may be used. However, the results of the analyses for these two loadings can be combined to control the exceedance level to a 5% maximum value in an optimal way by setting up span ranges linked to the loadings. It can be noted in Table 5.1 that the results in Figures 5.4, 5.5, and 5.6 for Loading A and Figures 5.10, 5.11, and 5.12 for Loading B can be used to select 5% exceedance values. For the shear force, for example, the heavier loading (Loading A) should be used for bridge spans between 20 ft to 35 ft and 135 ft to 200 ft, while the lighter loading (Loading B) can be used for spans between 35 ft and 135 ft. The advantage of separating the loading as shown is that the use of a lighter loading for the bridge load rating may provide an acceptable bridge rating and thereby avoid the need for load posting. Of course, the heavier loading shown in Figures 4.13, 4.14, and 4.15 for the NIRVs can be used to eliminate all exceedances.

Regarding the alternate method using HS-20 multipliers, the best approach appears to be requiring HS-20 rating factors above 1.0 for only certain bridges, rather than, for example, requiring all bridges to have a rating factor of at least 1.1 to be sure that all bridges can sustain the shear from the SOVs. From observing Figure 4.22 and Figure 4.24 it can be seen that even with no amplification of the HS-20 loads, there are some bridges where the CIRVs still encompass the SOVs. Obviously, from Figure 4.23 it

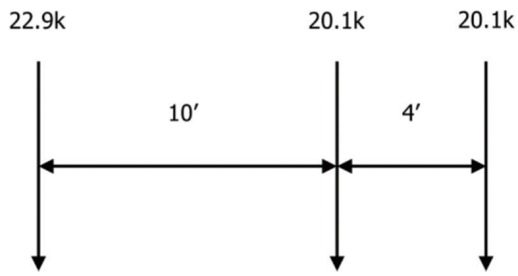

Figure 5.1 NIRV-1 with axle weights reduced to allow for up to 5% exceedance (GVW = 63.1 kips).

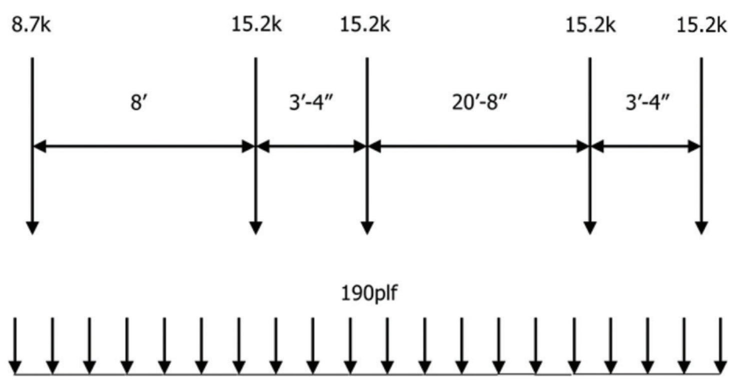

Figure 5.2 NIRV-2 with axle weights reduced to allow for up to 5% exceedance (GVW = 69.5 kips).

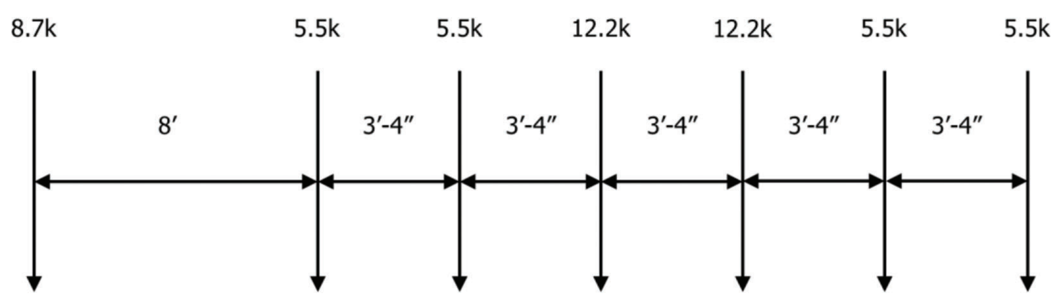

Figure 5.3 NIRV-3 with axle weights reduced to allow for up to 5% exceedance (only one truck shown; use two trucks spaced 20′ apart. GVW of one truck = 55.1 kips).

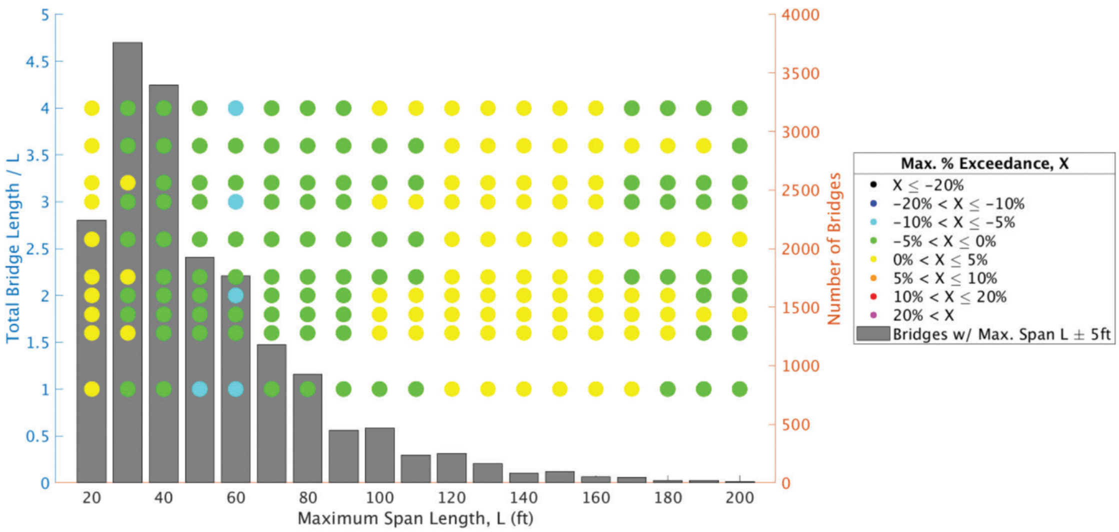

Figure 5.4 Depiction of the maximum shear exceedance occurring on each bridge in the suite if the NIRVs are adopted with reduced axle-weights allowing for up to a 5% exceedance.

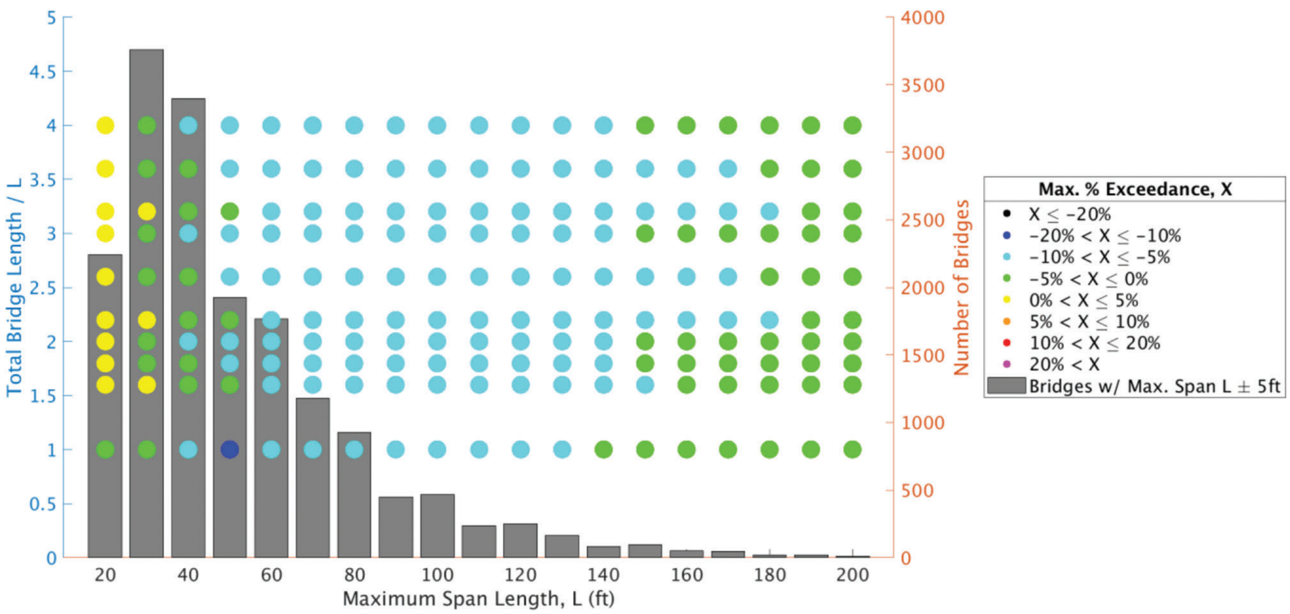

Figure 5.5 Depiction of the maximum positive moment exceedance occurring on each bridge in the suite if the NIRVs are adopted with reduced axle-weights allowing for up to a 5% exceedance.

can be seen that if a bridge has a rating factor of 1.0 or more for positive moment then it does not require any further analysis for positive moment, i.e., that bridge should be able to safely withstand those stresses from the SOVs. For shear, any bridge with a maximum span less than about 140 ft long should also be safe as long as it has a rating factor of at least 1.0 for the inspection manual rating loads. Lastly, if a bridge has a rating factor of 1.0 for negative moment, then unless that bridge has a maximum span length of about 30 ft that bridge is also safe for the negative moment caused by the SOVs.

Also based on these analyses, it is recommended that bridges with spans of 140 ft or longer should have an HS-20 rating factor of at least 1.1, otherwise those bridges should be re-evaluated to ensure that they can

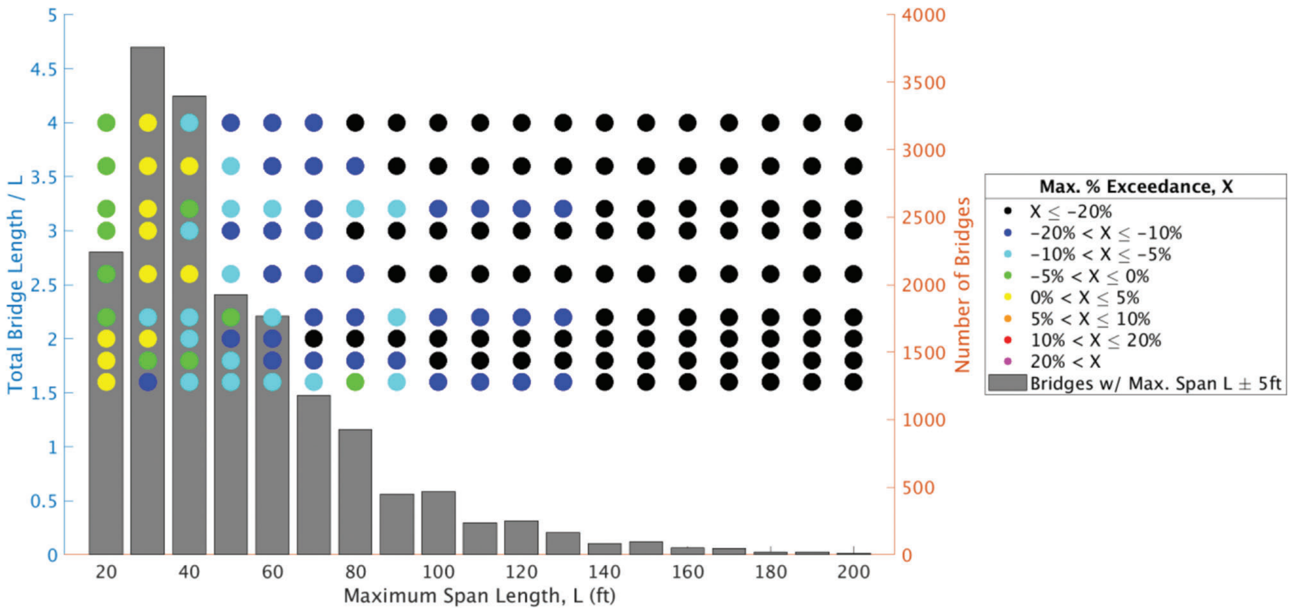

Figure 5.6 Depiction of the maximum negative moment exceedance occurring on each bridge in the suite if the NIRVs are adopted with reduced axle-weights allowing for up to a 5% exceedance.

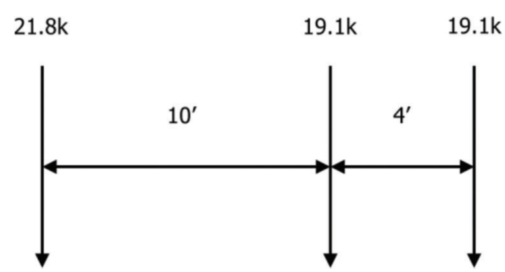

Figure 5.7 NIRV-1 with axle weights reduced to allow for up to 10% exceedance (GVW = 60 kips).

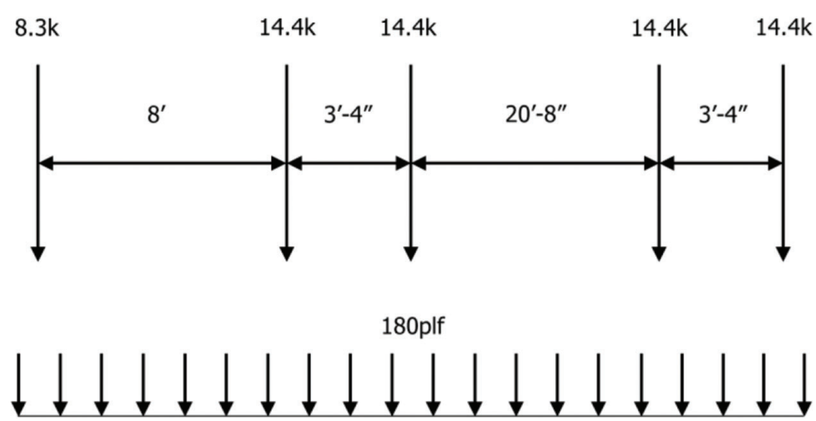

Figure 5.8 NIRV-2 with axle weights reduced to allow for up to 10% exceedance (GVW = 65.9 kips).

safely sustain the SOVs' shear stresses. For negative moment, it is recommended that bridges with maximum spans of about 30 ft should have an HS-20 rating factor of at least 1.05.

These recommendations are also shown in Table 5.2. The values shown therein are the multipliers on the HS-20 loading that limit the SOV exceedances of the CIRVs to a 5% maximum.

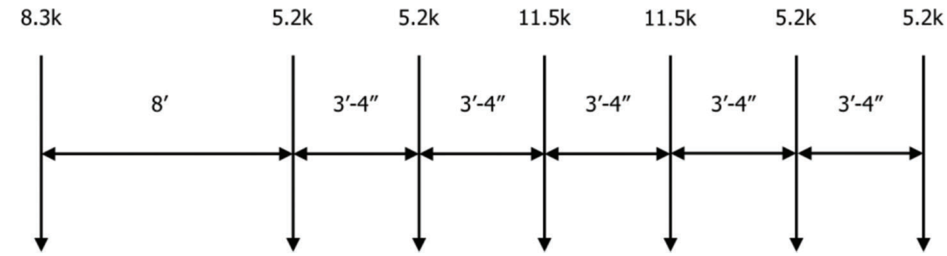

Figure 5.9 NIRV-3 with axle weights reduced to allow for up to 10% exceedance (only one truck shown; use two trucks spaced 20′ apart. GVW of one truck = 52.1 kips).

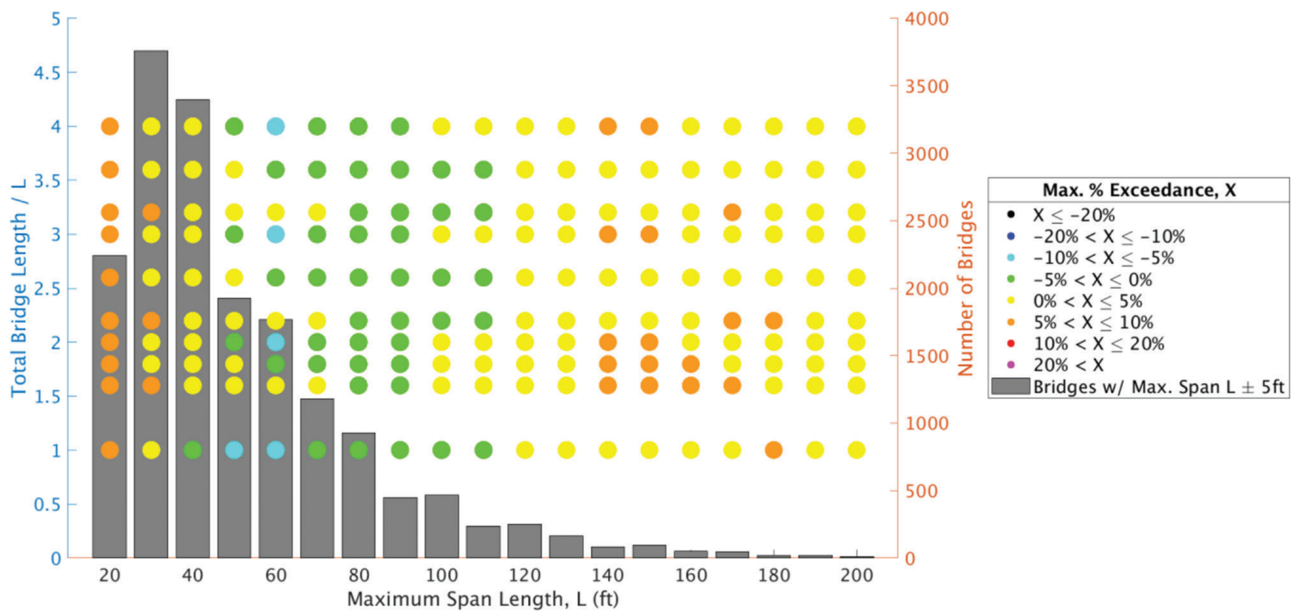

Figure 5.10 Depiction of the maximum shear exceedance occurring on each bridge in the suite if the NIRVs are adopted with reduced axle-weights allowing for up to a 10% exceedance.

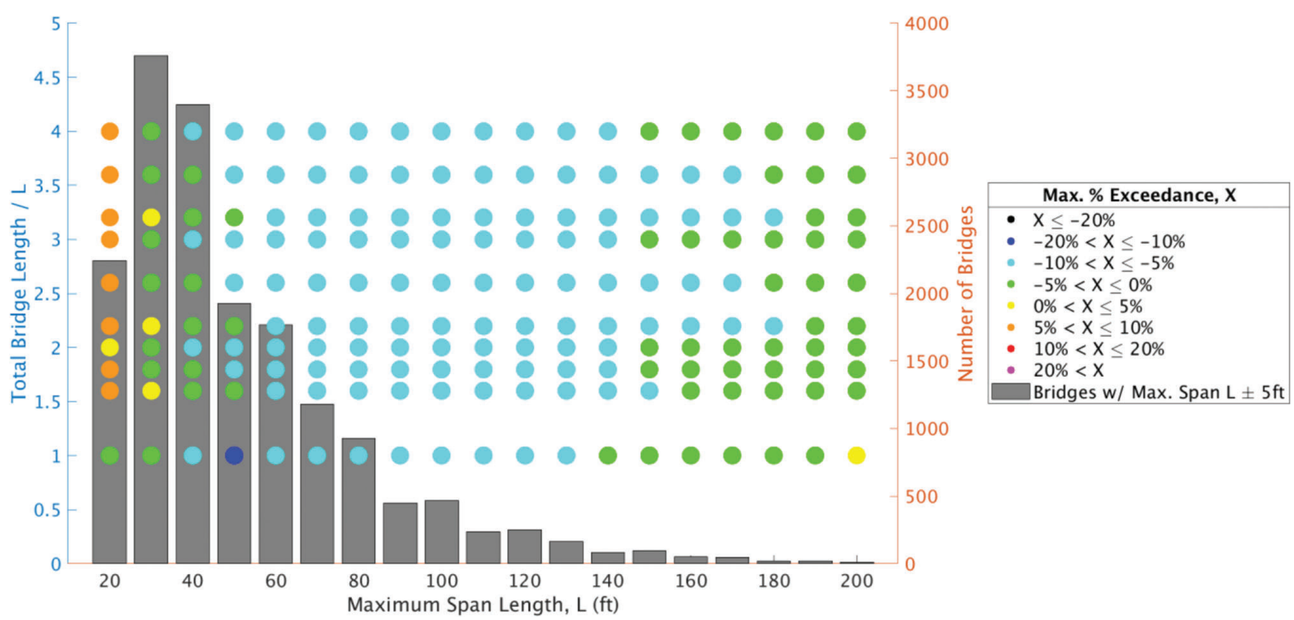

Figure 5.11 Depiction of the maximum positive moment exceedance occurring on each bridge in the suite if the NIRVs are adopted with reduced axle-weights allowing for up to a 10% exceedance.

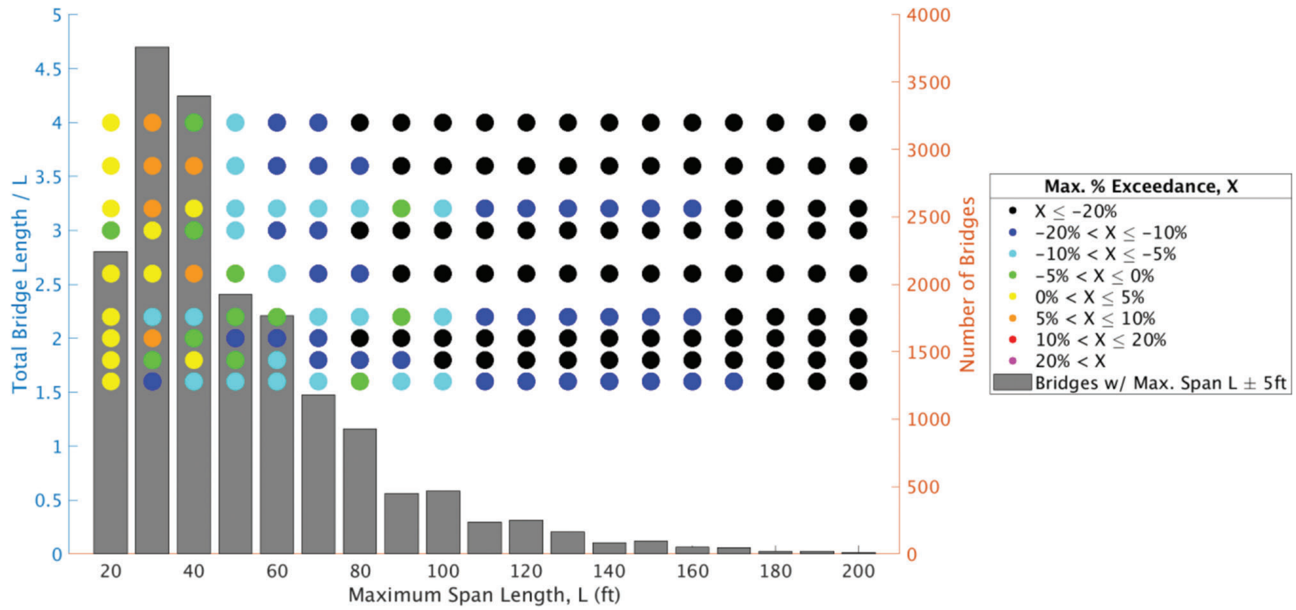

Figure 5.12 Depiction of the maximum negative moment exceedance occurring on each bridge in the suite if the NIRVs are adopted with reduced axle-weights allowing for up to a 10% exceedance.

TABLE 5.1
Load Types Versus Span Range to Limit Exceedance to 5%

	Loading A (Figures 5.1–5.3)	Loading B (Figures 5.7–5.9)
V	20′–35′, 135′–200′	35′–135′
+M	20′–25′	25′–200′
-M	20′–45′	45′–200′

TABLE 5.2
Multipliers on HS-20 Loading to Limit Exceedance to 5%

	Span Length (ft)								
	20	30	40	50	60	70	80	90	100
V	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
+M	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
-M	1.0	1.05	1.0	1.0	1.0	1.0	1.0	1.0	1.0

	Span Length (ft)									
	110	120	130	140	150	160	170	180	190	200
V	1.0	1.0	1.0	1.10	1.10	1.10	1.10	1.10	1.10	1.10
+M	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
-M	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

6. CONCLUSIONS AND FINDINGS

The adequacy of Indiana's baseline rating and posting vehicles (RIRVs) was evaluated via a beam-line analysis on a test set of 190 bridges. This set of bridges covered a representative range of span lengths and span ratios encompassing many of the structures on Indiana's roads. For this analysis, it was conservatively assumed that the exception SOVs would use the same load factors as routine commercial traffic. Under these conditions, it was determined that the RIRV bridge load rating and posting loads are not adequate and several types of legal vehicles (lumber commodities, farm commodities, and garbage trucks) had the potential to cause large and routine exceedances of the RIRV moment and shear envelopes. This indicates that bridges rated with the RIRVs and found to be safe relative to federal limits are not necessarily able to safely carry the state legal loads.

As a result, a set of three new loads were proposed to be added to the RIRVs, three new loads which can eliminate all of the exceedances found in this analysis, increasing the level of safety of the state's bridges and allowing for appropriate posting of unsafe bridges. All proposed rating loads are legal according to state law and resemble real vehicles. Furthermore, they consist of entities such as two-vehicle loads for negative moment and combined truck and lane loads, which are already represented in the MBE and should therefore not add any unnecessary complication to the rating practices already in place at both the state and county levels. Additionally, if the number of subsequently posted bridges is of concern, lighter weight alternatives to the new PIRVs are presented should a slightly lower factor of safety be deemed tolerable.

Lastly, in order to quickly implement the results of this study and evaluate the safety of Indiana bridges in a straightforward way, a number of amplification factors for the HS-20 loads were found, such that increasing the HS-20 by that amount would allow it, in combination with the remaining CIRVs, to encompass the SOVs on certain bridges. Given the appropriate amplification factor, bridges can be evaluated simply by checking that the rating factor for the HS-20, which should already be on hand, is equal to or greater than the given amplification factor. If so, the bridge can be assumed to be safe and no further analysis would be required for the time being. While this approach was developed primarily for use on county bridges where it is not expected that the PIRVs can be quickly implemented, it is possible for other bridge owners who have evaluated their bridges with the inspection manual loads to apply this method as well.

7. EXPECTED BENEFITS, DELIVERABLES, AND IMPLEMENTATION

This section briefly discusses the expected benefits of the research study, the deliverable product, and implementation of the research results. A wide range of commercial traffic is permitted to legally operate in the state of Indiana. These include truck vehicles that date back many years and are used for various different applications. Specifically, the following trucks were examined carefully: waste refuse trucks, ready mix truck, trucks included under the grandfathered provisions in the Indiana State Code, as well as other permissible loads identified in the state code that provide exceptions to the law for trucks that transport products from the farming and logging industries. Although these truck vehicles, which are referred to as Standard Operating Vehicles (SOVs), have been allowed to legally operate in Indiana, the current legal loads defined in Indiana (CIRVs) do not fully envelope these loadings. The aim of the study was to examine a reduced version (RIRVs) of the current state legal loads (CIRVs) that excludes design vehicles (H20, HS-20, and alternate military), NRL, and the EV trucks, to determine if new truck legal loadings (NIRVs) could be developed that, when combined with the RIRVs, will satisfactorily evaluate the load effects from the current standard operating vehicle loads. A second objective was to explore use of an amplifier for the HS-20 truck in the CIRV loadings to also be able to envelop the SOVs that operate currently on Indiana highways.

The deliverable product of this research is the definition of three new legal loads that, when combined with current AASHTO MBE loads (RIRVs), are capable of fully enveloping the load effects for moment and shear caused by the vehicles that are currently operating on Indiana roads. The benefit of using these new proposed legal loads is that the new state legal loads will be able to produce bridge load ratings that reflect the current loadings that operate at present in Indiana. This will improve the overall bridge safety by providing a realistic estimate of the truck loading effects.

Prior to implementing the new legal loads (NIRVs) and eliminating the design loadings as part of the CIRVs, an additional study of the frequency of the new legal loads, and the corresponding load factor that should be used, is needed. The current study focused on the severity of the NIRV loadings that would envelope the SOVs. However, the study used the most conservative load factor that corresponds to routine commercial traffic. A lower load factor may indeed be justified. Hence, the definition of a suitable load factor that reflects the frequency of loading for the exception vehicles should be completed to fully define the new legal loadings. Once this can be accomplished, then the new legal loading recommendations (truck loading severity) noted herein can be considered for future implementation as Indiana legal loads. It is also advisable that the additional study include an assessment of the anticipated impacts of the new legal loads (both load severity and generalized live load factor) on the state network of bridges, both in load postings and economic burden.

The recommendations for possible future implementation are in line with two of the key performance metrics in the INDOT strategic plan: (1) asset sustainability and (2) economic competitiveness. By using new legal loads that best reflect actual truck loads that are permitted to operate in Indiana, then the bridge response is modeled best, and their use will result in a safer bridge inventory overall. This will help to preserve the precious inventory of bridges owned by the state of Indiana. Also, the economic competitiveness of the state is enhanced by safely modeling the heavier exception vehicles that are allowed to operate on Indiana roads.

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APPENDICES

Appendix A. State Operating Vehicle Data

Appendix B. Supplementary Analysis of Rating Vehicles

APPENDIX A. STATE OPERATING VEHICLE DATA

The tables and figures in this appendix show many of the state legal load configurations (axle weights and distances between axles) that were considered in this study. Figures A.1 and A.2 show the original garbage truck manufacturer configurations, which were scaled to match the legal limits in the Indiana Code. These figures also show the original front axle weights, which were averaged in order to derive the axle weights used in analysis.

Table A.1 and Table A.3 show, for agricultural and lumber commodity trucks, respectively, the estimated maximum weight configurations allowed by either the FBF or the grandfather law. Table A.2 and Table A.4 show the same agricultural and lumber commodity trucks, this time with their GVWs increased by 10% and their axle weights increased accordingly. These increased loads were those used in analysis.

Table A.5 shows ready-mix truck configurations which were found to be illegal according to both the FBF and grandfather law, despite being derived from realistic estimates. Table A.6 shows both the legal and illegal ready-mix configurations, but with all of the liftable axles raised and all of the load supported by the three remaining axles. None of the configurations shown in these two tables were used for analysis.

2-axle Vehicles	Front Axle (lbs)	Rear Axle (lbs)	Wheelbase (in)
International Workstar (Rated)	12000	30000	240
Crane Carrier Company (Rated)	17000	27120	180
Kann Route King (Measured)	15917	22957	152

Scaled Front Axle (lbs)	Scaled Rear Axle (lbs)
9600	24000
15044	24000
16640	24000

Ave. Front Axle Weight = 13761 lbs. ≈ 14000 lbs.

Figure A.1 Derivation of front axle weight for two-axle garbage trucks.

3-axle Vehicles (Rated)	Front Axle (lbs)	Tandem Axle (lbs)	Wheelbase (in)
New Way Mammoth 40	20000	44000	208
Heil Half/Pack (32 cu. yd)	20000	48000	209
Heil Half/Pack (28 cu. yd)	20000	46000	197
Heil DuraPack 4060 (20 cu. yd)	16000	46000	155
Heil DuraPack 4060 (25 cu. yd)	20000	48000	187

Scaled Front Axle (lbs)	Scaled Tandem Axle (lbs)
19091	42000
17500	42000
18261	42000
14609	42000
17500	42000

Ave. Front Axle Weight = 17392 lbs. ≈ 17500 lbs.

Figure A.2 Derivation of front axle weight for three-axle garbage trucks.

Table A.1 Legal (FBF or Grandfather) Farm Commodity Configurations

Config #	Data Type	Legal Weight Configurations (weights in lbs., spacings in ft.)						GVW (kip)
1	Axle Weight	13,000	15,900	15,900	17,500	17,500		79.8
	Axle Spacing	10.7	4	32.1	10.2			
2	Axle Weight	13,000	15,900	15,900	17,500	17,500		79.8
	Axle Spacing	10.7	4	33.6	10.7			
3	Axle Weight	14,000	15,400	15,400	17,500	17,500		79.8
	Axle Spacing	11.9	4	32.1	10.2			
4	Axle Weight	14,000	15,400	15,400	17,500	17,500		79.8
	Axle Spacing	11.9	4	33.6	10.7			
5	Axle Weight	13,000	16,400	16,400	16,300	16,300		78.4
	Axle Spacing	10.7	4	30.1	4.1			
6	Axle Weight	13,000	16,800	16,800	16,600	16,600		79.8
	Axle Spacing	10.7	4	32.4	4.1			
7	Axle Weight	13,000	16,800	16,800	16,600	16,600		79.8
	Axle Spacing	10.7	4	33.1	4.1			
8	Axle Weight	13,000	14,900	14,900	15,200	15,200		73.2
	Axle Spacing	10.7	4	18.8	4.1			
9	Axle Weight	13,000	15,300	15,300	15,400	15,400		74.4
	Axle Spacing	10.7	4	23.6	4.1			
10	Axle Weight	13,000	15,800	15,800	15,700	15,700		76.0
	Axle Spacing	10.7	4	26.3	4.1			
11	Axle Weight	13,000	16,100	16,100	16,000	16,000		77.2
	Axle Spacing	10.7	4	28.1	4.1			
12	Axle Weight	14,000	16,100	16,100	16,500	16,500		79.2
	Axle Spacing	11.9	4	30.1	4.1			
13	Axle Weight	14,000	16,300	16,300	16,600	16,600		79.8
	Axle Spacing	11.9	4	32.4	4.1			
14	Axle Weight	14,000	16,300	16,300	16,600	16,600		79.8
	Axle Spacing	11.9	4	33.1	4.1			
15	Axle Weight	14,000	14,400	14,400	15,200	15,200		73.2
	Axle Spacing	11.9	4	18.8	4.1			
16	Axle Weight	14,000	15,000	15,000	15,600	15,600		75.2
	Axle Spacing	11.9	4	23.6	4.1			
17	Axle Weight	14,000	15,500	15,500	16,000	16,000		77.0
	Axle Spacing	11.9	4	26.3	4.1			
18	Axle Weight	14,000	15,800	15,800	16,200	16,200		78.0
	Axle Spacing	11.9	4	28.1	4.1			
19	Axle Weight	13,000	15,900	15,900	11,600	11,600	11,600	79.6
	Axle Spacing	10.7	4	32.1	5.1	5.083333		

20	Axle Weight	13,000	15,900	15,900	11,700	11,700	11,700	79.9
	Axle Spacing	10.7	4	33.6	5.3	5.333333		
21	Axle Weight	14,000	15,400	15,400	11,600	11,600	11,600	79.6
	Axle Spacing	11.9	4	32.1	5.1	5.083333		
22	Axle Weight	14,000	15,400	15,400	11,700	11,700	11,700	79.9
	Axle Spacing	11.9	4	33.6	5.3	5.333333		

Table A.2 Farm Commodity Configurations with 10% Exception

Config #	Data Type	Configurations +10% (weights in kips., spacings in ft.)						Final GVW (kips)
1	Axle Weight	13	17.7	17.7	19.7	19.7		87.8
	Axle Spacing	10.7	4	32.1	10.2			
2	Axle Weight	13	17.7	17.7	19.7	19.7		87.8
	Axle Spacing	10.7	4	33.6	10.7			
3	Axle Weight	14	17.2	17.2	19.7	19.7		87.8
	Axle Spacing	11.9	4	32.1	10.2			
4	Axle Weight	14	17.2	17.2	19.7	19.7		87.8
	Axle Spacing	11.9	4	33.6	10.7			
5	Axle Weight	13	18.2	18.2	18.4	18.4		86.2
	Axle Spacing	10.7	4	30.1	4.1			
6	Axle Weight	13	18.7	18.7	18.7	18.7		87.8
	Axle Spacing	10.7	4	32.4	4.1			
7	Axle Weight	13	18.7	18.7	18.7	18.7		87.8
	Axle Spacing	10.7	4	33.1	4.1			
8	Axle Weight	13	16.6	16.6	17.2	17.2		80.5
	Axle Spacing	10.7	4	18.8	4.1			
9	Axle Weight	13	17.0	17.0	17.4	17.4		81.8
	Axle Spacing	10.7	4	23.6	4.1			
10	Axle Weight	13	17.6	17.6	17.7	17.7		83.6
	Axle Spacing	10.7	4	26.3	4.1			
11	Axle Weight	13	17.9	17.9	18.1	18.1		84.9
	Axle Spacing	10.7	4	28.1	4.1			
12	Axle Weight	14	18.0	18.0	18.6	18.6		87.1
	Axle Spacing	11.9	4	30.1	4.1			
13	Axle Weight	14	18.2	18.2	18.7	18.7		87.8
	Axle Spacing	11.9	4	32.4	4.1			
14	Axle Weight	14	18.2	18.2	18.7	18.7		87.8
	Axle Spacing	11.9	4	33.1	4.1			
15	Axle Weight	14	16.1	16.1	17.2	17.2		80.5
	Axle Spacing	11.9	4	18.8	4.1			

16	Axle Weight	14	16.7	16.7	17.6	17.6		82.7
	Axle Spacing	11.9	4	23.6	4.1			
17	Axle Weight	14	17.3	17.3	18.1	18.1		84.7
	Axle Spacing	11.9	4	26.3	4.1			
18	Axle Weight	14	17.6	17.6	18.3	18.3		85.8
	Axle Spacing	11.9	4	28.1	4.1			
19	Axle Weight	13	17.7	17.7	13.1	13.1	13.1	87.6
	Axle Spacing	10.7	4	32.1	5.1	5.08		
20	Axle Weight	13	17.7	17.7	13.2	13.2	13.2	87.9
	Axle Spacing	10.7	4	33.6	5.3	5.33		
21	Axle Weight	14	17.2	17.2	13.1	13.1	13.1	87.6
	Axle Spacing	11.9	4	32.1	5.1	5.08		
22	Axle Weight	14	17.2	17.2	13.2	13.2	13.2	87.9
	Axle Spacing	11.9	4	33.6	5.3	5.33		

Table A.3 Legal (FBF or Grandfather) Lumber Commodity Configurations

Config #	Data Type	Legal Weight Configurations (weights in lbs., spacings in ft.)								GVW (kip)
1	Axle Weight	13,000	13,000	13,000	11,997	9,645	9,645	9,645		79.9
	Axle Spacing	10.7	4	21.0	8.5	6	6			
2	Axle Weight	13,000	11,600	11,600	10,224	10,224	10,224	6,545	6,545	80.0
	Axle Spacing	10.7	4	21.9	5.0	5	18.4	3.96		
3	Axle Weight	13,000	14,100	14,100	12,933	12,933	12,933			80.0
	Axle Spacing	10.7	4	31.8	6.0	6				
4	Axle Weight	13,000	14,700	14,700	12,422	12,422	12,422			79.7
	Axle Spacing	10.7	4	30.0	5.0	5				
5	Axle Weight	13,000	14,300	14,300	16,495	16,495				74.6
	Axle Spacing	10.7	4	29.6	4.3					
6	Axle Weight	13,000	14,300	14,300	16,495	16,495				74.6
	Axle Spacing	10.7	4	29.6	4.3					
7	Axle Weight	13,000	14,200	14,200	16,475	16,475				74.3
	Axle Spacing	10.7	4	29.4	4.5					
8	Axle Weight	13,000	14,200	14,200	16,475	16,475				74.3
	Axle Spacing	10.7	4	29.4	4.5					
9	Axle Weight	13,000	15,600	15,600	16,505	16,505				77.2
	Axle Spacing	10.7	4	29.4	4.1					
10	Axle Weight	13,000	15,600	15,600	16,505	16,505				77.2
	Axle Spacing	10.7	4	29.4	4.1					
11	Axle Weight	13,000	14,800	14,800	16,531	16,531				75.7
	Axle Spacing	10.7	4	29.2	4.1					
12	Axle Weight	13,000	14,800	14,800	16,531	16,531				75.7
	Axle Spacing	10.7	4	29.2	4.1					
13	Axle Weight	13,000	14,800	14,800	16,537	16,537				75.7
	Axle Spacing	10.7	4	29.3	4.1					

14	Axle Weight	13,000	14,800	14,800	16,537	16,537				75.7
	Axle Spacing	10.7	4	29.3	4.1					
15	Axle Weight	13,000	15,400	15,400	16,526	16,526				76.9
	Axle Spacing	10.7	4	30.9	4.2					
16	Axle Weight	14,000	12,500	12,500	11,997	9,645	9,645	9,645		79.9
	Axle Spacing	11.9	4	21.0	8.5	6	6			
17	Axle Weight	14,000	11,100	11,100	10,224	10,224	10,224	6,545	6,545	80.0
	Axle Spacing	11.9	4	21.9	5.0	5	18.4	3.96		
18	Axle Weight	14,000	13,600	13,600	12,933	12,933	12,933			80.0
	Axle Spacing	11.9	4	31.8	6.0	6				
19	Axle Weight	14,000	14,200	14,200	12,422	12,422	12,422			79.7
	Axle Spacing	11.9	4	30.0	5.0	5				
20	Axle Weight	14,000	13,800	13,800	16,495	16,495				74.6
	Axle Spacing	11.9	4	29.6	4.3					
21	Axle Weight	14,000	13,800	13,800	16,495	16,495				74.6
	Axle Spacing	11.9	4	29.6	4.3					
22	Axle Weight	14,000	13,700	13,700	16,475	16,475				74.3
	Axle Spacing	11.9	4	29.4	4.5					
23	Axle Weight	14,000	13,700	13,700	16,475	16,475				74.3
	Axle Spacing	11.9	4	29.4	4.5					
24	Axle Weight	14,000	15,100	15,100	16,505	16,505				77.2
	Axle Spacing	11.9	4	29.4	4.1					
25	Axle Weight	14,000	15,100	15,100	16,505	16,505				77.2
	Axle Spacing	11.9	4	29.4	4.1					
26	Axle Weight	14,000	14,300	14,300	16,531	16,531				75.7
	Axle Spacing	11.9	4	29.2	4.1					
27	Axle Weight	14,000	14,300	14,300	16,531	16,531				75.7
	Axle Spacing	11.9	4	29.2	4.1					

28	Axle Weight	14,000	14,300	14,300	16,537	16,537				75.7
	Axle Spacing	11.9	4	29.3	4.1					
29	Axle Weight	14,000	14,300	14,300	16,537	16,537				75.7
	Axle Spacing	11.9	4	29.3	4.1					
30	Axle Weight	14,000	14,900	14,900	16,526	16,526				76.9
	Axle Spacing	11.9	4	30.9	4.2					

Table A.4 Lumber Commodity Configurations with 10% Exception

Config #	Data Type	Configurations +10 % (weights in kips., spacings in ft.)								GVW+10% (kips)
1	Axle Weight	13	14.4	14.4	14	11	11	11		87.9
	Axle Spacing	10.7	4	21.0	8.5	6	6			
2	Axle Weight	13	12.8	12.8	12	12	12	7	7.38	80.6
	Axle Spacing	10.7	4	21.9	5.0	5	18.4	3.96		
3	Axle Weight	13	15.6	15.6	15	15	15			88.0
	Axle Spacing	10.7	4	31.8	6.0	6				
4	Axle Weight	13	16.3	16.3	14	14	14			87.6
	Axle Spacing	10.7	4	30.0	5.0	5				
5	Axle Weight	13	15.9	15.9	19	19				82.0
	Axle Spacing	10.7	4	29.6	4.3					
6	Axle Weight	13	15.9	15.9	19	19				82.0
	Axle Spacing	10.7	4	29.6	4.3					
7	Axle Weight	13	15.8	15.8	19	19				81.8
	Axle Spacing	10.7	4	29.4	4.5					
8	Axle Weight	13	15.8	15.8	19	19				81.8
	Axle Spacing	10.7	4	29.4	4.5					
9	Axle Weight	13	17.3	17.3	19	19				84.9
	Axle Spacing	10.7	4	29.4	4.1					
10	Axle Weight	13	17.3	17.3	19	19				84.9

	Axle Spacing	10.7	4	29.4	4.1					
11	Axle Weight	13	16.5	16.5	19	19				83.2
	Axle Spacing	10.7	4	29.2	4.1					
12	Axle Weight	13	16.5	16.5	19	19				83.2
	Axle Spacing	10.7	4	29.2	4.1					
13	Axle Weight	13	16.5	16.5	19	19				83.2
	Axle Spacing	10.7	4	29.3	4.1					
14	Axle Weight	13	16.5	16.5	19	19				83.2
	Axle Spacing	10.7	4	29.3	4.1					
15	Axle Weight	13	17.1	17.1	19	19				84.5
	Axle Spacing	10.7	4	30.9	4.2					
16	Axle Weight	14	13.9	13.9	14	11	11	11		87.9
	Axle Spacing	11.9	4	21.0	8.5	6	6			
17	Axle Weight	14	12.3	12.3	12	12	12	7	7.38	80.6
	Axle Spacing	11.9	4	21.9	5.0	5	18.4	3.96		
18	Axle Weight	14	15.1	15.1	15	15	15			88.0
	Axle Spacing	11.9	4	31.8	6.0	6				
19	Axle Weight	14	15.8	15.8	14	14	14			87.6
	Axle Spacing	11.9	4	30.0	5.0	5				
20	Axle Weight	14	15.4	15.4	19	19				82.0
	Axle Spacing	11.9	4	29.6	4.3					
21	Axle Weight	14	15.4	15.4	19	19				82.0
	Axle Spacing	11.9	4	29.6	4.3					
22	Axle Weight	14	15.3	15.3	19	19				81.8
	Axle Spacing	11.9	4	29.4	4.5					
23	Axle Weight	14	15.3	15.3	19	19				81.8
	Axle Spacing	11.9	4	29.4	4.5					
24	Axle Weight	14	16.8	16.8	19	19				84.9
	Axle Spacing	11.9	4	29.4	4.1					

25	Axle Weight	14	16.8	16.8	19	19				84.9
	Axle Spacing	11.9	4	29.4	4.1					
26	Axle Weight	14	16.0	16.0	19	19				83.2
	Axle Spacing	11.9	4	29.2	4.1					
27	Axle Weight	14	16.0	16.0	19	19				83.2
	Axle Spacing	11.9	4	29.2	4.1					
28	Axle Weight	14	16.0	16.0	19	19				83.2
	Axle Spacing	11.9	4	29.3	4.1					
29	Axle Weight	14	16.0	16.0	19	19				83.2
	Axle Spacing	11.9	4	29.3	4.1					
30	Axle Weight	14	16.6	16.6	19	19				84.5
	Axle Spacing	11.9	4	30.9	4.2					

Table A.5 Illegal Ready-Mix Configurations with 8 yd^3 Normal Weight Concrete

Model	Data	Axle Weights (kips) and Axle Spacings (ft)						GVW (kips)
2006 FD3000	Weights	20.8	20.8	20.8				62.4
	Spacings	14.3	4.33					
2006 FD4000	Weights	16.7	17.5	14.9	14.9			64.0
	Spacings	9.08	4.17	4.33				
2006 FDB4000	Weights	20.9	17.2	17.2	8.91			64.2
	Spacings	13.7	6.00	13.2				
2006 FD6000	Weights	17.6	3.90	3.90	16.6	16.6	9.76	68.3
	Spacings	6.33	3.83	4.00	4.50	4.50		
2016 FD3000	Weights	21.5	21.5	21.5				64.5
	Spacings	15.1	4.50					
2016 FD4000	Weights	19.0	9.10	19.0	19.0			66.2
	Spacings	10.58	4.50	4.50				
2016 FDB4000	Weights	18.6	18.6	18.6	10.7			66.5
	Spacings	14.4	4.50	10.9				
2016 FD5000	Weights	16.8	8.04	16.8	16.8	9.64		68.1
	Spacings	9.67	4.42	4.50	4.42			

Table A.6 4+ Axle Ready-Mix Trucks with Axles Lifted (8 yd^3 Normal Weight Concrete)

Model	Data	Axle Weights (kips) and Axle Spacings (ft)			GVW (kips)
2006 FD4000	Weights	23.9	20.0	20.0	64.0
	Spacings	13.3	4.33		
2006 FDB4000	Weights	12.3	26.0	26.0	64.2
	Spacings	19.7	13.2		
2006 FD5000	Weights	16.8	24.5	24.5	65.7
	Spacings	14.3	4.33		
2006 FDB5000	Weights	16.6	24.2	24.2	64.9
	Spacings	13.3	4.33		
2006 FD6000	Weights	17.4	25.4	25.4	68.3
	Spacings	14.2	4.50		
2006 FDB6000	Weights	15.0	25.7	25.7	66.3
	Spacings	14.5	4.33		
2006 FDB7000	Weights	12.3	28.3	28.3	68.9
	Spacings	14.5	4.33		
2016 FD4000	Weights	22.6	21.8	21.8	66.2
	Spacings	15.1	4.50		
2016 FDB4000	Weights	10.2	28.1	28.1	66.5
	Spacings	14.4	4.50		
2016 FD5000	Weights	16.1	26.0	26.0	68.1
	Spacings	14.1	4.50		
2016 FD6000	Weights	19.3	25.8	25.8	70.9
	Spacings	16.9	4.50		
2016 FDB6000	Weights	16.3	26.2	26.2	68.7
	Spacings	14.9	4.50		
2016 FDB7000	Weights	9.8	30.8	30.8	71.5
	Spacings	14.5	4.50		

APPENDIX B. SUPPLEMENTARY ANALYSIS OF RATING VEHICLES

This appendix contains a graph of the load effect exceedances caused by the SOVs when they are compared to the rating loads from the CIRVs. In this figure, the HS-20 loads from the Inspection Manual have been increased by a lesser value compared to Figure 4.25.

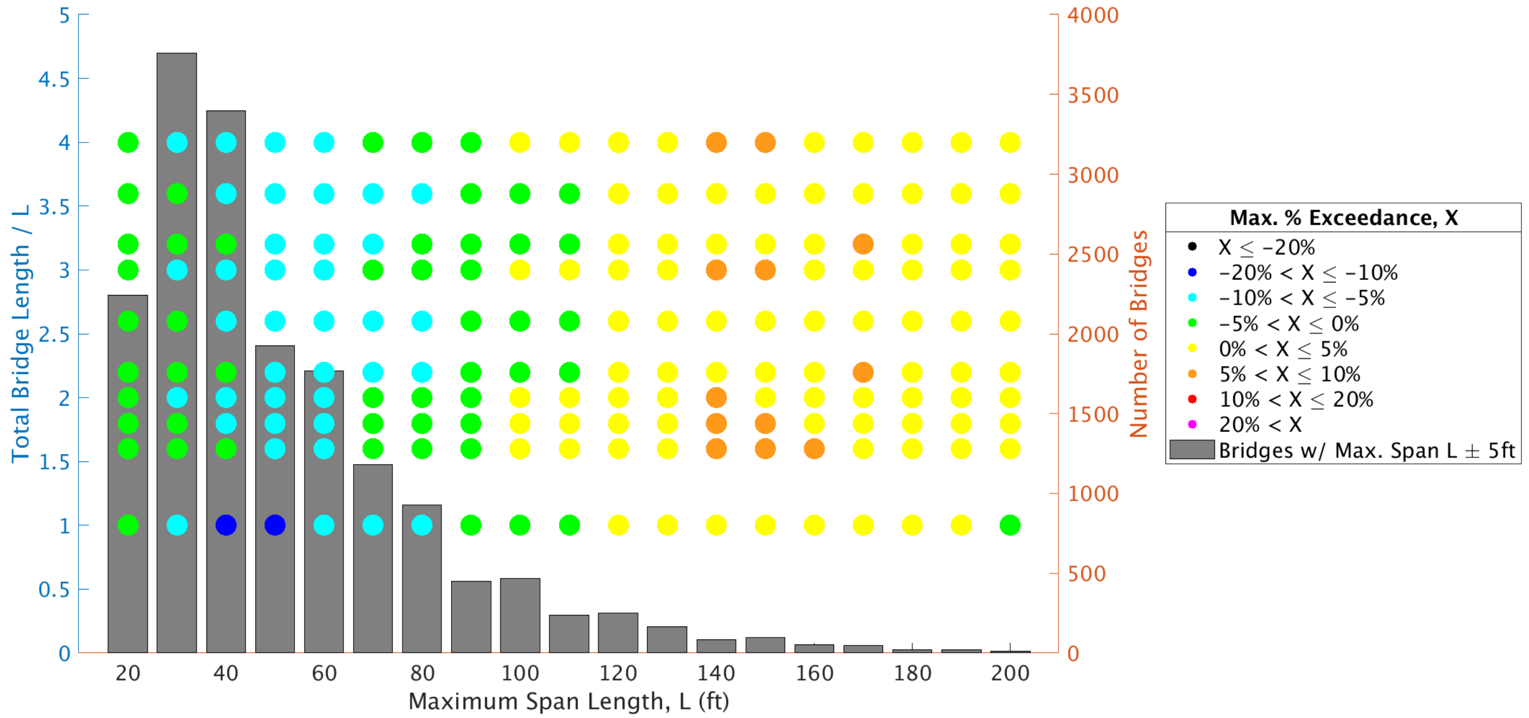

Figure B.1 Shear envelope comparison between the SOVs and the CIRVs with the HS-20 increased by 5%.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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