Load and Resistance Factor Rating Methodology Recommendations for Missouri Bridges

November 2024
Final Report

Project number TR202122
MoDOT Research Report number cmr 24-021

PREPARED BY:

Thiagarajan Ganesh, Ph.D., P.E., University of Missouri at Kansas City

John J Myers, Ph.D., P.E., Co-Principal Investigator, Missouri University of Science and Technology

John Finke Ph.D., P.E., Co-Principal Investigator, Jacobs Engineering

PREPARED FOR:

Missouri Department of Transportation

Construction and Materials Division Research Section

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. cmr24-021	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Load and Resistance Factor Rating Methodology Recommendations for Missouri Bridges		**5. Report Date** June 2024 Published: November 2024
		6. Performing Organization Code
7. Author(s) Thiagarajan Ganesh, Ph.D., https://orcid.org/0000-0001-5645-232X John Finke Ph.D. John Myers Ph.D., https://orcid.org/0000-0001-5269-8218 Bao Tran M.S., Ronald Cheruiyot M.S., Nirav Khanal		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Department of Natural and Built Environment University of Missouri-Kansas City 350K Flarsheim Hall, Kansas City, MO 64110 Department of Civil, Architectural and Environmental Engineering Missouri University of Science and Technology 1401 N. Pine St., Rolla, MO 65409 Jacobs Engineering Group, 1001 Highlands Plaza Drive W, Suite 400 St. Louis, MO 63110		**10. Work Unit No.**
		11. Contract or Grant No. MoDOT project # TR202122
12. Sponsoring Agency Name and Address Missouri Department of Transportation (SPR-B) Construction and Materials Division P.O. Box 270 Jefferson City, MO 65102		**13. Type of Report and Period Covered** Final Report (June 2021-December 2023)
		14. Sponsoring Agency Code
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MoDOT research reports are available in the Innovation Library at https://www.modot.org/research-publications.		

16. Abstract

Traditionally, MoDOT performed bridge load ratings using the Load Factor Rating (LFR) methodology. With the adoption of Load and Resistance Factor Design based Load and Resistance Factor Rating (LRFR) methodology, MoDOT is migrating to LRFR for rating bridges. The primary goal of this study is to develop and recommend load posting policies using the LRFR methodology consistent with the current LFR policy. The goal was accomplished using MoDOT-provided information on approximately one hundred reinforced concrete, prestressed concrete, and steel bridges each, and about thirty concrete culverts throughout the state and in different commercial zones. The research conducted to compare the two rating methodologies has shown that the LFR and LRFR methodologies of rating differ in (a) bridges rated in LFR govern in interior girders while with the LRFR method, most bridges will govern in the exterior girders; (b) LRFR ratings are lower than the LFR ratings; (c) the number of posted bridges increased for LRFR over those required to be posted by LFR. This points to a necessary change associated with the LRFR posting threshold to meet the current practice used by MoDOT. Recommendations based on the study of the various objectives applicable to each of the bridge/culvert types have been provided in this report.

17. Key Words Load Factor Rating, Load and Resistance Factor Rating, Load posting, Steel bridges, Concrete bridges, Prestressed concrete bridges; Bridges; Culverts; Load Factor; Load and resistance factor design		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified.	**20. Security Classif. (of this page)** Unclassified.	**21. No. of Pages** 289	**22. Price**

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

Load and Resistance Factor Rating Methodology Recommendations for Missouri Bridges

Final Report

June 2024

Principal Investigator

Thiagarajan Ganesh, Ph.D., P.E., Associate Professor

University of Missouri, Kansas City

Co-Principal Investigators

John J Myers, Ph.D. P.E., Professor,

Missouri University of Science and Technology, Rolla

John Finke Ph.D. P.E., Structures Manager

Jacobs Engineering, St. Louis

Authors

Thiagarajan Ganesh, John Finke, John Myers, Bao Tran, Ronald Cheruiyot, Nirav Khanal

Sponsored by

Missouri Department of Transportation

A report from

University of Missouri, Kansas City

Natural and Built Environment (Civil Engineering)

350K, Flarsheim Hall, Kansas City 64110

ACKNOWLEDGMENTS

The authors would like to thank the Missouri Department of Transportation and the Missouri Center for Transportation Innovation for sponsoring this research. The help of graduate student Sadeq Annooz of Missouri S&T with some aspects of formatting the initial report is gratefully acknowledged. The authors would also like to thank the Program Manager, Missouri Department of Transportation Technical Advisory Committee and Ms. Kayley Bozarth (MCTI) for their assistance in the development of this project and report.

Table of Contents

List of Tables

List of Figures

ACRONYMS

AASHTO – American Association of State Highway Transportation Officials

ADTT- Average Daily Truck Traffic

ASD – Allowable Stress Design

ASR – Allowable Stress Rating

BIRM - Bridge Inspector's Reference Manual

CZRT – Commercial Zone Rating Truck

CZSU – Commercial Zone Single Unit

FAST – Fixing America's Transportation Act

FHWA – Federal Highway Administration

GWT – Gross Weight

IM – Impact Factor

Klf – kips per linear foot

LFD – Load Factor Design

LFR - Load Factor Rating

LRFD – Load and Resistance Factor Design

LRFR – Load and Resistance Factor Rating

MCE – Manual for Condition Evaluation of Bridges

MoDOT – Missouri Department of Transportation

NBI - National Bridge Inventory

NCHRP - National Cooperative Highway Research Program

NRL – Notional Rating Load

RF – Rating Factor

SHV – Special Haul Vehicles

WIM -Weigh-in-Motion

Executive Summary

Traditionally, MoDOT has performed bridge load ratings using a method called load factor rating (LFR). Now, however, with changes to bridge design and heavier vehicles traveling Missouri's highways, MoDOT is working to adopt an updated system called load and resistance factor rating (LRFR). The primary goal of this study is to develop and recommend load posting policies using the LRFR method that are consistent with the current LFR policy. To aid the task, MoDOT provided data for about 100 bridges for each of the three bridge types, including reinforced concrete, prestressed concrete, and steel, as well as data for about 35 concrete culverts throughout the state and in different commercial zones.

The study has shown that LFR and LRFR differ in (a) bridges analyzed in LFR govern in interior girders while when using LRFR, most bridges will govern in the exterior girders; (b) LRFR ratings are lower than LFR ratings; (c) the number of posted bridges increased for LRFR over those required to be posted by compared to using LFR. This suggests possible changes to the LRFR posting thresholds to better mesh with current MoDOT practices. Findings from the study are briefly summarized below.

Steel Bridges: Use of the current thresholds for commercial zone single unit (CZSU) and commercial zone relay truck (CZRT) seems very conservative and leads to more bridges being posted. The research suggests that posting thresholds used for CZSU (45 tons) and CZRT (70 tons) within the commercial zones should be reduced to their gross weight (GWT) of 40.8 tons and 51 tons, respectively. The H20L model, the current live load model for LFR, has a posting threshold of 30 tons and is recommended to be revised to 31 tons in LRFR. By studying minimum factors for all the Missouri live loads, a minimum factor of 0.91 is conservatively suggested for posting purposes for all the bridges in the same way that the factor of 0.86 is currently used in LFR by MoDOT.

Changing the Service II limit state factor from 1.3 to 1.0 showed a significant reduction, up to 30%, in the number of bridges that required posting. For bridges that have spans greater than 200 feet, most MoDOT vehicles still envelop American Association of State Highway Transportation Officials (AASHTO) vehicles, while some will require a factor. Generally, truck trains have the lowest rating loads and, therefore, govern by being the most conservative in both the LRFR and LFR.

The ratings for multi-lane loaded bridges are more conservative than the single-lane loaded bridges when using both LFR and LRFR.

Prestressed Concrete Bridges: The study shows no significant difference in rating load and number of bridges requiring posting when using LFR or LRFR.

When using LRFR for prestressed bridges and the seven vehicles enveloped, thresholds ranging from 25-40 tons and factors ranging from 0.87 to 1.0 are recommended for H20L, MO3S2, and CZRT. There are only six bridges from the sample of 100 prestressed bridges that have load ratings controlled by the Service III limit state when using LRFR. Excluding the service limit state from the LRFR rating load at the legal load level is recommended.

Reinforced Concrete Bridges: For H20L, a threshold of 31 tons with 0.97 factor is recommended to encapsulate vehicles operated within the state. Similarly, a threshold of 40 tons with a factor of 0.93 is proposed for the MO3S2 vehicle. For the MoDOT commercial single-unit truck CZSU, a threshold of 40.8 tons with a factor of 0.92 is proposed for the MO3S2 vehicle. Lastly, a threshold of 51 tons with a factor of 1 is proposed for the MoDOT commercial vehicle CZRT.

Culverts: All but three of the 35 concrete culverts analyzed in this study using AASHTOWare bridge rating software BrR v7.1 used allowable stress design (ASD). By comparing LFR and LRFR for the H20L and MO3S2 vehicles, the study concluded that LFR has higher rating factors and rating loads than LRFR. There were just two culverts in commercial zones subject to CZSU and CZRT, making it difficult to develop conclusions about rating trends. Despite the lack of data, the available points parallel a trend shown by Still, as was the case with H20L and MO3S2, the load rating results for LRFR were about 65%-70% compared to rating loads in LFR. This reduction for the LRFR rating might be less than that for the LFR because the live load distribution factor could be more conservative when using the load and resistance factor design (LRFD).

Chapter 1: Introduction

When producing load ratings for highway bridges, the Missouri Department of Transportation (MoDOT) currently uses the load factor rating (LFR) method found in the American Association of State Highway and Transportation Officials (AASHTO) Manual for Condition Evaluation of Bridges (MCE) [1]. However, with the introduction of AASHTO's Manual for Bridge Evaluation (MBE) [2] and the load and resistance factor rating (LRFR), MoDOT must change its bridge rating and load posting practices.

Since April 2000, when LRFR was introduced for the National Bridge Inventory (NBI), understanding of this method has improved, and transportation departments in some states have started using it for rating bridges. In 2006, the Federal Highway Administration (FHWA) issued a memorandum requiring the use of LRFR with HL-93 loading for all new and reconstructed bridges that were designed using load and resistance factor design (LRFD) specifications. In the memorandum, a table of different scenarios was provided where load rating data exported to the NBI needed to be reported using LRFR.

MoDOT has recently updated its load rating policy to reflect better the wide range of heavier vehicles legally traveling along Missouri roads. These updates are predominantly based on LFR, and while they include LRFR methodology for general load rating, they do not for load posting determinations. MoDOT would like to implement a load posting policy with LRFR that is consistent with the current policy regarding the number of bridges requiring load postings.

This comparative study is performed on a representative sample of prestressed concrete, steel, and reinforced concrete bridges and culverts from county-owned bridge inventory in Missouri at a legal load level of LRFR rating. The LRFR method used by AASHTO [3] is calibrated and published using a reliability-based procedure compatible with the association's LRFD specifications [4]. To be consistent with the reliability-based limit states, the LRFR methodology is developed and detailed in the National Cooperative Highway Research Program's (NCHRP) Project 12-46 [5, 6]. Calibrations provide a reliability level of β=2.5 and 3.5 over a five-year rating period for operating and inventory ratings, respectively. Considering that truck weight data can be generic, and calibration of live load factors is conservative, the national LRFR procedures for bridge evaluation allow state transportation departments to adjust live load factors based on the state's weigh-in-motion (WIM) data. Rating is done at the strength limit state and checked for serviceability. The methodology can be applied to the rating of existing bridges, the posting of loads on certain bridges, and the checking of permit vehicles.

Bridges are typically required to be visually inspected every two years (National Bridge Inspection Standards 23 CFR 650 Subpart C January 13, 2005 [7]), with each bridge component assigned a numerical condition rating between 0 and 9 and a rating of 4 or lower classified as structurally deficient. The live load capacity of a bridge for a given vehicle must have a rating of 1.0 or higher to be safe. Every structural component is rated and the one with the lowest rating determines the overall rating of the bridge. The types of ratings performed are inventory rating, which represents the routine live load the bridge can carry, and operating rating, which is used to determine the maximum live load for vehicles that cross the bridge less frequently.

The allowable stress rating (ASR), LFR, and LRFR are outlined in the MBE [2]. FHWA policies mandate that bridges designed using allowable stress design (ASD) and all bridges designed using load factor design (LFD) be rated using LFR and all bridges designed using AASHTO's LRFD with HL-93 loading be rated using LRFR. Some of the key differences between LFR and LRFR are a) new live load models, b) new live load distribution factors, c) new impact factors, d), new load factors, e) different multiple presence factors, and f) greater emphasis on serviceability. Some important issues with the LRFD/LRFR method of rating are as follows:

1. Whether the design level reliability of 3.5 is appropriate for evaluation,
2. Should all serviceability limit states be imposed on existing bridges,
3. How should overweight permit loads be evaluated,
4. Design impact factors (33%) may be too conservative for evaluation checks,
5. HL-93 loading does not resemble actual trucks and is a notional load not suitable for posting,
6. LRFD only addresses redundant superstructure systems, while many existing bridges are nonredundant,
7. LRFD is focused on new bridges or non-degraded bridges, and
8. Older materials & connections (rivets) are not covered in the LRFD specifications.

The AASHTO Manual for Bridge Evaluation [3] is a critical resource for the load rating of bridges. Live loads are often specific to the states and their needs. The load rating is live load specific, and MoDOT has updated load rating policies to account for the heavier loads on Missouri roads based on the LFR methodology. LRFR methodology is used for general load ratings but not load posting. The overall goal of this project is to develop and recommend load posting policies using the LRFR methodology in a way that is consistent with the current LFR policy. This recommendation will be submitted in the final report and will be based on the analysis of several bridges using the two rating methods.

1.1 Background

Over the years different vehicles, such as H-15, HS20-44, HS25, and HL-93, have been used to design bridges. Bridges age with time and can become structurally deficient. Legal loads are a standard set of vehicles that are used to rate a bridge, and load rating is performed for the safety of the public and vehicles. States have laws that govern what vehicle loads are allowed legally on their roads without a permit. Legal Load Rating Vehicles are notional vehicle models that represent these legal loads. In case bridges do not have sufficient capacity, restricted loads are posted. Traditionally, MoDOT rates bridges using the LFR method, while the ASR methodology is used for timber bridges. Recently, MoDOT updated its load rating policy to reflect the use of heavier vehicles, and this project intends to incorporate LRFR methodology while being consistent with the current LFR system. The goal is to have a similar number of bridges requiring load postings. A set of vehicles will be analyzed for use with a group of typical bridges using the different rating methods. The results and observations will be compared, and recommendations will be made on ways to implement LRFR.

1.2 Load Rating

Load rating is used to quantify the vehicular live load capacity of a bridge. A rating of 1.0 or higher means the bridge can safely carry a given vehicle. Each structural component is rated, with the lowest rating controlling the overall rating of the bridge. There are two levels of load rating. The inventory level represents the routine live load capacity a bridge can support over an indefinite time. The operating level measures the live load capacity for less frequent vehicles and is commonly used to determine the maximum permissible live load that bridge can carry.

AASHTO policy requires bridges designed by allowable stress design (ASD) to be rated by either LFR or LRFR. This policy also requires all bridges designed after October 1, 2007, to use LRFD specification, part of the national trend in the direction of LRFR (FHWA 2006). In the scope of this project, only LFR and LRFR methods are used, and comparative data is investigated.

1.2.1 Rating Equation

The general load rating equation for both the LFR and LRFR methods is expressed similarly and represents the ratio between the live load capacity of a member to its live load demand. As shown in equation 1-1:

$$Rating\ factor = \frac{Capacity - Dead\ Load\ Effect}{Live\ Load\ Effect} \qquad Equation\ 1-1$$

The numerator represents the live load capacity of a member, which is the difference between the factored capacity and the dead load effect applied to the factored dead load. The denominator represents the factored live load's model effect.

LFR can be applied to structures designed before October 2010 using MBE standards. LFR can still be applied to newer bridges. However, it is mandated that these newer bridges are rated LRFR, but not necessarily for posting. Capacities, resistance factors, and live load distribution factors are based on the LFD Design Specification for Highway Bridges, 8th Edition (AASHTO, 2017). Load factors are developed assuming normal traffic and overload conditions. However, MBE does not provide additional guidance for adjusting the load factors to reflect actual conditions more accurately. LFR represents a "tried and true approach" to the rating problem [6].

LRFR was developed to be consistent in philosophy with the AASHTO LRFD Bridge Design Specification (AASHTO, 2017) in its use of reliability-based limit states. The LRFR allows for a realistic and accurate approach to the safe load capacity of the bridge under a specific limit state. In applying the method for the design live load, if the strength check value of the rating factor (RF) is > 1.0, no action is required. However, if the RF < 1.0, a check for the operating level rating is performed, and the load rating for posting is determined. When the RF is between 0.3 and 1.0, the posting load is given as

$$Posting\ load = \left(\frac{W}{0.7}\right)[RF - 0.3] \qquad Equation\ 1-1$$

where W is the weight of the rating vehicle and RF = Legal load rating factor. If the rating factor is less than 0.3, the bridge should be closed.

LRFR is flexible enough to allow different state transportation departments to use live load factors depending on state-specific vehicle configurations or other considerations. Ghosn et al. [8] made such adjustments and used them to calibrate the LRFR for New York state bridges. Major differences between LFR and LRFR are outlined in Table 1-1.

Table 1.1: Differences between LFR and LRFR

Rating Methodology	**LRFR**	**LFR**
Capacity	According to LRFD	According to LFD
Condition and System Factors	Φ – Resistance Φ_C – Condition Φ_s – System	---
Distribution Factors	LRFD Formulas	"S Over" Formulas
Dead Load Factors	λ_{DC} – 1.25 λ_{DW} – 1.5	A_1 – 1.3
Live Load Factors	λ_L Inventory – 1.75 Operating – 1.35 Legal – 1.4 to 1.8 Permit – 1.15 to 1.8	A_2 Inventory – 2.17 Operating – 1.3
Impact Factor	Constant	Span Length Dependent

1.3 Objectives

The main objective of the project is to determine a plan for the adoption of LRFR that addresses the following areas:

1. Review MoDOT's current load rating vehicle models and load posting thresholds and make recommendations on how these models should be incorporated into LRFR.
2. Determine if the standard live load factors for LRFR are still applicable to MoDOT's vehicle models and, if needed, provide recommendations for changes.
3. Provide recommendations for the use of the various system and condition factors in LRFR, including how they might influence a good inspection program.
4. Review how MoDOT determines load posting needs for bridges and provide recommendations for using LRFR to produce similar outcomes with respect to the total number of bridges requiring posting.

5. Provide recommendations for the use of LRFR for super load and routine overweight permit loads rating analysis.
6. Review MoDOT's current AASHTOWare load rating models for a variety of bridges and provide recommendations for the adjustments that will be needed to allow for LRFR.
7. Review MoDOT's current practice for determining single lane live load distribution factors on slab bridges and provide recommendations for a similar approach using LRFR.
8. Review how MoDOT currently uses LFR for culverts and, if needed, make recommendations for changes for using LRFR.
9. Provide recommendations on how MoDOT's current use of a combination of single lane and multi-lane rating results along with truck traffic volume for determining load posting needs can be incorporated into LRFR.
10. Determine whether the current live load factors MoDOT uses for special hauling vehicles (SHV) would be appropriate for use on MoDOT's commercial zone vehicle (CZV) models.
11. Determine whether to include serviceability limit states on prestressed concrete bridge load ratings, which are currently optional for legal load ratings and for permit load ratings.
12. Investigate MBE requirements for load rating of structures with spans longer than 200 feet and provide ways to allow for reasonable load rating of these structures without a refined analysis.
13. Provide recommendations for the use of LRFR Service II load factors for steel bridges, which tend to produce significantly lower posting values compared to serviceability checks using LFR.

These objectives are achieved by performing analysis of steel, prestressed and reinforced concrete in AASHTOWare with bridge models provided by MoDOT and compare the current LFR rating results with the rating results using the LRFR method. At the outset some steps were taken to lay the foundation for the project. They were:

- Request MoDOT for the current rating vehicle models and load posting thresholds currently in use. MoDOT provided The Bridge Inspector's Reference Manual (BIRM).
- Request MoDOT to provide load rating vehicle details.
- Review NCHRP reports 454 [9] and 406 [10] on system and condition factors to know when it is appropriate to use these factors. System factors are factors used to reflect the redundancy level of the bridge structure while condition factors are applied to take care of various bridge uncertainties depending on the inspection information.
- Request MoDOT to provide its current factors, formulas, and policies in use for load posting needs on bridges including those used for various types of vehicles.

- Request information on MoDOT's current super loads and routine overweight permit loads and also check the envelop process.
- Request that MoDOT provides bridge samples for this study. About 100 prestressed, steel, and concrete bridges, and 35 culvert models have been provided.
- Procure AASHTOWare BrR v7.1 software licenses, learn how to create and run different types of bridge models with it,
- Research load posting and load rating policies of other states. Table A.1 in the Appendix gives details of some of the load rating and load posting polices of various states.

Chapter 2: Introduction to Bridge Rating

Bridge load rating is used to evaluate the ability of different structural members of a bridge to carry a given live load. Bridges are rated to determine their safe loading capacities. Bridge owners use ratings to determine load posting needs and if strengthening or replacement of the bridge is needed. The MBE bases ratings on the current structural conditions, existing traffic conditions, material properties used for bridge construction, and loads. According to MBE Section 6; C6.1.1, the load rating of a bridge should not be undertaken without recent field inspections, which:

- Provide the condition data and other critical non-condition data necessary for evaluation.
- Minimize the possibility of the evaluator making gross errors in accessing the component or connection.
- Improve bridge safety through early discovery of deterioration or signs of distress that could signal impeding failure.

2.1 Load Rating Methodologies

The MBE lists three methods to perform load ratings on bridges, which include:

- Allowable Stress Rating (ASR)
- Load Factor Rating (LFR)
- Load and Resistance Factor Rating (LRFR)

A brief description of each of these methods follows.

2.1.1 Allowable Stress Rating (ASR)

Allowable stress rating has existed since the load rating of bridges started. This method has been used to perform load ratings on older bridges in Missouri and is still used for masonry and timber structures.

2.1.2 Load Factor Rating (LFR)

Load factor rating has been in use since the late 1980's. Factored dead loads, factored live loads, and the factored capacity of the member are used in this type of rating method. AASHTO defines two rating levels for LFR. The inventory level represents the routine live load where stress levels from the loadings are kept within the design limits. The operating level rates the bridge for the occasional live loads that cause higher stress and is commonly used to determine the maximum permissible live load. MBE provides the rating equations for ASR and LFR as shown in equation 2-1:

$$RF = \frac{C - A_1}{A_2 L(1 + I)} \qquad Equation\ 2-1$$

Where:

- RF = Live load rating factor
- C = Capacity of the member, based on the rating method. For ASR, calculations are typically done in terms of stresses. For LFR, calculations are done in terms of moments or shears.
- D = Dead load effect on the member. For ASR and serviceability checks in LFR, dead load stresses are calculated differently for composite versus non-composite loads.
- L = Live load effect on the member.
- I = Live load impact factor.
- A1 = Factor applied to dead loads. A1 = 1 for ASR and A1 = 1.3 for LFR.
- A2 = Factor applied to live loads. A2 = 1 for ASR. For LFR, A2 = 2.17 for the inventory level and A2 = 1.3 for the operating level.

States can determine the load posting levels for bridges rated with the above methods. Missouri uses a level between inventory and operating, while some states use one or the other. Missouri requires posting at 86% of the operating level when using LFR. If ASR is used, the posting level is 68% of the yield strength of the materials used in construction.

2.1.3 Load and Resistance Factor Rating (LRFR)

LRFR was developed to be consistent in philosophy with AASHTO's LFRD bridge design specifications in its use of reliability-based limit states. LRFR allows for a realistic and accurate approach to the safe load capacity of the bridge under a specific limit state. This method is somewhat similar to LFR in terms of how it uses factored loads and factored capacity to determine the rating factors. For LRFR, the rating factor is given by equation 2-2:

$$RF = \frac{C - \gamma_{DC}DC - \gamma_{DW}DW \pm \gamma_P P}{\gamma_{LL}(LL + IM)} \qquad Equation\ 2-2$$

Where:

- RF = Rating factor
- C = Capacity for limit state, given as

$C = \varphi_C \varphi_S \varphi R_n$ for the strength limit states.

$\varphi_C \varphi_S \geq 0.85$ lower limit on combined factors

- C = f_r for service limit states
- f_r = Allowable stress per LRFD code

- R_n = Nominal capacity of member
- DC = Dead load due to structural components and attachments
- DW = Dead load due to wearing surface and utilities
- P = Permanent loads other than dead loads
- LL = Live load effect
- IM = Dynamic load allowance (Impact)
- γ_{DC} = Dead load factor for structural components and attachments
- γ_{DW} = Dead load factor for wearing surface (ACP/HMA) and utilities.
- γ_P = Load factor for permanent load
- γ_{LL} = Live load factor
- φ_C= Condition factor
- φ_S= System factor
- φ= Resistance factor

Design load rating, legal load rating, and permit load rating are all performed on bridges with LRFR. Currently, MoDOT does not use LRFR in determining the need for posting loads on bridges, and therefore this research will help transition to this method. Since this research compares the existing method of LFR being used to rate bridges in Missouri and the new LRFR method, it is important to differentiate between them. Some of the ways they differ are explained below.

2.2 Comparative Study of the LFR and LRFR Methodologies

2.2.1 Dead Load Effect

A distinct feature in the LRFR and LFR rating equation is the dead load effect. LRFR methodology, based on the AASHTO LRFD Bridge Specification Manual, separates the dead load into structural components/attachments and the wearing surface. Under each circumstance, the dead loads are categorized into long-term composite acting on the structure and the non-composite elements. This allows for unique and accurate load factors to be applied to each category based on their variable statistics. For LFR, the load factor, γ_{DL}=1.3 for all the dead loads [2]. With LRFR, the dead load factor for structural components and attachments is γ_{DC}=1.25, and for wearing surface and utilities, $\gamma_{DW} = 1.5$ unless the in-place thickness can be verified by field measurement, then γ_{Dw} can be taken as 1.25.

2.2.2 Live Load Effect

The live load factors for the two methods are also different. The γ_{LL} factor in LFR is fixed at 2.17 for inventory rating and 1.3 for operating rating for all traffic conditions and vehicle loadings. In LRFR, however, the live load factor varies with vehicular loading, bridge average daily truck traffic (ADTT), and rating level. Distribution factors for each member are approximate numerical values that account for how live load effects are distributed to each member.

Specifically, the distribution factor represents how a vehicle's effect on the bridge is passed through the deck and distributed to each girder. LFR uses the live load distribution factor from the AASHTO specifications using a simplistic girder spacing approach. LRFR uses the distribution factor from equations found in AASHTO's LRFD manual, which are more detailed under varied girder spacing and material because additional effects in transverse load distribution, such as deck stiffness are considered [11]. The distribution factor for live load with LRFD is more complicated than AASHTO specifications but is designed to be more inclusive and accurate.

2.2.3 Nominal Capacity Difference

Capacity differences between LFR and LRFR are affected by the differences between the design codes in calculating the capacities and also the system and condition factors being applied to LRFR. These factors are described below.

2.2.3.1 System Factor

The MBE recognizes that a span's ultimate strength, rather than its component strength, should be the basis for load rating [11]. System redundancy was considered in fixing rating criteria for the AASHTO specifications [9, 12]. System factors are multipliers applied to the nominal resistance to reflect the level of redundancy of the complete superstructure system. The MBE defines bridge redundancy as the capacity of a bridge's structural system to carry loads after one or more of its members suffer damage or failure. The reason for including system factors in the ratings is that they help justify the reliability targets inherent in the AASHTO operating stress levels [9]. Table 2.1 gives system factor information for the various bridge types.

Table 2.1: System Factor: φ_s for Flexural and Axial Effects (MBE Table 6A.4.2.4-1)

Superstructure type	$\boldsymbol{\varphi_s}$
Welded Members in Two-Girder/Truss/Arch Bridges	0.85
Riveted Members in Two-Girder/Truss/Arch Bridges	0.90
Multiple Eye bar Members in Truss Bridges	0.90
Three Girder Bridges with Girder Spacing 6 ft	0.85
Four Girder Bridges with Girder Spacing ≤ 4 ft	0.95
All other Girders Bridges and Slab bridges	1.00
Floor beams with spacing > 12 ft and noncontinuous stringers	0.85
Redundant Stringer Subsystems between Floor beams	1.00

System factors, as shown in Table 2.1, are used to maintain an adequate level of system safety. Nonredundant bridges are required to have members with higher safety levels than those of similar bridges with redundant configurations. If an engineer can demonstrate the presence of adequate redundancy in a superstructure system, then the system factor may be taken as 1.0, $\varphi_s = 1.0$. In some instances, the value of redundancy may be sufficient to use a value of $\varphi_s > 1.0$, but in no instance should $\varphi_s > 1.2$. Subsystems with redundant members should not be penalized if the overall system is redundant. For narrow bridges (e.g., 1-lane bridges) with closely spaced three- and four-girder systems, all the girders are almost equally loaded, and there is no reserve strength available. Therefore, φ_s decreases to 0.85. System factors are not appropriate for shear since such failures are brittle. $\varphi_s = 1.0$ is assigned for evaluation. Table 2.1 denotes system factors for common simple-span and continuous bridges. Both MBE and NCHRP report 454 [9] recommend the use of NCHRP report 406 [10] to examine redundancy more carefully because it considers the details of the member and span geometry.

2.2.3.2 Condition Factor $\boldsymbol{\varphi_c}$

According to *MBE section 6A.4.2.3*, the use of condition factors might be considered optional depending on an agency's load rating practice. Condition factors account for uncertainty in the resistance of deteriorated members and the likelihood of future deterioration of these members between the inspection cycles. Deteriorated members are prone to future deterioration when compared to intact members and might warrant the use of condition factors. Improved inspection and field measurements will reduce uncertainties inherent in identifying the true extent of deterioration for calculating the nominal member resistance. MBE incorporates a condition factor based on member conditions during an inspection. The value φ_c decreases with the increasing member deterioration. Member deterioration reduces a component's legal load rating [9]. When using LRFR, the MBE calls for the following condition factors depending on the structural condition of the member. If element-level condition data is not collected, NBI Ratings for the superstructure can be used to set φ_c (condition factor), as shown in Table 2.2.

Table 2.2: Condition Factors per MBE Table C6A.4.2.3-1

Condition Factor φ_c	NBI Rating	Equivalent Member Structural Condition
1.00	Rating 6 or higher	Good / Satisfactory
0.95	Rating 5	Fair
0.85	Rating 4	Poor

Chapter 3: Literature and Methodology Review

The results of a detailed literature search for work done in this area are presented here. Hearn [13] performed an extensive study of load posting methods and practices, and several aspects are relevant to this report. In most cases, posting is required if the load capacity is less than legal loads. The NBI, which has information on structure type, condition, year built, structure owner, route, average daily traffic, load rating values, rating methods, and load posting status, indicates that about 10% of bridges post load capacities (about 61,000 out of 610,000 bridges). USDOT policy requires states to use LRFR for structures designed or replaced after October 2010 to report load ratings. For other structures, load ratings may be reported using LRFR or LFR. Weight limits for load-posted structures may be set at operating ratings, inventory ratings, or intermediate levels, and the AASHTO MBE provides a load-posting equation for use with LRFR that yields intermediate levels proportional to a structure's rating factor. Twenty-two survey states post bridges at the operating rating, and 12 states use intermediate levels between inventory and operating ratings. Intermediate levels are viewed as dependent on structure conditions and load path redundancy. Five states post at the inventory rating, and four use AASHTO's posting equation. Specifically,

1. Delaware posts at four levels in the range of the inventory rating to the operating rating. Structures in poor condition are posted at the inventory rating, while structures in good condition with load path redundancy are posted at the operating level. Other factors that affect posting levels are detour length, annual average daily truck traffic (AADTT), and enforcement of weight limits.

2. Massachusetts posts at inventory rating. However, no posting is done if a bridge has an inventory rating over 5% below the weights of Massachusetts posting trucks.

3. Missouri posts for load at the operating rating and intermediate levels. The posting level depends on the load rating method, fatigue vulnerability, and bridge location.

4. Montana uses inventory ratings and posts bridges with an operating rating of less than 40 tons for an AASHTO Type 3-3 vehicle.

5. New York posts at the operating rating for bridges in good condition that are load path redundant. Bridges are posted below the operating rating if primary members are in poor condition or bridges are not load path redundant. It also excludes permit loads on bridges with a primary member with a condition rating below 4 or structural decks with a condition rating below 2. In New York's condition rating scale, ratings below 4 indicate extensive, serious deterioration.

6. Oklahoma posts its bridges in its system when operating ratings are below 23 tons for an AASHTO H truck, below 36 tons for an AASHTO HS truck, or below 45 tons for an AASHTO Type 3-3 combination vehicle.

7. Texas' level for posting depends on structure conditions, load path redundancy, and traffic volume. Texas publishes guidance for posting levels for structures on the state system and not on the state system.

8. Virginia posts concrete bridges at operating rating and steel bridges at the average of inventory rating and operating rating.

3.1 Condition Ratings

Load ratings and load postings are based on the existing conditions of structures. Deterioration in components can reduce their load capacity and must be recognized in the evaluation of load posting. For LRFR, AASHTO provides a condition factor as one way to include the deterioration of bridges in load rating computations. Forty-one survey states use field-measured dimensions to evaluate the remaining sections of a structure's components. Fifteen states use material tests to obtain material strengths. Eighteen states use the AASHTO condition factor. Specifically,

1. Florida prefers to use field measurements of deterioration in components but allows the use of the condition factor if measurements are not available.
2. Kansas uses the health index of superstructure elements as a condition factor. If the load rating computation indicates a need for posting, explicit evaluations with field measurements are made.
3. Massachusetts requires field measurements to quantify deterioration and applies field material sampling and testing if material properties are unknown.
4. Maryland includes section losses in load ratings when losses are significant.
5. Michigan includes section losses when losses are greater than 25% of the original values of a section's properties.
6. Nebraska uses field measurements for structures with low NBI general condition ratings (GCRs).
7. Nevada uses reduced material properties in load computations for components with deterioration and applies field measurements to define section properties of the components.
8. New Mexico requires field measurements of components for the load rating of deficient structures.
9. New York recognizes deterioration by a reduction to a structure's operating rating.
10. Oregon uses field measurements for deteriorated sections and a condition factor.
11. Tennessee reduces section properties and material stress limits for known deterioration.
12. Virginia defines its condition factor and relates it to NBI GCRs [25].
13. Washington uses field measurements of remaining sections when available.
14. Wisconsin uses field measurements of sections and makes further reductions to capacity if deterioration includes features that could be stress concentrations.

3.2 Research Related to Load Posting

Structures are posted for load when their safe load capacity is not adequate for legal loads or routine overweight permit loads. Most survey states use operating-level load ratings to set weight limits for load-posted structures. Table 3.1 shows the methods and load-rating vehicles, Table 3.2 lists the load-rating vehicles, and Table 3.3 contains the level of rating used by some of the states that neighbor Missouri. The data in these tables summarizes responses collected in 2021 for this project.

Table 3.1: Basis for Load Rating

State	ASR	LFR	LRFR
Illinois		Y	Y
Indiana		Y	
Iowa	Y	Y	Y
Kansas		Y	
Kentucky	Y	Y	Y
Nebraska	Y	Y	
Oklahoma	Y	Y	Y
Tennessee	Y	Y	Y
Texas	Y	Y	

Table 3.2: Load Rating Vehicles

	AASHTO Vehicle			State	
State	HS20	Type 3, 3S2, 3-3	SU4, SU5, SU6, SU7	Legal Loads	Permit Load
Illinois				Y	
Indiana	Y				
Iowa		Y		Y	
Kansas	Y	Y			
Kentucky	Y			Y	
Nebraska	Y				
Oklahoma	Y	Y		Y	
Tennessee	Y	Y		Y	
Texas	Y			Y	Y

Table 3.3: Level for Load Posting

State	Inventory Rating	Operating Rating	LRFR Posting Equation	Intermediate Level
Illinois		Y		
Indiana	Y			
Iowa		Y		
Kansas				Y
Kentucky				Y
Nebraska		Y		
Oklahoma		Y	Y	
Tennessee	Y			
Texas	Y	Y		

Murdock [11] performed a study for the Alabama Department of Transportation (ALDOT) comparing the use of LFR and LRFR on a representative sample of 95 bridges. LRFR design, legal, and permitting ratings were considered. AASHTO design and legal vehicles and Alabama legal vehicles were included, along with a sample of overweight loads. The study used AASHTOWare Virtis and BRASS Engine, and interior and exterior girders were examined for moment and shear effects. Conclusions included the following:

1. Design level rating
   a. LRFR produced lower moment and shear ratings in exterior and interior girders.
   b. Flexural ratings controlled over shear ratings in LFR.
   c. Moment ratings in exterior girders tend to control over those of interior girders in LRFR.
   d. Prestressed bridges tend to have the highest LRFR/LFR ratio compared with other material types.
2. Legal load rating
   a. ALDOT legal loads were not enveloped by AASHTO legal loads or the HL-93 model.
   b. No dominant girder effect was noticed in LFR. However, exterior girders seem to control more than interior girders in LRFR.
   c. Moment load effects generally produced lower ratings in LRFR than in LFR, while shear load effects were equal or lower in LRFR.
   d. Variations in live load factors and the system and condition factors tend to lower the ratings in LRFR.
   e. Load posting values using LRFR were found to be significantly lower than the values under LFR.
   f. The number of bridges required to be load posted was much larger for LRFR compared to LFR.
3. Permit load rating
   a. A slightly greater number of bridges were considered for permitting in LFR than LRFR.
   b. LRFR tends to produce equal or lower moment rating factors than LFR.
   c. Exterior girders tend to control over interior girders for moment loads under LRFR.
4. Dead load, capacity, and live load effect ratios
   a. Moment capacities and dead load effects for reinforced concrete bridges were similar in both rating methods. Prestressed concrete simple and continuously supported bridges tended to have a capacity ratio (LRFR/LFR) of 1.1, and steel continuously supported bridges had a ratio of 1.3.

b. Variations in moment rating factors can be attributed to the live load factor, the live load distribution factor, and the impact factor.

c. Shear capacities were similar for steel bridges.

d. Shear capacities of reinforced concrete and prestressed concrete bridges showed significant variations.

3.3 NCHRP Report 700

A detailed study was conducted with NCHRP Report 700 to analyze 1,500 different types of bridges using AASHTOWare Virtis®. The objective was to compare LFR and LRFR for both moment and shear. Vehicle types considered were design vehicles, three AASHTO legal loads, and eight additional permit/legal vehicles. AASHTOWare Virtis® software (version 6.1.0) was used in combination with the Wyoming Department of Transportation's bridge analysis and structural rating system BRASS-GIRDER, working with both LFR and LRFR. Results were analyzed using the methods outlined in NCHRP Project 12-50 to provide recommendations and proposals for changes to the AASHTO MBE. The bridge types analyzed included simple span and continuous span structures made of steel (rolled beam, built-up beam, plate girder), reinforced concrete slab, and T-beam and prestressed concrete (I-Beam, Box Beam) materials. The findings were as follows:

1. The number of girders that passed the LFR (>1.0) but not the LRFR was significant. Results varied for different types of girders, and several influences were noted, including:
   a. Shear rating of concrete components
   b. Checking for Service III limit state
   c. Rating bearing stiffeners in steel bridges
   d. Checking interface shear between girders and cast-in-place decks
   e. The effect of shear on the stress in longitudinal reinforcement at the ends of concrete girders
2. If the additional design criteria used in LRFR were ignored, then the number of bridges not passing LRFR was reduced. It was proposed that some of these criteria be ignored unless there are visible signs of distress in the bridge, and it was also suggested that checking the service limit states be optional.
3. Changing the live load factors for legal loads to correspond to the target reliability index also resulted in a reduction in the number of bridges not passing LRFR. Based on the study, a target reliability index of 2.5 instead of 3.5 was proposed for legal loads.

3.4 Survey of Neighboring States

Engineers from the transportation departments of neighboring states were contacted for information regarding several questions, and they provided the following responses.

1. What methodology is currently being used to load rate bridges? Do you use LRFR or LFR, or ASR in some cases?
   a. **Arkansas:** All bridges designed after October 2010 are rated using LRFR. The balance is rated using LFR, with the exception of timber bridges, which are rated with ASR. As time allows, all bridges are being transitioned to LRFR.
   b. **Kansas:** LRFR and LFR are used for bridges built in 2010 and beyond. Any bridge before 2010 is evaluated at LFR, while a small number of timber bridges use ASD/ASR.
   c. **Illinois:** All new structures are rated in LRFR, while most existing structures are rated in LFR. A small number of structures are rated with ASR, but any rating updates on these would be in LFR. There is also a rational method of evaluation used for concrete structures without plans that is based on the physical condition of the structure and corresponding assigned rating factors.
   d. **Iowa:** LRFR is used for new bridges and LFR for existing bridges.
   e. **Tennessee:** LRFR is used as the primary rating method. ASR is used for timber elements. LFR is used on metal pipes.
2. Is there website literature that is publicly available for viewing?
   a. **Arkansas:** None at this time.
   b. **Kansas:** All public information is available at: https://kart.ksdot.org/
   c. **Illinois:** The following link includes several resources related to load ratings: http://www.idot.illinois.gov/doing-business/procurements/engineering-architectural-professional-services/Consultants-Resources/bridge-load-ratings.
   d. **Iowa:** The Iowa Bridge Rating Manual can be found at: https://iowadot.gov/siims/IowaDOT_BridgeRatingManual.pdf
   e. **Tennessee:** Information is listed under “Inventory and Appraisal” at tn.gov.
3. Has there been a study comparing LRFR and LFR where LRFR was adopted? If so, what were the findings with respect to reinforced concrete, prestressed concrete, and steel girder bridges?
   a. **Arkansas:** No study has been performed. Such a study was judged inconclusive and an inefficient use of time.
   b. **Kansas:** No official study has been done for adopting LRFR for structures that have been built before 2010.
   c. **Illinois:** No formal study of this nature has been performed.
   d. **Iowa:** No study has been performed.

e. **Tennessee:** The transportation department conducted a study with Tennessee Tech University. Prestressed concrete and steel bridges were included in the study. The results showed that when moving from LFR to LRFR, some ratings will decrease, and others will increase. It also showed that LRFR produced heavier moment loads for exterior beams.

4. Have there been any issues using bridge rating (BrR) software and what are the workarounds that were used, if any?

a. **Arkansas:** There are certainly limitations with BrR when looking at more complex structures. In some instances, workarounds were developed with BrR to get a reasonable rating. This includes the use of line girders and conservative assumptions regarding geometry, etc. Some structures simply cannot be modeled in BrR. In these cases, a combination of finite element method (FEM) analysis and post-processing (Excel, MathCAD, etc.) was used to get a load rating. The department is trying to develop a rating tool to go along with these ratings to facilitate future updates and overweight permit analysis. The most common type of tool is usually an Excel file with influence lines from the FEM results and macros to evaluate user-input fields along with these influence lines. Example structures that cannot be modeled in BrR include stay cables, arched trusses, tied arches, steel boxes, post-tensioned boxes, and spandrel arches.

b. **Kansas:** BrR has lots of quirks that have required in-house work arounds. The major one is curved girder structures. LRFR is used for this, and the LFR trucks are put into the inventory and operating categories rather than legal.

c. **Illinois:** The transportation department has a BrR license, but it is not the primary rating tool. The main program for rating is LARS, which is used because of the Illinois automated permitting system uses transfer files created by LARS.

d. **Iowa:** The transportation department has a BrR license, but it is not the primary rating tool.

e. **Tennessee:** AASHTO BrR has a learning curve when starting out, but it is a powerful load rating tool. The "Help Topic" provides a lot of insight. "Spec Check" is also useful if there are issues. We have resolved numerous issues on bridges with this feature.

5. Does the transportation department load rate bridges in-house or use consultants?

a. **Arkansas:** With rare exceptions, load ratings are done in-house.

b. **Kansas:** Most bridges are rated in-house, but, whether they are an in-house design or a consultant design, must be approved by the transportation department. Complex bridge models have been done by consultants in the past, but they still need approval.

c. **Illinois:** Consultants are used for most complex structures, especially when BrR cannot be used because there is not an existing rating tool. Many new structures are also initially rated by consultants with transportation department review. Then the rating of the structure is handled in-house in future instances, such as for deterioration or minor rehabilitation.

d. **Iowa:** All non-complex bridges are rated in-house. Unique and complex bridges are rated by consultants because a staff of only two engineers does not have the time to analyze complex bridges.

e. **Tennessee:** Until 2019, the transportation department performed 99% of load rating in-house. However, due to the Fast Act initiative and other FHWA programs, consultants are now used.

6. Based on the rating, what are load posting policies for bridges examined using LFR and LRFR?

   a. **Illinois:** Section 4.4.5 of the transportation department's structural services manual is available online. Load postings are required when the operating rating factor falls below 1.0 for any of the state's legal posting vehicles. Illinois also performs ratings on a set of routine permit vehicles. If any of these operating rating factors fall below 1.0, the structure is limited to legal loads only. This policy applies for both LFR and LRFR ratings.

3.5 Information from Other States

Minnesota: Most new or updated load ratings are computed using LRFR, as LFR and ASR are mostly historical but are still used in certain situations. For existing bridges that must be reevaluated for a new legal or exclusion vehicle that has been implemented through a policy change, the structure is rated using the method used during the most recent evaluation.

Use LRFR as follows:

- All new structures.
- Any structure originally designed using LRFD.
- Most major preservation or bridge rehabilitation projects.

Use LFR as follows:

- With overweight permit load evaluations of most existing structures (the only exception is for structures that require ASR)
- Any structures originally designed using LFR that require re-evaluation of a bridge component due to condition change or collision damage/impact.

Delaware, Louisiana, and Maine use only LRFR for their bridges. A brief questionnaire was sent to officials of these states and their responses are noted below.

Q1. How was LFR phased out, and what type of changes were made to implement LRFR?

Q2. How many bridges did not meet posting policy after using LRFR – especially when using the MBE equation?

Delaware: Responses from Delaware are as follows.

- Re-rating of all bridges with LRFR began in 2008/2009. Prior to then, most bridges were load-rated using LFR. Re-rating started with interstate bridges and advanced based mostly on the hierarchy of roadway with local bridges being completed last. To date, about 96% of NBI-length bridges are complete and the remaining should be done over the next year.
- There were no adjustments to posting policies that needed to be made because the AASHTO MBE is used for this.
- For the most part, the number of posting restrictions for bridges analyzed with LRFR compared to those that were previously load posted using LFR were in the same ballpark (within 10-15%). There were a few bridges that required load posting using LRFR that didn't with LFR. Load posting restrictions were able to be removed for about 6-10 bridges using LRFR that were originally posted using LFR per ASD.

Louisiana: Responses from Louisiana are as follows.

- Louisiana implemented LRFR in 2009. The only exception to the LRFR method is when rating timber bridges, which can use the allowable stress method. The posting policy remains the same, with some adjustments due to the greater number of legal trucks in LRFR.
- There are no posting change statistics that indicate that LRFR implementation had a large impact. The first few years of LRFR use focused mainly on bridges that had never been rated, or on bridges that had conditions that dropped from poor to worse. There were some new postings due to the LRFD code changes, such as those for continuous stringers and exterior slab strips. Louisiana developed its research and used advanced methods (finite element or load testing) to resolve these issues.
- Louisiana uses the MBE equations for posting legal loads. If the bridge needs to be closed for all legal loads, we use the bridge capacity directly for passenger car posting.

Indiana: Responses from Indiana are as follows.

- Indiana has been moving towards LRFR for the past five years. At this time, more than 77% of 6,300-plus bridges have been inspected using LRFR. The remaining have been analyzed using either LFR (12%), ASR (<1%), or engineering judgment (8%).
- Indiana's posting policy is similar regardless of which method has been used and is described in Part 3 of Indiana's Bridge Inspection Manual which is available for review at: https://www.in.gov/dot/div/contracts/standards/bridge_inspection/inspector_manual/index.htm

Maine: Responses from Maine are as follows:

- The Maine Transportation Department has load-rated all the bridges in its inventory using LRFR except an extraordinary bridge or two.
- Load posting procedures and policies were provided.

Colorado: Responses from Colorado are as follows:

- Colorado uses ASR, LFR, and LRFR, and the rating method uses BrR and follows guidelines suggested by MBE.
  - All bridges designed with LRFR or designed after Sept. 30, 2010, are rated using the LRFR method.
  - All existing ASD and LFD bridges, except timber bridges, are rated with LFR or LRFR.
  - Timber bridges are rated using ASR.
- There are no different load posting policies for ASR, LFR, and LRFR. Legal loads include the three AASHTO legal loads, AASHTO single-unit trucks, and the two emergency vehicles.
- Based on the historical success of transportation department practice, a safe posting load as specified in the MBE equation 6A.8.3-1 should not be used.
- The posting load for legal vehicles is based on the lowest load rating in truncated US tons of any primary members such as girders, in-span hinges, stringers, trusses, floor beams, truss connections, etc.

Tennessee: Responses from Tennessee are as follows:

- LRFR is used as the primary rating methodology, ASR is used for timber elements, and LFR is used on metal pipes.
- Generally, when moving from LFR to LRFR, some ratings decreased and others increased. Results also showed that LRFR produced heavier moment loads for exterior girders.

South Dakota: Responses from South Dakota are as follows:

- For the live load vehicles defined in the transportation department's load-rating manual, LRFR is required for all new and reconstructed bridges as well as for all rehabilitation and repair designs involving a substantial structural alteration. Currently, BrR doesn't support LRFR for timber, so allowable stress rating is permissible for new timber structures.

- LRFR is encouraged for existing bridges, but ratings for some structures might be undesirable. Bridges built before 2010 that didn't use LRFD may still use LFR. Allowable stress rating is only permissible on timber or masonry structures.
- The transportation department requires the load rating of each bridge to determine its safe loading capacity by the MBE and the department's load-rating manual. When unrestricted legal loads exceed that allowed under the operating or legal rating levels the bridge is posted by the MBE, the load rating manual, or by state law. If a bridge is not capable of carrying statutory loads, it is posted for a reduced load limit. The decision to load-post a bridge is made by the bridge owner based on an agency's load-posting practices. The guidelines are provided to assist the department and local bridge owners in establishing posting weight limits. Bridges that are determined not capable of carrying 3 tons are closed.
- If any of the special hauling vehicles, three type 3 trucks, or emergency vehicles have rating factors below 1 for a given bridge, it will be posted. However, postings are limited for emergency vehicles to bridges within a mile of interstate access.

Chapter 4: Load Rating Procedures using LRFR

Load rating determines the safe live load capacity of a bridge. Load rating calculations establish a rating factor (RF) and a safe live load capacity in tons for a specific vehicle. The main types of ratings are a) inventory rating (IR) and b) operating rating (OR). Axial force, bending moment, shear, and any interaction capacities are also considered in rating the bridge using strength criteria, and the bridge is checked for serviceability considerations. In the LRFR method of rating, the inventory rating is calibrated to a reliability index of $\beta=3.5$, while the operating rating is calibrated to $\beta=2.5$. This reliability-based approach, consistent with LRFD, is used to provide uniform reliability.

LFR and LRFR require the collection of different sets of data. For LRFR, data includes a) actual wearing surface thickness, b) weights of non-structural attachments and utilities, c) depth of fill (for culverts), d) number and position of traffic lanes and e) surface conditions of the roadway. Traffic data collected includes a) ADTT and b) posted load limit. The load rating process in LRFR methodology starts with the design load rating using AASHTO's 1993 highway live loading design (HL93), followed by the legal load ratings and then the permit load ratings. Figure 4.1 shows a flow chart of the load rating process using the LRFR method.

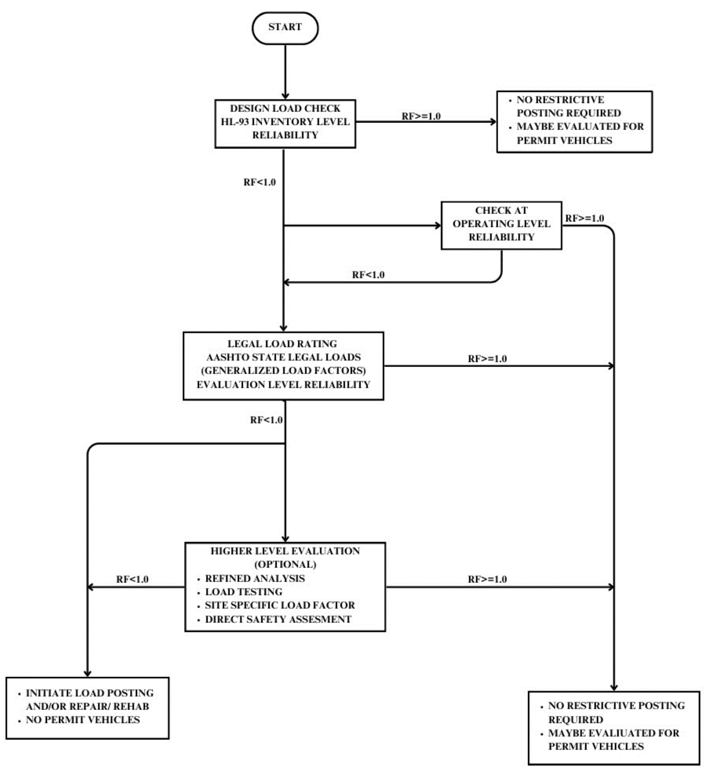


Figure 4.1: Flow Chart Showing the LRFR Load Rating Process

4.1 Design Load Rating

It is important to note that HL-93 is a notional load and hence is not used for load posting purposes. An RF < 1.0 for design loads is typical for load rating using AASHTO and/or state legal loads and permit vehicles and their requirements for posting. The RF of a design loads is reported to the NBI.

4.2 Legal Load Rating

If the RF < 1.0 for HL-93 loads with a β=3.5, the bridge is rated for AASHTO and/or state legal loads at a reliability index of β=2.5. This procedure is different from the LFR process of inventory and operating rating. Load rating is typically performed for each of the legal loads (AASHTO Type 3, Type 3-3, and Type 3S2 and special haul vehicles and other state legal loads). Load posting is determined by the load posting policies of each state if the RF for legal loads is < 1.0.

4.3 Load Rating Equation for Strength Loading

The LRFR strength limit general load rating equation is given as equation 3-1

$$RF = \frac{C-\gamma_{DC}DC-\gamma_{DW}DW \pm \gamma_P P}{\gamma_L L(1+IM)} \qquad \text{equation 3-1}$$

Where:

- RF is the rating factor.
- $C=\emptyset_c \emptyset_s \emptyset R$ is the member capacity.
- γ_{DC} is LRFD load factors for structural components and attachments = 1.25.
- γ_{DW} is LRFD load factor for wearing surfaces and utilities.
- γ_P is LRFD load factor for permanent loads other than dead loads respectively.
- $\emptyset_c$ is the condition factor.
- $\emptyset_s$ is system factor.
- $\emptyset$ is LRFD resistance factor.
- R is the member resistance.
- DC is the dead load effect due to structural components and attachments.
- DW is the dead load effect due to wearing surface and utilities.
- L is the live load effect.
- IM is the dynamic load allowance.

DC represents the dead load effect due to structural components $\gamma_{DC} = 1.25$, DW is the dead load effect due to wearing surface and utilities $\gamma_{DC} = 1.50$, and $\gamma_{DW} = 1.25$ when overlay thickness is measured, γ_L is the live load factor and has a value of 1.75 for inventory level rating (for HL-93 for states that allow exclusion loads), and 1.35 for operating level ratings (for states that comply with the federal weight laws including formula B). In addition, for legal loads, the live load factor varies from 1.4 to 1.8 for ADTT ranging from 100 to 5000. Table 4.1 gives the live load factors in detail.

Table 4.1: Live Load Factor for Various Rating Levels

Rating loads and level	Live Load Factor
Inventory level – HL93 for states that allow exclusion loads	1.75
Operating Level – HL93 for states that comply with federal weight laws including formula B weight restrictions	1.35

Legal loads	Live Load Factor
Unknown	1.45
ADTT > 5000	1.45
ADTT < 1000	1.3

4.4 System Factor $\varnothing_s$

System factors reflect the level of redundancy of the complete superstructure system and are used to maintain an adequate level of system safety and to raise the system reliability from an operating level to an inventory level. It is important to note that system factors are not appropriate for brittle shear failures and are relevant in ductile systems. Table 4.2 gives the system factors as shown in the MBE.

Table 4.2: System Factor for Various Types of Redundancies from MBE Table 6A.4.2.4-1

Superstructure Type	φ_s
Welded Members in Two-Girder/Truss/Arch Bridges	0.85
Riveted Members in Two-Girder/Truss/Arch Bridges	0.90
Multiple Eye Bar Members in Truss Bridges	0.90
Three Girder Bridges with Girder Spacing at 6 ft	0.85
Four-Girder Bridges with Girder Spacing ≤ 4 ft	0.95
All other Girders Bridges and Slab Bridges	1.00
Floor Beams with Spacing > 12 ft and Noncontinuous Stringers	0.85
Redundant Stringer Subsystems between Floor Beams	1.00

4.5 Condition Factor $\varnothing_c$

Condition factors account for capacity reductions in members that have deteriorated enough to cause uncertainty and variability in resistance. The reduction factors account for increases in the reliability index from 2.5 to 3.5. It is preferred to have element-level condition data to determine the condition factor. Condition factors per MBE are shown in Table 4.3

Table 4.3: Condition Factors per MBE Table 6A.4.2.3-1

Structural Condition of the Member	NBI Rating Equivalent	φ_c
Good or Satisfactory	≥ 6	1.00
Fair	5	0.95
Poor	4	0.85

4.6 Dynamic Allowance

Standard impact factor (IM) is applied with all load models. However, it is applied to HL-93 design truck and not to the design lane load. Table 4.4 shows the impact factor per the MBE.

Table 4.4: Impact Factors per MBE Table 6A.

Component	Impact Factor
All Components – Fatigue and Fracture Limit States	15 %
All Components – Other Limit States	33%

Optional IM Values	Impact Factor
Smooth Riding Surface	10 %
Minor Surface Irregularities	20 %
Major Surface Irregularities	33%
Permits (slow-moving vehicles)	0 %

4.7 Serviceability Rating

The serviceability rating equation is like the strength rating equation except that the member capacity C is the resistance in terms of the stress as given in the LRFD specifications. System factors are multipliers used to reflect the level of redundancy with non-redundant systems having their capacities reduced resulting in lower rating factors.

4.8 Load Posting per MBE

When determining the design live load of HL-93, if the strength check value of RF is > 1.0, no action is required. However, if the RF is < 1.0, a check for the operating level rating is performed, and the load rating is posted. When 0.3 < RF < 1.0, the posting load is given as (W /0.7) [(RF) - 0.3], where W is the weight of the rating vehicle and RF = legal load rating factor. If the rating factor is < 0.3, the bridge should be closed. The LRFR incorporates the flexibility to allow different state transportation departments to use live load factors depending on state-specific vehicle configurations or other considerations.

4.9 MoDOT Existing Bridge Rating Practice

Statewide legal loads, commercial zone legal loads, and Fixing America's Transportation Act (FAST Act) emergency vehicles all need to be considered for load posting bridges in Missouri per Section 15.11 of the BIRM. For the scope of this project and report, only statewide legal loads (H20 Legal Truck and MO3S2), and commercial zone legal loads, including commercial zone model single unit vehicles (CZSU) and commercial zone model combination configurations (CZRT), are considered. Details of the live loads are shown in Figure 4.2

4.10 MO Statewide Legal Vehicles

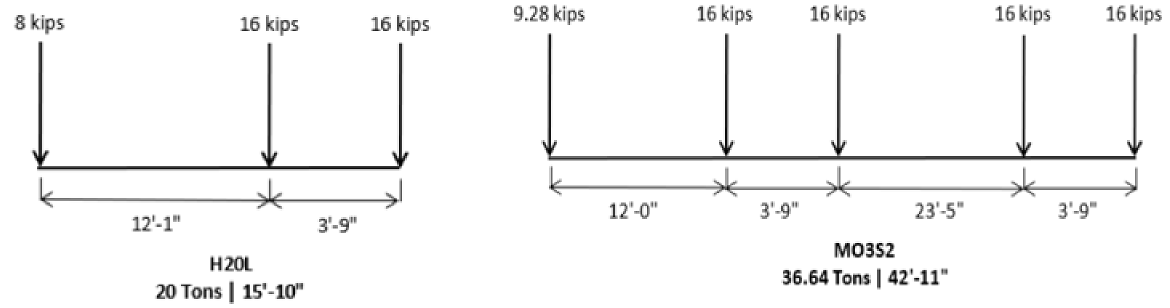


Figure 4.2: Missouri Legal Load Vehicles

Section 15.11.1 of the BIRM stipulates that two legal vehicles are analyzed for bridges across Missouri. The legal load model for single-unit vehicles is the H20 legal truck with a gross weight of 20 tons. Load posting for single-unit vehicles is required when the load capacity for the H20L vehicle is less than 30 tons. The legal load model for combination configurations is MO3S2. Load posting for combination configurations is required when the load capacity for the MO3S2 vehicle is less than 45 tons. Figure 4.2 shows the details of these two legal loads. Figures B.1 and B.2 in Appendix B show the schematic of the vehicles as represented in BrR 7.1.

4.11 Commercial Zone Single Unit (CZSU) Vehicles

St. Joseph, Kansas City, Columbia, St. Louis, and Springfield make up the commercial zones within Missouri according to BIRM section 15.11.2. Bridges that are located within commercial zone boundaries and have passed the regular screenings for load posting are also required to be evaluated for load posting based on commercial zone vehicle models. Posting for CZSU (shown in Figure 4.3) is required when the load capacity is less than 45 tons.

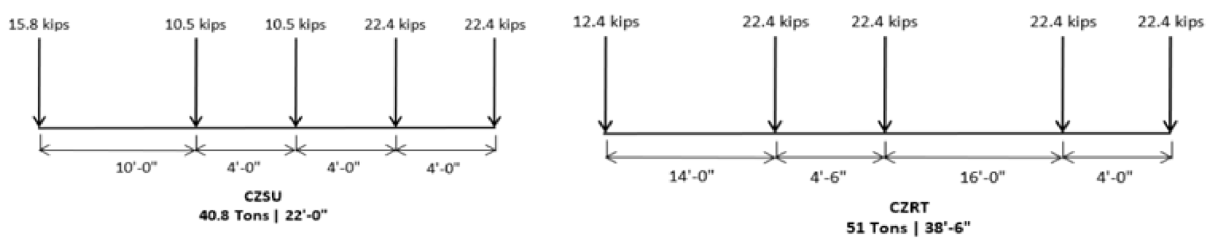


Figure 4.3: Missouri CZSU and CZRT Load Vehicles

Posting for CZRT with a gross weight (GWT) of 51 tons, (shown in Figure 4.3) is required when the load capacity is less than 70 tons. Currently, other vehicles such as emergency vehicles EV2 and EV3 and special permit vehicles MO5 and 4S3P are not considered for this project with MO5 expected to phase out in 2023. Figures B.3 and B.4 in Appendix B show the schematic of the vehicles as represented in BrR 7.1. In addition, this research used H20L, CZSU, and CZRT truck trains, and their representations in BrR 7.1 are shown in Figures B.5, B.6, and B.7 in Appendix B.

Missouri currently rates bridges using LFR and ASR, and per BIRM, Section 15.10.3.1, posting levels are determined by using 86% of the operating rating for LFR and by using 68% of the yield strength for member capacity calculations using ASR. Table 4.5 shows the details of MoDOT's load-posting vehicles and posting policy.

Table 4.5: Load Rating Levels and Posting Vehicles for MoDOT

Truck	Inventory	Operating	Posting
HS20	X	X	X
H20L	X	X	X
MO3S2	X	X	X
CZSU	X	X	X
CZRT	X	X	X
SU5	X	X	X
EV2		X	
EV3		X	
MO5		X	
4S3P		X	

4.12 AASHTO Legal and Special Haul Vehicles (SHV)

AASHTO designates legal load vehicles as Type 3, Type 3-S2, and Type 3-3. Special hauling vehicles are closely spaced, multi-axle single-unit trucks such as dump trucks, construction vehicles, solid waste trucks, and other hauling trucks. SHVs generally comply with Bridge Formula B and are for this reason considered legal in all states if a state's laws do not explicitly exclude the use of such vehicles.

NCHRP Project 12-63 (Report 575, 2007) studied various truck configurations and state legal loads and found that AASHTO legal load vehicles are not representative of all legal loads, specifically SHVs. As a result, legal load models for SHVs were developed and adopted by AASHTO in 2005. The SHV load models in the MBE include those for SU4, SU5, SU6, and SU7 multiple-axle SHVs, and there is also a notional rating load (NRL) model that envelops the four single unit load models and serves as a screening load. If the load rating factor for the NRL model is 1.0 or greater, then there is no need to rate for the single-unit loads. However, if the load rating factor for the NRL is less than 1.0, then the single-unit loads need to be considered during load rating and posting. Details of the AASHTO SHVs are described below.

4.12.1 AASHTO Legal Loads

The AASHTO legal load vehicles are sufficiently representative of routine average truck configurations in use today and are used as vehicle models for load rating. When a load rating shows that a bridge does not have sufficient capacity for any one of these standard legal vehicles, the bridge must be posted for load.

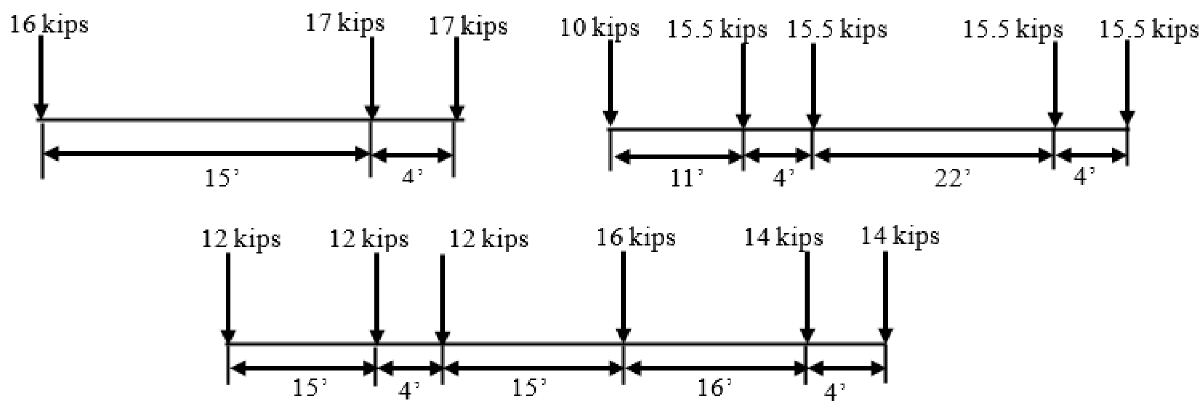


Figure 4.4: AASHTO Legal Loads Type 3 (top left), Type 3S2 (top right) and Type 3-3 (bottom)

The Type 3 legal vehicle is a three-axle single-unit vehicle with a GWT of 50,000 pounds (25 tons). The Type 3S2 legal vehicle is a five-axle semi-tractor and trailer combination with a GWT of 80,000 pounds (40 tons). The Type 3-3 legal vehicle is a six-axle combination of a single-unit vehicle pulling a loaded trailer with a GWT of 80,000 pounds (40 tons). Figure 4.4 shows the configuration of these three vehicles. Figures B.8, B.9, and B.10 in Appendix B show the schematic of the three AASHTO legal load vehicles as represented in BrR 7.1. Figures B.11, B.12, and B.13 in Appendix B show the truck train representation for Type 3, Type 3S2, and MO3S2 vehicles.

4.12.2 SU4, SU5, SU6 and SU7

SU4, which is a four-axle vehicle with a GWT of 54,000 pounds (27 tons), SU5 is a five-axle vehicle with a GWT of 62,000 pounds (31 tons), SU6 is a six-axle vehicle with a GWT of 69,500 pounds (34.75 tons) and SU7 is a seven-axle vehicle with a GWT of 77,500 pounds (38.75 tons). Figure 4.5 shows the details for each vehicle configuration.

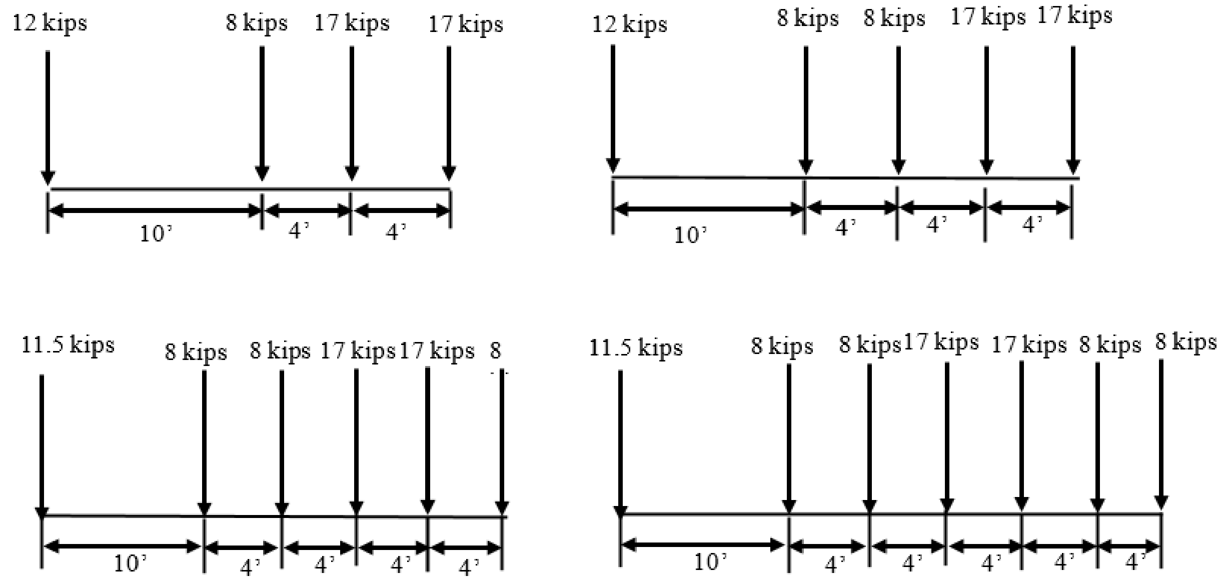


Figure 4.5: AASHTO Special Haul Vehicles SU4 (top left), SU5 (top right), SU6 (bottom left) and SU7 (bottom right)

4.13 MoDOT Bridge Data and Bridge Classifications

For this study, MoDOT produced data for 100 prestressed concrete (PS), 110 steel (ST), and 101 reinforced concrete (RC) bridges, specifically the .xml files that were used for rating the bridges using LFR. This section describes the various details and classifications related to this information.

4.13.1 Location

Commercial zones are urban areas in the state that have unique weight regulations. Commercial zones are defined in state law in Section 304.190 RSMo and include St. Joseph, Kansas City, Columbia, St. Louis, and Springfield. Table 4.6 shows the distribution of the bridges in commercial and non-commercial zones.

Table 4.6: Bridge Distribution by Commercial and Non-Commercial Zones

Area	PS Bridges	Steel Bridges	RC Bridges
Commercial Zone	41	21	2
Non–Commercial Zone	59	89	99

4.13.2 Year Built

Table 4.7 shows the type and number of bridges built since 1920.

Table 4.7: Bridge Distributions by Decade Built

Year Built	Steel	Concrete	Culverts	PS- Concrete	Total
1920-1929	2	25	1	0	28
1930-1939	4	23	7	2	36
1940-1949	8	15	1	0	24
1950-1959	18	22	10	1	51
1960-1969	55	15	9	2	81
1970-1979	10	2	3	5	20
1980-1989	4	0	3	13	20
1990-1999	3	0	0	10	13
2000-2009	5	0	1	43	49
2010-2019	1	5	0	29	35
TOTAL	110	107	35	105	357

4.13.3 Design Methodology

Table 4.8 shows how many bridges were built with each design method.

Table 4.8: Bridge Distributions by Design Method

Design Method	PS	Steel	Concrete
Allowable Stress Design – ASD	10	99	102
Load Factor Design – LFD	76	11	2
Load and Resistance Factor Design LRFD	14	0	3

4.13.4 Girder Structure and Continuity

Sample bridges are a mix of continuous spans and simply supported spans. The structures use a variety of girder types including stringer, tee beam, slab, and box beam (multiple/single). Table 4.9 shows several prestressed bridges with different types of continuity and girder structures.

Table 4.9: Prestressed Concrete Bridge Distributions by Continuity

Material Support	Stringer Multiple Beam/Girder	Box Beam/Girder Single	Box Beam/Girder Multiple	Tee Beam	Slab	Total
Simple	9	12	18	5	2	46
Continuous	42	0	0	12	0	54
Total	51	12	18	17	2	100

4.13.5 Number of Spans

Bridge superstructures can have one span (simple support) or more than one span (continuous). The number of spans in continuous superstructures can vary from two to 11 spans. Table 4.10 details the number of spans among different types of bridges.

Table 4.10: Bridge Distributions Based on Number of Spans

Span	Steel	Concrete	Culverts	PS-Concrete	Total
1 Span	7	15	1	24	47
2 Spans	6	3	27	13	49
3 Spans	56	64	7	43	170
4 Spans	26	14	0	13	53
5-10 Spans	15	11	0	10	36
>10 Spans	0	0	0	2	2
Total	110	107	35	105	357

4.13.6 Span Length

Superstructures with multiple spans often have a beginning span and end span equal in length. Table 4.11 shows the span length ranges of different bridges.

Table 4.11: Bridge Distributions Based on Longest Span Length

Length (Ft)	Steel	Concrete	Culverts	PS-Concrete	Total
0-30	0	4	24	0	28
31-50	2	9	11	1	23
51-80	5	19	0	4	28
81-120	11	37	0	22	70
120-200	35	28	0	39	102
201-350	36	10	0	32	78
351-999	13	0	0	7	20
>1000	8	0	0	0	8
Total	110	107	35	105	357

4.14 BrR Load Rating, Rating Levels

This project used BrR version 7.1. A template was created that used the same vehicles that MoDOT currently uses for LFR. The template was used for both LFR and LRFR as a baseline for the study. The vehicles and the rating levels are described in the following sections.

4.14.1 LFR Methodology

Sample bridges were rated with inventory rating and operating rating levels for nine different vehicle live load models including design load HS 20-44, statewide legal loads H20L and MO3S2, commercial zone vehicles CZSU and CZRT, permit vehicles SU5 and 4S3P, and emergency vehicles EV2 and EV3. Table 4.12 shows the rating vehicles and the rating levels currently used by MoDOT.

Table 4.12: LFR Live Load Vehicles and Rating Levels

Live Load	Inventory	Operating	Legal Operating
HS20	X	X	
H20L	X	X	
MO3S2	X	X	
CZSU	X	X	
CZRT	X	X	
SU5	X	X	
4S3P		X	
EV2			X
EV3			X

Table 4.13 shows the rating vehicles and levels used for AASHTO legal loads.

Table 4.13: SHV and AASHTO Vehicles

Live Load	Inventory	Operating
SU4		X
SU5		X
SU6		X
SU7		X
Type 3		X
Type 3S2		X
Type 3-3		X

4.14.2 LRFR Methodology

Design Load: Sample bridges were analyzed with design live load models HL 93 and HS 20-44 for both inventory and operating ratings.

Legal Load: This rating level is equivalent to the operating level, using statewide legal loads H20L and MO3S2, commercial zone vehicles CZSU and CZRT, emergency vehicles EV2 and EV3, permit vehicle 4S3P, special hauling vehicles SU4, SU5, SU6, and SU7, and AASHTO vehicles Type 3 legal load, Type 3S2, and Type 3-3.

Chapter 5: Results for Steel Bridges

The results from the analyses of steel bridges are presented in this chapter. The types of plots used in the presentation are:

- LRFR versus LFR plots
- MoDOT vehicle versus AASHTO vehicle plots for rating vehicle live loads
- MoDOT vehicle versus single unit vehicle plots for rating vehicle live loads

5.1 Comparisons of the LFR and LRFR Methods

The results from this analysis were used to compare the LFR being used by MoDOT to LRFR. Both the rating loads and rating factors from the two methods were contrasted. LRFR rating factors/loads are plotted on the y-axis, while the corresponding LFR factors/loads are plotted on the x-axis. The comparisons were done at the operating level for both LFR and LRFR. In Figure 5.1, if the plot point falls in region A, the ratings for LRFR are greater than for LFR. Conversely, if the plots fall in region B, LFR has higher ratings than LRFR.

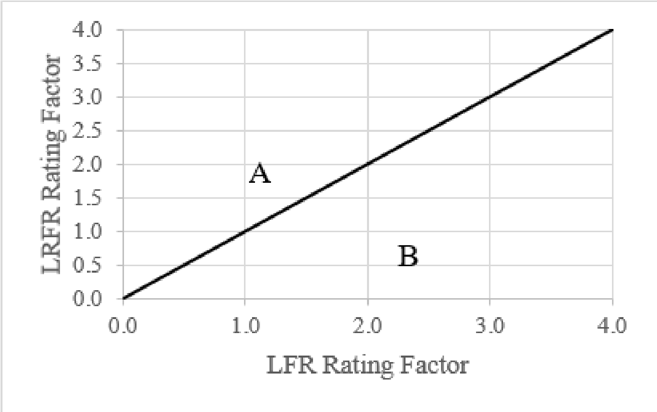


Figure 5.1: LFR vs LRFR Graph

5.2 MoDOT Verses AASHTO Vehicle Plots for Rating Loads

The study compared MoDOT vehicles H20L, MO3S2, CZSU, and CZRT to AASHTO legal load vehicles Type 3 legal truck, Type 3S2 legal truck, and Type 3-3 legal truck to determine the enveloping vehicles or factors that will help determine posting loads. Figure 5.2 shows that if the plots fall in region A above the 45-degree line, the rating loads for the AASHTO vehicles are greater than that of MoDOT vehicles. If the plots fall in region B, the rating loads of the MoDOT vehicles have a higher rating than that of the AASHTO vehicles. If the plots fall in region A above the 45-degree line, the rating loads for the MoDOT vehicles are less than that of the AASHTO vehicles, hence enveloping AASHTO vehicles. In case MoDOT vehicles do not envelop AASHTO vehicles then a factor is determined so that all the points are above the 45-degree line.

If this factor is obtained when enveloping, it is then recorded and compared with similar factors obtained from the comparisons of the MoDOT vehicles and the corresponding AASHTO single-unit vehicles. If a factor, less than 1.0, is used to shift the plots above the 45 degrees line, then the factor for that vehicle is noted. Comparisons are made with the factors of the AASHTO vehicles and the least factor of all the comparisons can be used as the posting load scaling factor. The steps to determine the LRFR threshold and the factor are described below.

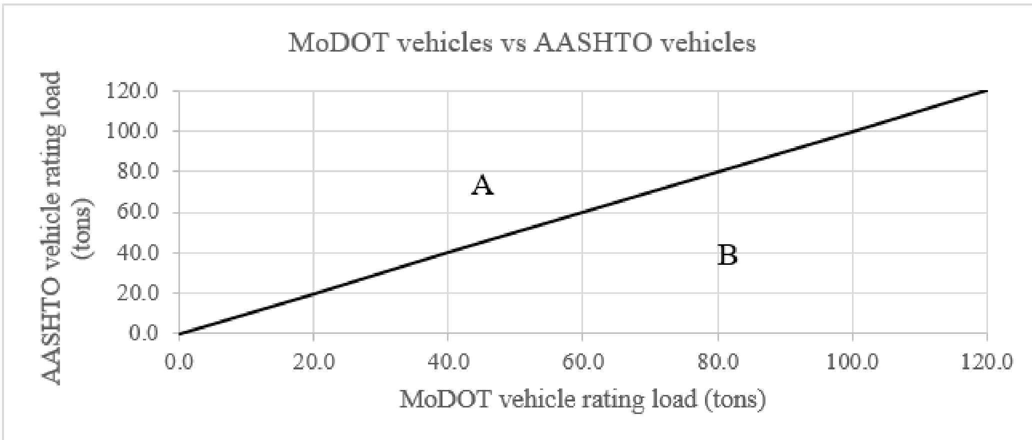


Figure 5.2: MoDOT vs. AASHTO Vehicle Rating Load Comparison Graph

Steps to determine the LRFR Threshold and Factor: This section describes the procedure for determining the LRFR threshold and then the LRFR factor that can be used like the 0.86 factor that the BIRM uses for LFR.

- Using BrR 7.1, the rating factor and rating loads for both LFR and LRFR analyses for all the bridges are exported to the developed Excel file.
- For the rest of the steps, the threshold load for LFR is the current value stated in BIRM for that specific vehicle (for example 30 tons for H20L). For LRFR, determining this factor is described in the subsequent steps.
- After setting the initial value of the LRFR threshold as the GWT of the vehicle, graphs as shown in Figure 5.3 are plotted between LRFR and LFR rating factors and rating loads, for the corresponding MoDOT and AASHTO vehicles, with each point representing a specific bridge.
- The threshold for LRFR is adjusted in such a way that the number of bridges required to be posted in LFR with the BIRM threshold is similar to the adjusted LRFR threshold. The value of this threshold is likely to be higher than the GWT of the vehicle. However, this threshold (26 tons in this example) has a few points in the red zone as shown in Figure 5.4 (the graph on the left). The red zone is the region that has an unsatisfactory rating (factor/load) for both the LRFR and the LFR. Hence, the threshold is increased so that there are no points in that region. Moving the threshold to 31 tons as shown in Figure 5.4 (the graph on the right) achieves this purpose.
- In the Excel file, only vehicles that have posting loads in both LFR and LRFR (with the revised posting loads) are kept and the LRFR factor is adjusted such that the slope of the points plotted in the graph is close to 1.0. An iterative procedure is used to determine this factor.

- Using the updated threshold value for LRFR and the LRFR factor and restoring the bridges that were removed during the LRFR posting load calculation, the number of bridges that require posting for both methods is determined.

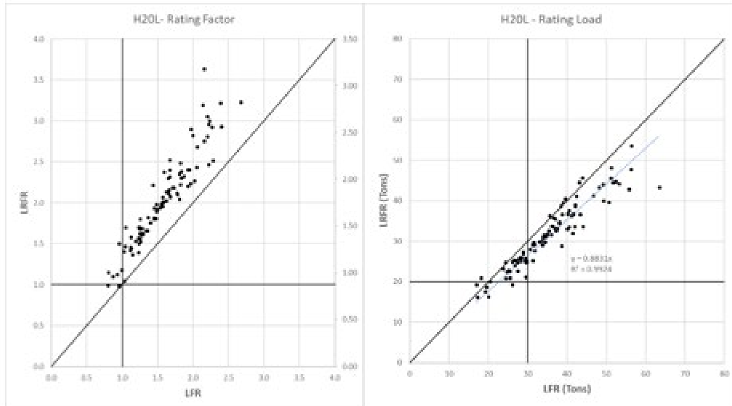


Figure 5.3: H20L Rating Factors (left) and Rating Load (right) Comparison

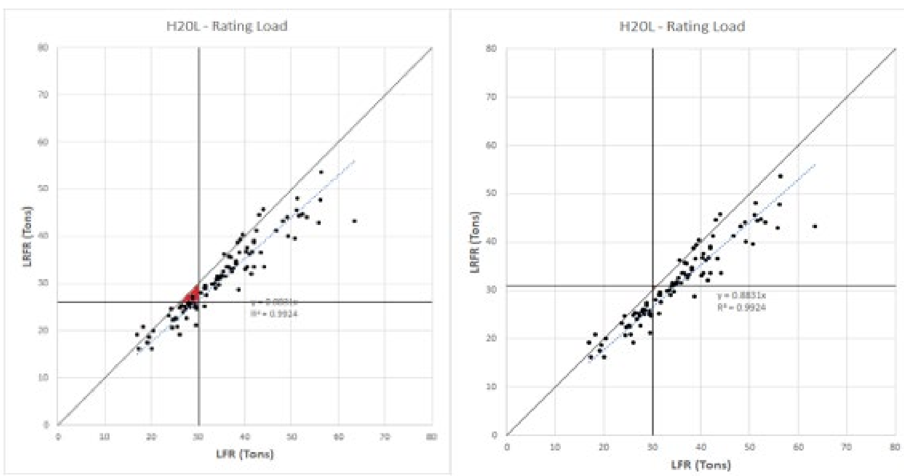


Figure 5.4: Problem with Selection of GWT 26 Tons as Threshold (left) and New Proposed Threshold (right)

Steps to determine the LRFR Threshold and Factor for MoDOT vs AASHTO Vehicles

- The rating factor and rating loads for both LFR and LRFR analyses with BrR 7.1 for all the bridges are exported to the developed Excel file.
- The GWT of the MoDOT vehicles and the GWT of the AASHTO / SUVs are used as thresholds to be compared in the Excel file.
- If all the points on the plot on the graph obtained from the Excel file are not above the 45-degree line, all the points are shifted above the 45-degree line using a factor.
- For shifting, we take the rating load ratio of the AASHTO legal/SUV vehicle and the MoDOT vehicle, and the minimum value of the ratio obtained is taken as a factor. The factor is then multiplied by the rating load of the MoDOT vehicle to get the new rating

load for MoDOT vehicles, which shifts all the points above the 45-degree line in the rating load graph.

- To determine the threshold for the MoDOT vehicle, the threshold must be equal or greater than the GWT of the compared AASHTO/ SUVs vehicle, then, the MoDOT vehicle is said to encapsulate the AASHTO/ SUVs. For example, to envelop SU4 (SUV), H20L (MoDOT vehicle) must have threshold equal or greater than SU4 maximum GWT, 27 tons.

5.2.1 MoDOT Vehicles Verses SUVs for Rating Loads

Rating loads from the analysis of SUVs were compared to MoDOT vehicles to determine if MoDOT vehicles envelop the SUVs and if not, what factors can be used by each type of SUV for it to be enveloped by the MoDOT vehicles. AASHTO SU4, SU5, SU6 and SU7 vehicles were used.

5.3 Comparison of LFR and LRFR Methodologies of Ratings for Various Vehicle Types

Comparisons of data for LFR and LRFR for rating loads and rating factors for various MoDOT vehicles was done to determine the relationship between the two rating methods.

5.3.1 H20L Rating Factors and Rating Loads Comparisons

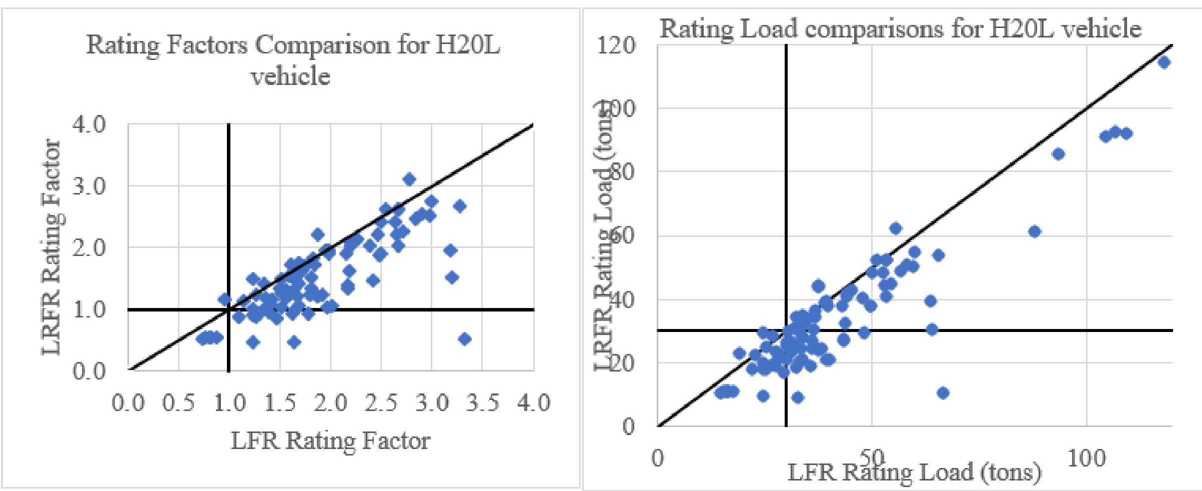


Figure 5.5: H20L Rating Factors (left) and Rating Load in Tons (right) Comparison

The rating factors and rating loads, as seen in Figure 5.5, from the rating of bridge models using the H20L vehicle showed that LFR had higher rating factors and rating loads than LRFR. There were only a few bridges that had their rating loads and rating factors higher in LRFR.

5.3.2 MO3S2 Rating Factors and Rating Loads Comparisons

A comparison of data from rating factors and rating loads for MO3S2 vehicles is shown in Figure 5.6 and indicates that LFR had greater rating loads and factors than LRFR.

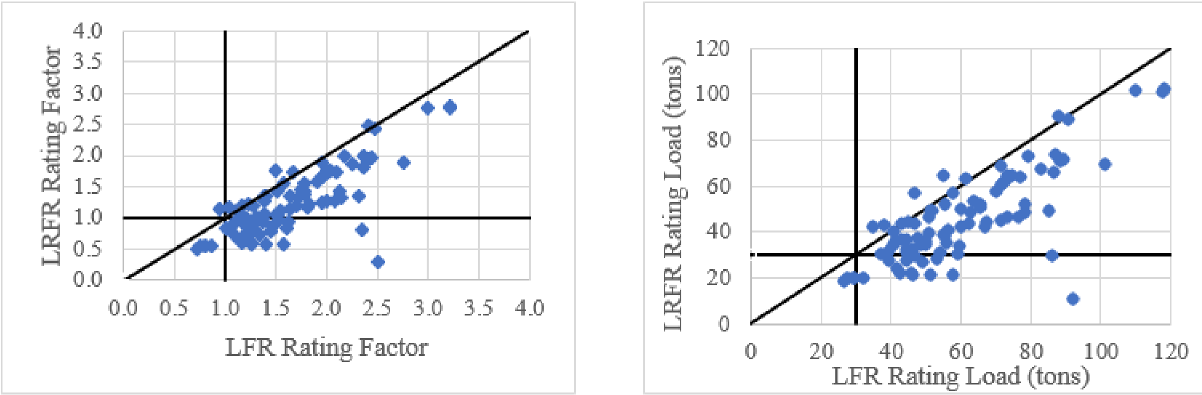


Figure 5.6: MO3S2 Rating Factors (left) and Rating Load (right) Comparison

5.3.3 CZSU Rating Factors and Rating Loads Comparisons

The rating factors and rating loads shown in Table C.1 (Appendix C), were obtained from the rating of bridge models using the CZSU vehicles. The comparisons of the rating factors and the rating loads for LFR and LRFR are shown in Figure 5.7. Table C.1, shows that for LFR, most bridges govern at the interior girders, while that for LRFR, most girders govern at the exterior girders. It can be seen from Table C.1 and Figure 5.7 that LFR has higher rating loads and rating factors than LRFR. Table C.1 also shows that two bridges need to be posted in LFR, while in LRFR, five bridges need to be posted. The posting decisions are based on the LFR thresholds currently being used by MoDOT and shown in Table 5.2.

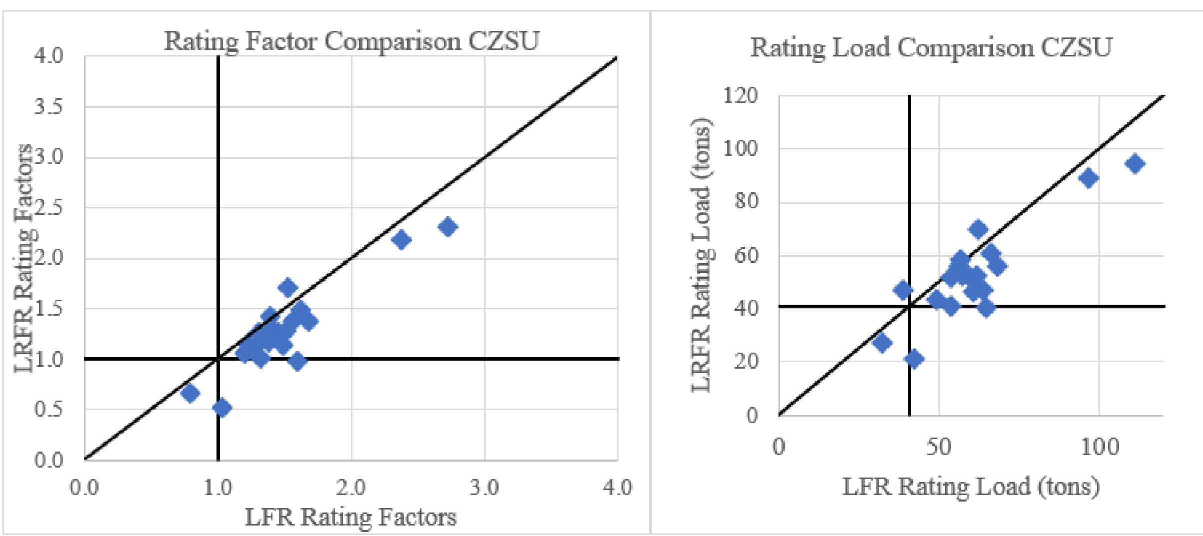


Figure 5.7: CZSU Rating Factors (left) and Rating Load (right) Comparison

5.3.4 CZRT Rating Factors and Rating Loads Comparisons

The rating factors and rating loads shown in Table C.2 in Appendix C are from the rating of bridge models using CZRT vehicles. The data shows that LFR had higher rating loads and rating factors than LRFR. For LFR, Missouri uses a threshold of 70 tons for posting for this vehicle model. When using the same threshold for both methods, LRFR shows more vehicles being posted than LFR. Table C.2 also shows that exterior girders governed for three bridges in LFR while in LRFR, the number of bridges increased to 12. The bridges where the exterior girders govern have all the controlling ratings in exterior girders while those where the interior girders govern had their governing rating from interior beams or girders which show the lowest ratings. Figure 5.8 shows the comparison of the rating factors and rating loads for the CZRT vehicle.

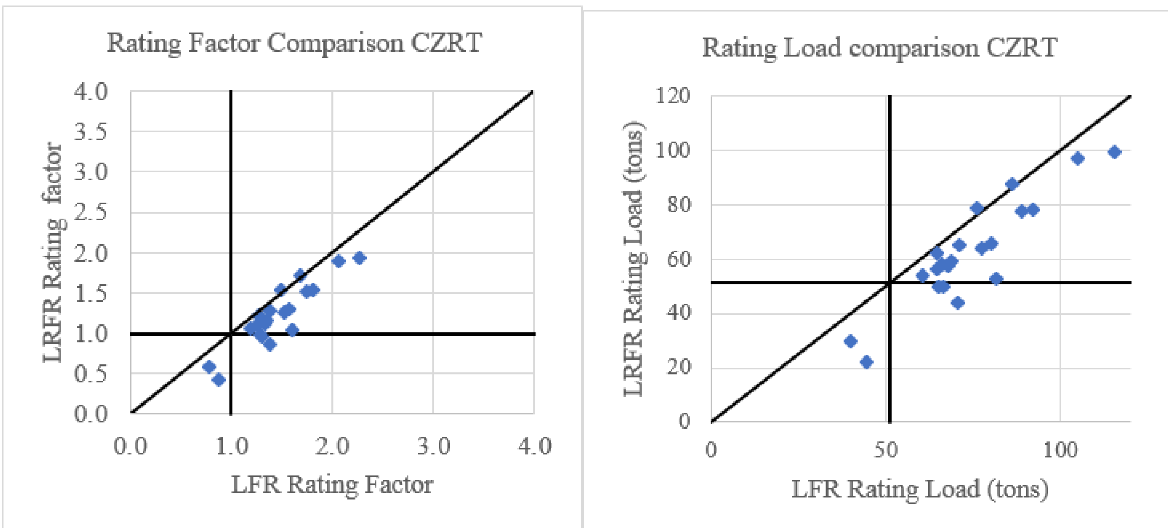


Figure 5.8: CZRT Rating Factors (left) and Rating Load (right) Comparison

5.3.5 SU5 Rating Factors and Rating Loads Comparisons

Figure 5.9 shows LFR and LRFR rating factors and rating loads for SU5 vehicles, and the results show the same trend as the vehicles already analyzed. LFR shows higher rating loads and rating factors than LRFR. The number of bridges posted for each method, the girders that failed in each method, and whether they failed in exterior or interior girders are shown in Table 5.1.

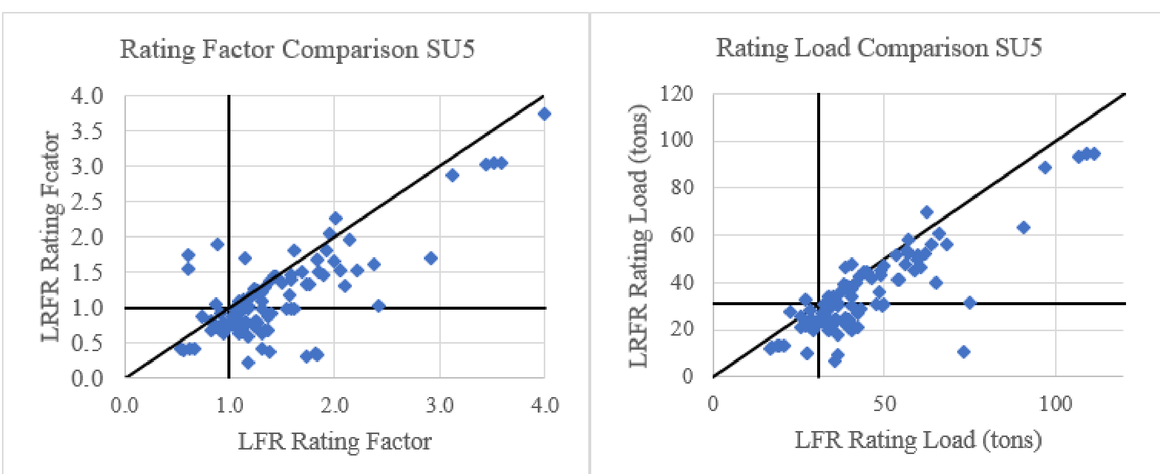


Figure 5.9: SU5 Comparison Graphs for Rating Factors (left) and Rating Loads (right)

Table 5.1: Summary Table for the LFR and LRFR Comparison of the Number of Bridges in Various Categories

H20L	LFR	LRFR
Bridges requiring posting	22/95	43/95
Bridges where exterior girders govern	28	75
Bridges where interior girders govern	67	20
MO3S2	LFR	LRFR
Bridges requiring posting	24/95	53/95
Bridges where exterior girders govern	32	77
Bridges where interior girders govern	63	18
CZSU	LFR	LRFR
Bridges requiring posting	3/21	5/21
Bridges where exterior girders govern	3	13
Bridges where interior girders govern	18	8
CZRT	LFR	LRFR
Bridges requiring posting	10/21	15/21
Bridges where exterior girders govern	3	12
Bridges where interior girders govern	18	9
SU5	LFR	LRFR
Bridges requiring posting	0/21	1/21
Bridges where exterior girders govern	7	17
Bridges where interior girders govern	14	4

5.3.6 Discussion of the LRFR and LFR Comparison Results

The data shown in the above graphs indicates that a majority of bridges have higher rating factors and rating loads in LFR than in LRFR, suggesting that LRFR is a more conservative method of rating bridges compared to the current method being used by MoDOT. The comparison also shows that LRFR results in posting a greater number of bridges. Although LFR also posts some bridges, it is not as many as with LRFR. With LFR, posting is based on thresholds being used by MoDOT H20L, MO3S2, CZSU, and CZRT vehicles. Posting for LRFR also employed the thresholds being used by MoDOT for the LFR method. Thresholds are shown in Table 5.2. Most bridges analyzed by LFR show that interior girders governed for most of the bridges. On the other hand, in LRFR, the majority of the bridges were governed by the exterior girders as shown in Table 5.1.

Table 5.2: Posting Thresholds Used for the Posting Loads for Various Vehicle Types

Vehicle	LFR posting Threshold used (Tons)	LRFR posting threshold used (Tons)	Application zones
H20L	30	30	All
MO3S2	45	45	All
CZRT	70	70	Commercial zone
CZSU	45	45	Commercial zone
SU5	RF <1.0	RF <1.0	Commercial zone

The bridges that are posted using both LFR and LRFR for CZSU and CZRT vehicle models are bridges in commercial zones. In the case of steel bridges, only 21 bridges were in commercial zones. The data in Table 5.3 shows the percentage change for posting between LFR and LRFR. The change ranges between 14.3% and 30.5%, with the least being CZRT vehicles and the most being MO3S2 vehicles. The percentage is calculated by comparing the number of bridges posted to the total number of bridges rated for the vehicle type in their respective zones and methods of rating.

Table 5.3: Percentage Posting changes

Vehicle	LFR posted	LFR % Posted	LRFR posted	LRFR % Posted	Percentage increase
H20L	22/95	23%	43/95	45%	22%
CZSU	2/21	9.5%	5/21	23.8%	14.3%
MO3S2	24/95	25.3%	53/95	55.8%	30.5%
CZRT	10/21	47.6%	15/21	71.4%	23.8%

MO3S2 vehicles show a higher number of bridges posted compared to H20L vehicles when using both LFR and LRFR. In commercial zones, CZRT vehicles show a higher number of bridges posted compared to CZSU vehicles.

5.4 Comparisons of MoDOT and AASHTO Vehicles Using LRFR

The ratings, using LRFR, for MoDOT legal load vehicles H20L and MO3S2 were compared with the corresponding ratings of AASHTO legal load vehicles Type 3, Type 3S2 and Type 3-3. Figures 5.10 and 5.11 show the plots of H20L vehicles against the three AASHTO legal load vehicles.

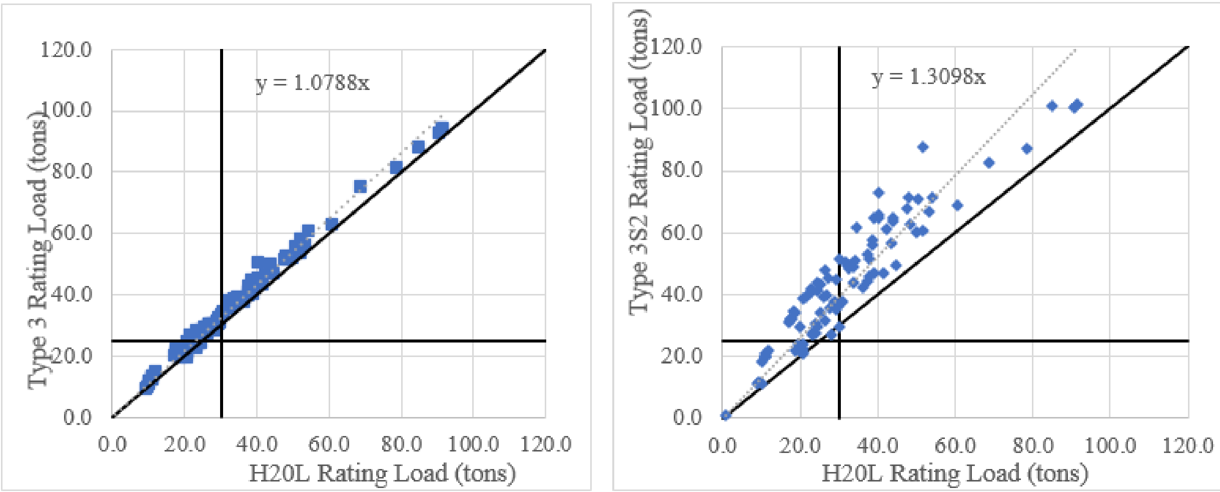


Figure 5.10: Comparison of H20L and Type 3 and Type 3S2

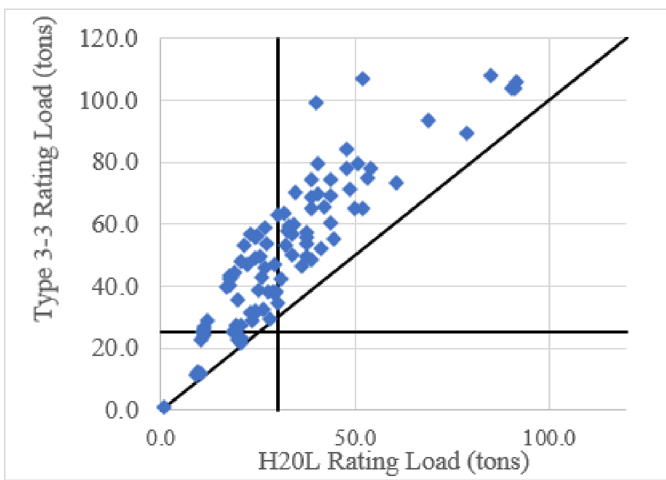


Figure 5.11: Comparison of H20L and Type 3-3

These comparisons show that H20L has lower rating loads than the AASHTO vehicles. Therefore, H20L envelops AASHTO legal loads when using LRFR. H20L and Type 3 vehicle plots show that they are close in their posting loads but generally H20L governs against Type 3.

5.4.1 H20L vs AASHTO Legal Loads and Single-Unit SHVs

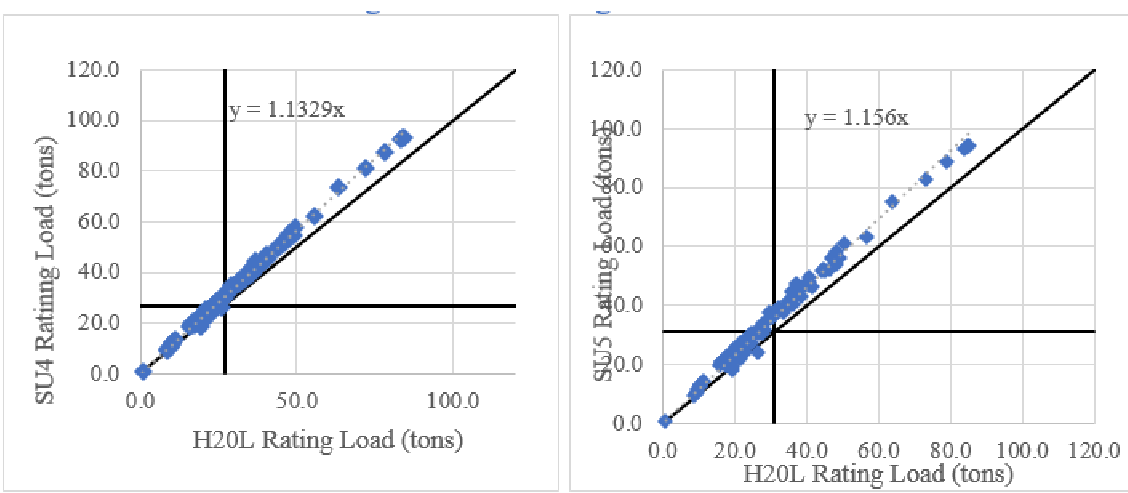


Figure 5.12: Comparisons of H20L, SU4 and Type SU5

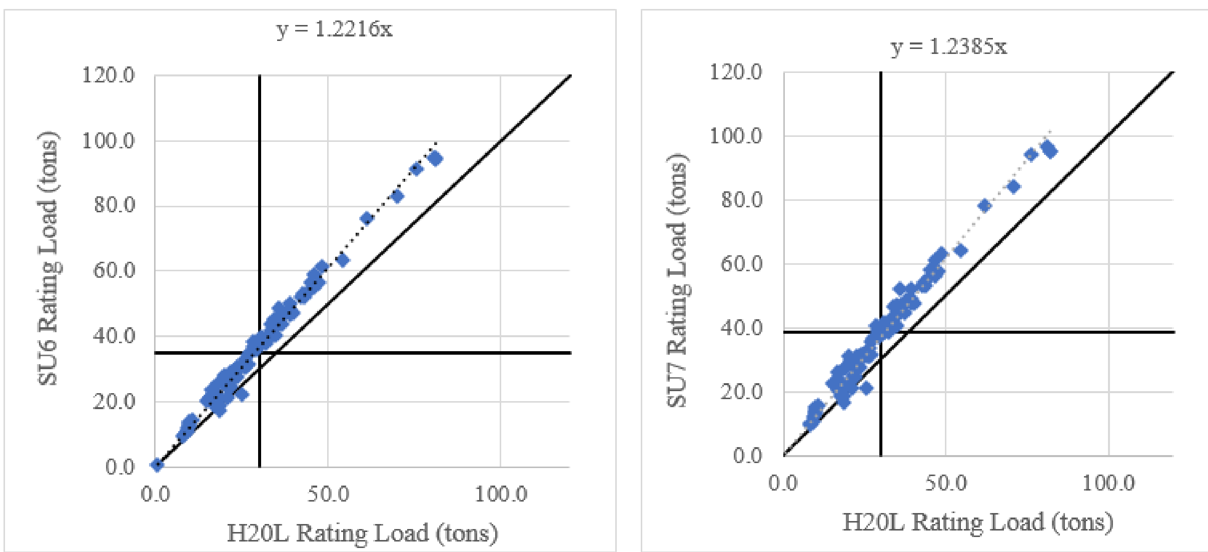


Figure 5.13: Comparisons of H20L, SU6 and SU7

Figures 5.12 and 5.13 compare the SU4, SU5, SU6, and SU7 vehicles with the H20L vehicle Since all the plots in Figure 5.13 are to the left of the 45-degree line, we can conclude that the H20L vehicle envelops all the single unit vehicles when using LRFR.

5.4.2 Comparison of MoDOT MO3S2 Legal Load and AASHTO Legal Load Vehicles

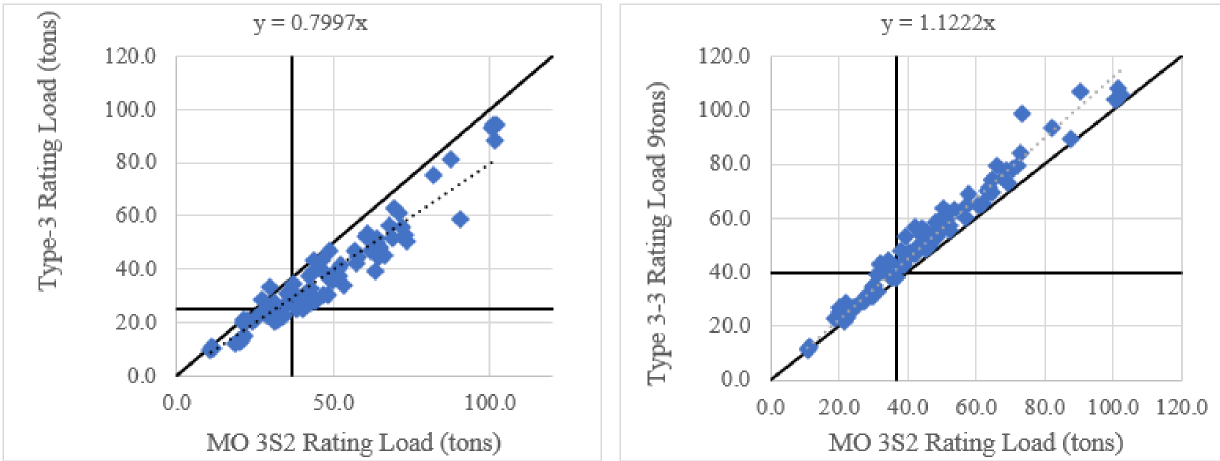


Figure 5.14: Comparison of Type 3-3 and MO3S2 Without Factor (left) and With Factor (right)

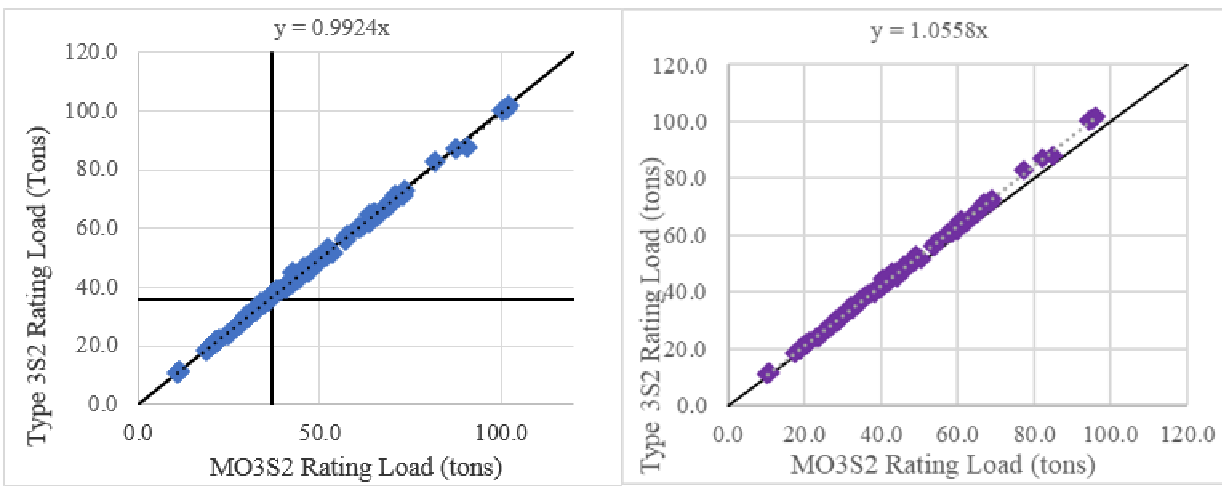


Figure 5.15: Comparison of MO3S2 and TYPE 3S2 Without a Factor (left) and With a Factor of 0.95 (right)

Figures 5.14 and 5.15 compare the Type 3, Type 3-3 and Type 3S2 vehicles with the MO3S2 vehicle when using LRFR. Since the plots are below the 45-degree line in Figure 5.15, it can be seen that MO3S2 does not govern for AASHTO Type 3 vehicle. Figure 5.15 shows that MO3S2 governs against Type 3-3 since the plots are above the 45-degree line. MO3S2 vehicle governs against Type 3S2 with the use of a shift factor since these two loads are close to each other. Figure 5.15 shows that a shift factor of 0.95 shifts all the plots above the 45-degree line to ensure that MO3S2 vehicle envelops AASHTO Type 3S2.

5.4.3 Comparison of MoDOT's CZRT Vehicles with AASHTO Vehicles

Figures 5.16 and 5.17 compare the Type 3, Type 3-3, and Type 3S2 AASHTO vehicles with CZRT MoDOT commercial zone vehicles.

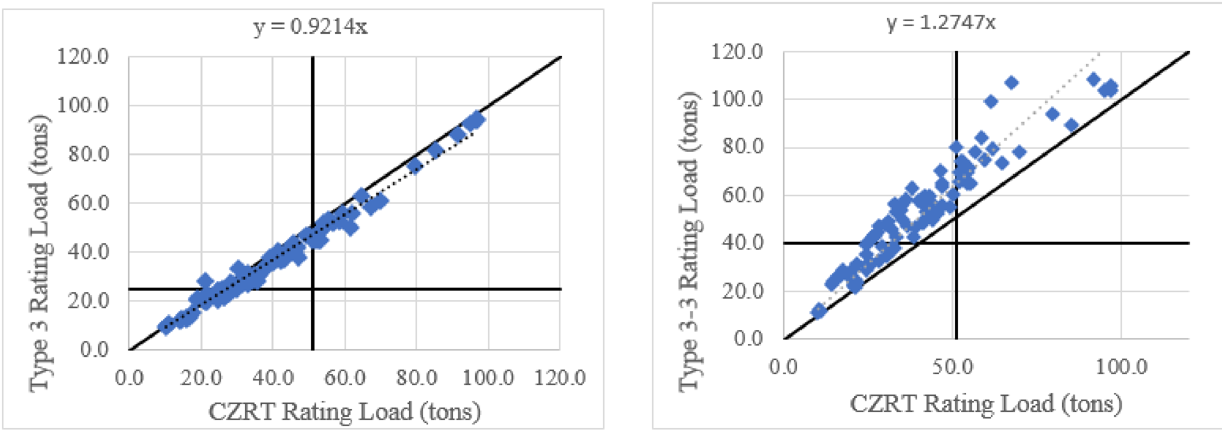


Figure 5.16: Comparison of CZRT and Type 3 (left) and Type 3-3 (right)

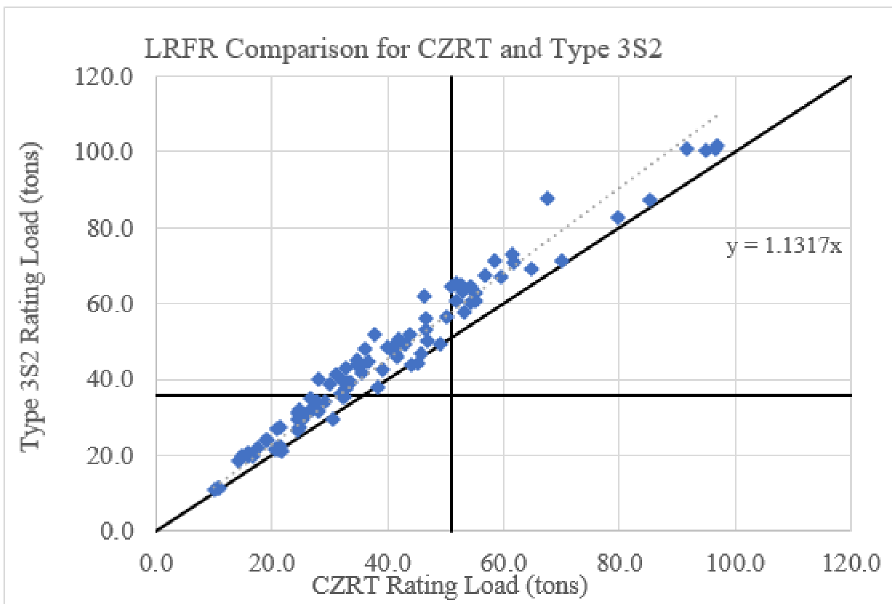


Figure 5.17: Comparison of CZRT and Type 3S2

The graph on the left side of Figure 5.16 compares the rating loads of CZRT and Type 3 vehicles in LRFR and shows that CZRT cannot envelop AASHTO Type 3 vehicles because most plots are below the 45-degree line. The graph on the right side of Figure 5.16 shows that CZRT vehicles envelop Type 3-3 AASHTO vehicles since all the plots are above the 45-degree line. Figure 5.17 shows that CZRT vehicles can also envelop Type 3S2 AASHTO vehicles since most points are above the 45-degree line.

5.4.4 Comparison Between MoDOT's CZSU and Single Unit Vehicles

Figures 5.18 and 5.19 compare the SU4, SU5, SU6 and Type SU7 vehicles with CZSU vehicles.

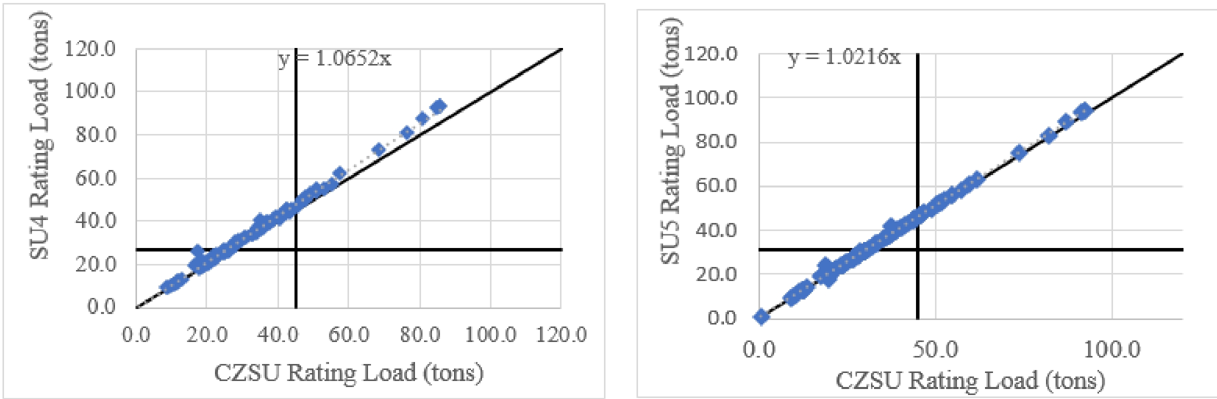


Figure 5.18: Comparison of CZSU and SU4 (left) and SU5 (right)

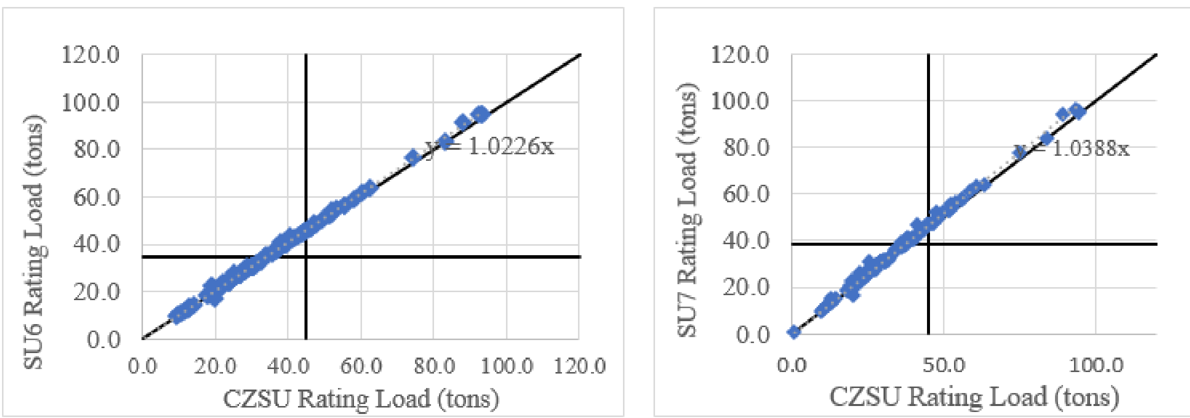


Figure 5.19: Comparison of CZSU and SU6 (left) and SU7 (right)

For MoDOT vehicles to govern the AASHTO vehicles two conditions must be met.

1. First, the data points must be above the 45-degree line when MoDOT vehicles are on the x-axis and the comparison vehicle on the y-axis.

2. Second, the x-axis vertical line must be shifted across the x-axis to ensure that there are no plots between the vertical line and the 45-degree line.

From these values, we can generate a factor to shift the plots above the 45-degree line and then form another value for the posting thresholds for MoDOT vehicles. The threshold load and the factor are determined by taking the following steps.

1. The left side of Figure 5.20 compares H20L and SU4 with no factor applied. The vertical line shows a GWT for H20L of 20 tons.

2. The left side of Figure 5.20 also shows some comparison points in the triangular region where the three lines intersect with each other. To avoid this, we shift the y-line onto the x-axis representing the GWT of 27 tons and this will represent our threshold.

3. A factor of 0.95 is used to ensure that the plots are above the 45-degree line as shown in the right side of Figure 5.20, which represents our posting factor.

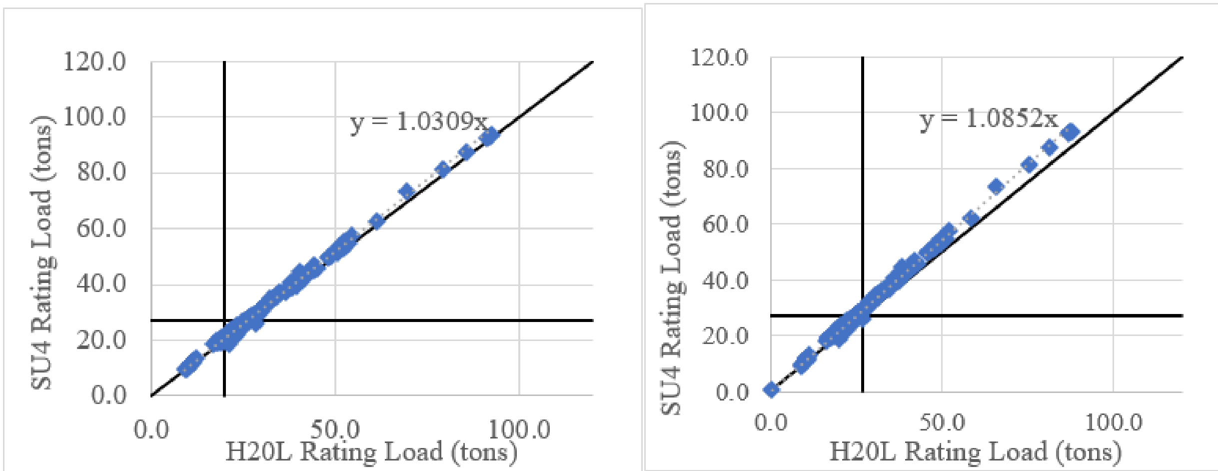


Figure 5.20: H20L and SU4 Comparisons Without Factor (left) and With Factor (right)

The right side of Figure 5.20 shows that we shifted the H20L line from its GWT of 20 tons to 27 tons to be able to govern over SU4 without using a factor. From the graphs comparing CZSU and single-unit vehicles, we can conclude that when a factor is used to shift all the points above the 45-degree line, then CZSU governs against the single-unit vehicles in LRFR.

Factors were generated from the graphs in our research that allowed the MoDOT vehicles to envelop the AASHTO vehicles. The final factors that will be used in calculating posting loads for MoDOT vehicles are shown in Table 5.4. Although the formula used to calculate posting loads in LRFR is shown in Equation 3 of AASHTO MCE 2003, MoDOT wanted its approach to posting loads given that the AASHTO equation is harsh on bridges with low ratings. The following data was generated from the analysis of steel, prestressed, and reinforced concrete bridges.

The lowest factor obtained was 0.94 for SU5 vehicles and therefore it is recommended as the factor to be used for posting load requirements when using LRFR for steel bridges. It allows H20L vehicles to envelop SU4, SU5, and Type 3 vehicles. It will also be easier to use than the AASHTO MCE 2003 formulas for bridges with the lowest rating factors. The LFR currently used by MoDOT has a factor of 0.86 for its posting load requirements.

5.5 Recommended Factors for Posting Loads for Steel Bridges

Table 5.4: Recommended LRFR Thresholds and Factors for H20L

Vehicles	H20L - 20 Tons Recommended Thresholds (Tons)	H20L - 20 Tons Factor
SU4	27.00	0.95
SU5	31.00	0.94
SU6	35.00	0.93
Type 3	25.00	1.00

The H20L vehicle will require a higher threshold value in LRFR to envelop SU6 and SU7 vehicles. Therefore, it is recommended that when posting loads using LRFR, MoDOT use H20L to envelop SU4, SU5, and TYPE 3 vehicles with a threshold of 31 tons and a scaling factor of 0.94.

The ability of MO3S2 vehicles to envelop Type 3-3 and Type 3S2 AASHTO vehicles is notable. Table 5.5 shows the results obtained by shifting the plots above the 45-degree line and shifting the GWT line.

Table 5.5: Recommended LRFR Thresholds and Factors for MO3S2

Vehicles	MO3S2 - 36.64 Tons Recommended Thresholds (Tons)	MO3S2 - 36.64 Tons Factor
Type 3-3	40.00	1.00
Type 3S2	GWT (36.64)	0.96

MO3S2 envelops both Type 3S2 and Type 3-3 vehicles with a threshold weight of 40 tons and a scaling factor of 0.96, which was the lowest factor obtained when MO3S2 was compared with these two vehicles. Table 5.6 shows the recommended thresholds and factors for CZSU with the AASHTO single-unit vehicles SU4, SU5, SU6, and SU7.

Table 5.6: Recommended LRFR Thresholds and Factors for CZSU

Vehicles	CZSU - 40.8 Tons Recommended Thresholds (Tons)	CZSU - 40.8 Tons Shifting Factor
SU4	GWT (40.8)	0.91
SU5	GWT (40.8)	0.99
SU6	GWT (40.8)	0.99
SU7	GWT (40.8)	0.99

CZSU vehicles do not require posting thresholds to envelop SU4, SU5, SU6, and SU7 but they do require a posting factor of about 0.91. This factor shifts all the points above the 45-degree line for CZSU and therefore envelops SU7. With a GWT of 40.8 tons, CZSU can act as a threshold for all single-unit vehicles because the GWT line on the x-axis does not have to shift.

Table 5.7 shows the recommended thresholds and factors for CZRT with the AASHTO legal vehicles Type 3-3 and Type 3S2. Type 3 was not considered because (as seen in Figure 5.16) CZRT did not envelop this vehicle and if a factor is used to envelop, it will be below 0.86, which is currently being used by MoDOT for LFR posting.

Table 5.7: Recommended LRFR Thresholds and Factors for CZRT

Vehicles	CZRT - 51 Tons Recommended Thresholds (Tons)	CZRT - 51 Tons Shifting Factor
Type 3-3	51	1.00
Type 3S2	51	0.97

CZRT vehicles can envelop Type 3-3 and Type 3S2 vehicles with GWT as the threshold. The current threshold currently used by MoDOT in LFR of 70 tons for CZRT seems to be high and is likely to require more bridges to be posted in commercial zones. The posting limit is this high because of the different types of heavy vehicles that are allowed by Missouri law in commercial zones. Therefore, CZRT, with a posting factor of 0.97 and a GWT of 51 tons can envelop AASHTO Type 3-3 and Type 3S2 vehicles. Table 5.8 summarizes the recommended enveloping values and posting factors.

Table 5.8: Recommended Factors and Thresholds for Posting Loads

Vehicle	Threshold	Factor	Enveloping
H20L	31	0.94	SU4, SU5, Type 3
MO3S2	40	0.95	Type 3-3, Type 3S2
CZSU	GWT (40.8 Tons)	0.91	SU4, SU5, SU6, SU7
CZRT	GWT (51 Tons)	0.97	Type 3-3, Type 3S2

5.6 Service II Factors Analysis

Another objective of this research was to provide recommendations for the use of LRFR Service II load factors for steel bridges, which tend to result in significantly lower posting values when compared to serviceability checks using LFR. Ninety-five steel bridges used LRFR with Service II live load factors of 1.3 and 1.0. Table C.3 in Appendix C shows the BrR library LRFR load factors with a Service II factor of 1.3 and Table C.4 shows the BrR library LRFR load factors with Service II changed to 1.0.

The tables below summarize these results and show the number of bridges posted for both LFR and LRFR when the Service II factor is 1.3. Results were also determined for CZRT and CZSU vehicles, with 21 bridges determined to be in commercial zones. Table 5.9 gives a summary of the number of vehicles that need to be posted.

Table 5.9: Posted vehicles for Service II = 1.3

Vehicles	LFR	LRFR
H20L	22/95	49/95
MO3S2	24/95	53/95
CZSU	3/21	5/21
CZRT	10/21	15/21

Table 5.10 summarizes the number of bridges posted for both LFR and LRFR when the Service II factor was changed to 1.0. Commercial zone vehicles are included with 21 bridges out of 95 determined to be in commercial zones.

Table 5.10: Posting for Service II Live Load Factor = 1.0

Vehicles	LFR	LRFR
H20L	22/95	35/95
MO 3S2	24/95	41/95
CZSU	3/21	5/21
CZRT	10/21	14/21

Table 5.11 shows the number of bridges affected by changes in Service II factors. This table provides the number and percentages of the total number of bridges affected. All 95 bridges analyzed were included whether they were in commercial zones or not.

Table 5.11: Percentage Change Due to Service II Factor Change

Vehicle Type	Service II bridges affected	Percentage affected
H20L	53/95	56%
CZSU	48/95	51%
MO3S2	46/95	48%
CZRT	45/95	46%
SU5	49/95	52%

Results showed that rating factors and rating loads improved on bridges affected by a margin of between 0%-30%. The number of bridges affected varied depending on the vehicle type. H20L vehicles had the highest number of bridges affected at 53, while CZRT types were the least affected at 45.

Results showed that those bridges that improved by 30% in rating load for a particular vehicle will most likely fail by Service II-steel flexure stress. Furthermore, bridges that improved in rating by less than 30% but more than 0% will show a change in limit state from Service II-steel flexure stress to Strength I steel flexure stress.

The change in Service II factor from 1.3 to 1.0 reduced the number of bridges posted with those rated with H20L at operating level decreasing by 29%, MO3S2 by 23%, and CZRT by 7%. The CZRT vehicles within the commercial zones didn't show any improvement. This might be because the bridge sample size was insufficient to produce a percentage. Table 5.12 summarizes the percentage improvement in posting loads when the Service II factor was reduced to 1.0.

Table 5.12: Percentage Improvement for Service II = 1.0

Vehicle	Service II = 1.3	Service II = 1.0	Percentage reduction
H20L	49	35	29%
CZSU	5	5	0%
MO3S2	53	41	23%
CZRT	15	14	7%

Changes in Service II factors show significant improvement in posted bridges and can improve the posting and rating loads by up to 30%. MoDOT has to decide whether to reduce this value.

Service II limit state for design, or the inventory level rating for design load i.e., HL-93:

The overload factor of 1.3 can be traced back to the AASHTO Standard Specifications (3.5, 3.22, 10.57 and C10.57). AASHTO LRFD C3.4.1 indicates that "From the point of view of load level, this combination is approximately halfway between that used for Service I and Strength I Limit states. An evaluation of WIM data from 31 sites around the country (Kulicki et al., 2015) indicated that the probability of exceeding the load level specified in Table 3.4.1-1 for this limit state could be less than once every six months."

This commentary is based on the SHRP2 R19B and NCHRP 12-83. The researchers at that time found that from WIM data alone, 1) there is not much basis to lower load factor, 2) site-specific evaluation of unique sites were warranted, 3) design for single load is warranted and 4) use of single lane MPF hard to justify for this limit state. From an overload calibration, LFD yields a β about 1.6 – 2.0 with a COV of 0.32 – 0.92. Current Service II results in a mean β of 1.8 with a COV of 0.09. This β seems high for a service limit state. However, the researchers found little support from technical committees to reduce the LL factor. Therefore, no change was made to the LL factor of 1.3 for Service II from those two projects.

Service II limit state for the operating level rating for design load i.e., HL-93 and legal load rating:

AASHTO MBE C6A.6.4.2.2 indicated that "It is important to note that the live load factors for Service II limit state were not established through reliability-based calibration but were selected based on engineering judgment and expert opinion. The level of reliability represented by this serviceability check is unknown."

5.7 Investigation on Rating of Structures with Spans Over 200 Feet

Another objective of this research was to investigate MBE requirements for load rating of structures with spans longer than 200 feet and provide ways to allow for reasonable load rating of these structures without a refined analysis. From the bridges provided the research team had data for five steel bridges with spans greater than 200 feet.

For permit live loads, MBE Article 6A.4.5.4.1 provides rating guidance and states that "The live load to be used in the evaluation for permit decisions shall be the actual permit truck or the vehicle producing the highest load effect in a class of permit vehicles operating under a single permit. The loading shall consider the truck weight, its axle configuration and distribution of loads to the axles, designated lane position, and any speed restriction associated with the issuance of the permit."

MBE further states that "For spans up to 200 ft, only the permit vehicle shall be considered present in the lane. For spans between 200 and 300 ft, and when checking negative moments in the continuous span bridges, an additional lane load shall be taken as 0.2 klf (kips per linear foot) in each lane. The lane load may be superimposed on top of the permit vehicle (for ease of analysis) and is applied to those portions of the spans where the loading effects add to the permit load effects."

For routine commercial traffic live loads, MBE Article 6A.4.4.2a provides rating guidance on span lengths greater than 200 feet. "For span lengths greater than 200 feet, critical load effects shall be created by: AASHTO Type 3-3, or state legal load multiplied by 0.75 and combined with a lane load of 0.2 kips per linear feet." It also states that "Dynamic load allowance shall be applied to AASHTO legal vehicles and state legal loads but not the lane loads. If the ADTT is less than 500, the lane load may be excluded and the 0.75 factor be changed to 1.0 if, in the engineer's judgment, it is warranted."

Missouri commercial zone legal loads CZSU and CZRT and state legal load MO3S2 were used to conduct research for this report along with AASHTO legal vehicles Type 3, Type 3-3, and Type 3S2. All of these vehicles were modified by multiplying by 0.75 and combining with a lane load of 0.2 kips per linear foot. Train trucks of each of the vehicles were also created 30 feet apart with no lane load being added as shown in Table C.5. Truck trains created in BrR 7.1 are shown in Figures B.5, B.6, B.7, and B.13 in Appendix A. The legal live load models and combination used for this study are listed below:

1. CZRT
2. CZRT Truck Train
3. CZRT*0.75 + Lane
4. CZSU
5. CZSU Truck Train
6. CZSU*0.75 + Lane
7. H20L
8. H20L Truck Train
9. H20L*0.75 + Lane
10. MO3S2*0.75 + Lane MO3S2

11. MO3S2
12. MO3S2 Truck Train
13. Type 3
14. Type 3 Truck Train
15. Type 3*0.75+ Lane
16. Type 3-3
17. Type 3-3 Truck Train
18. Type 3-3*0.75 + Lane
19. Type 3S2
20. Type 3S2 Truck Train
21. Type 3S2*0.75+ Lane

Nine bridges from the models provided for this study had spans greater than 200 feet and five of these were able to be successfully rated in BrR 7.1 software. For these, the following investigations were conducted.

1. Comparison of LFR and LRFR rating factors and loads for these bridges.
2. Comparison of the single-lane and multilane ratings for the train trucks for these bridges.
3. Comparison of the rating loads and factors of the MoDOT and AASHTO vehicles.

The calculation of the rating loads was based on MBE section C6.A.4.4.2.1a which states that "Usually, bridges are load rated for all AASHTO trucks and lane loads to determine the governing loading and governing load rating. A safe load capacity in tons may be computed for each vehicle type (See article 6A.4.4.4). When the lane type and load model govern the load rating, the equivalent truck weights for use in calculating a safe load capacity for the bridge shall be taken as 80 kips." Therefore, for this study, the rating loads taken from the rating factors were compared to determine the performance of these vehicles regardless of their class.

Calculations were adjusted after finding that BrR 7.1 software does not automatically apply the formulas from the MBE in its ratings for bridges that have lengths greater than 200 feet. Section 6A.4.4.2.1a of MBE states that "For spans greater than 200 ft, critical load effects shall be created by, AASHTO Type 3-3 or state legal load multiplied by 0.75 and combined with a lane load of 0.2 klf. Dynamic load allowance shall be applied to the AASHTO legal vehicles and state legal loads but not the lane load." Manual adjustments to each vehicle by multiplying by 0.75 each axle load and adding a lane load of 200 pounds per linear foot. Truck train vehicles were not adjusted for lane or axle loading. Table C.5 shows how axle loads for H20L were adjusted in BrR by multiplying by 0.75. The results from the five bridges are shown in the following sections.

5.8 Comparisons of the LFR and LRFR for Bridges Longer than 200 Feet

5.8.1 Bridge A2074 Data Comparisons

Table D.1 and Figure 5.21 compare LRFR and LFR for Bridge A2074, which had a span of 212.5 feet. Posting loads were based on posting thresholds currently used by MoDOT and shown in Table 5.2. For LFR, the rating load that was below the threshold was posted by multiplying by 0.86. For LRFR a multiplication factor of 0.91 was used since that was the least factor obtained from vehicle comparisons shown in Table 5.8. Examples for determining values for CZRT with a rating factor of 0.87 in LFR and 0.417 in LRFR are shown below.

Gross Vehicle Weight of CZRT = 51 tons

LFR Rating Load = 0.87*51 = 44.41 tons

LFR Posting Load = 0.86*44.41 = 38.19 tons

LRFR Rating Load = 0.417*51 = 21.27 tons

LRFR Posting Load = 21.27*0.91 = 19.36 tons

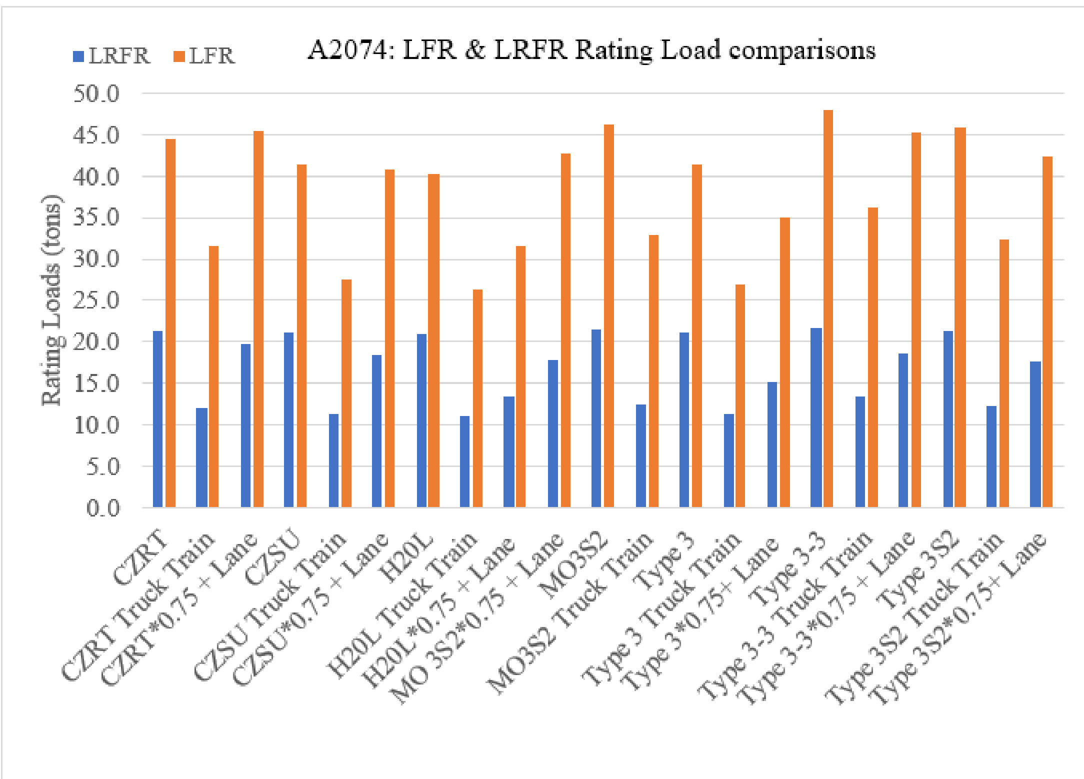


Figure 5.21: Column of A2074 for LFR & LRFR Rating Load Comparisons

5.8.2 Bridge A3069 Data Comparisons

Table D.2 and Figure 5.22 compare LRFR and LFR for Bridge A3069. This bridge spanned 230 feet.

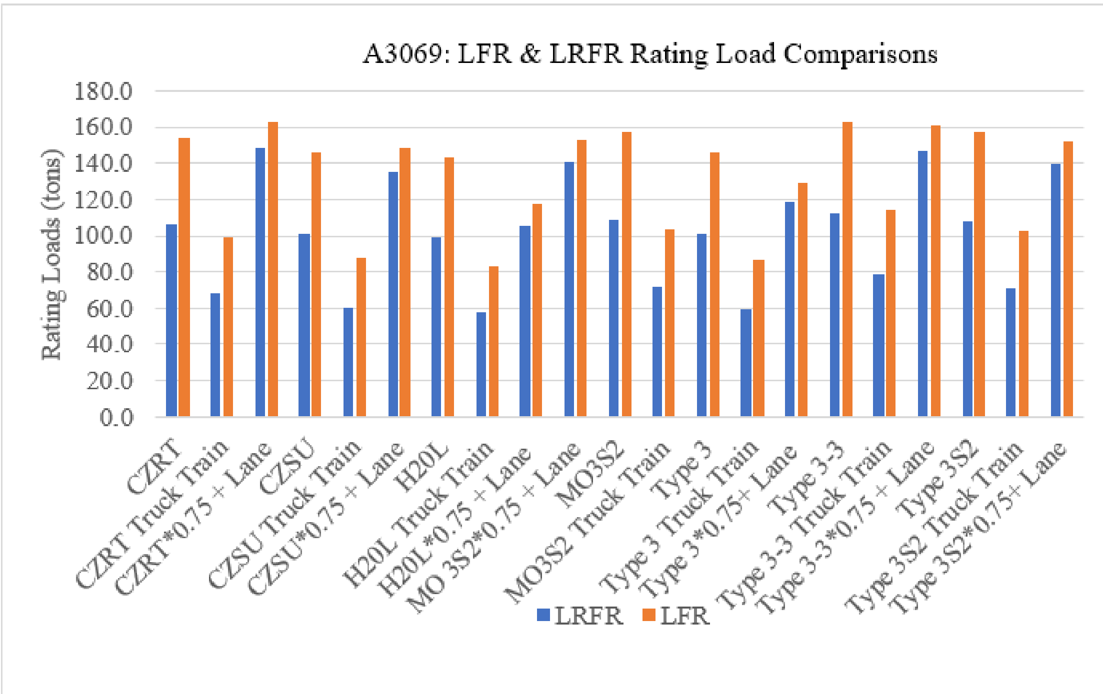


Figure 5.22: Column of A3069 for LFR & LRFR Rating Load Comparisons

5.8.3 Bridge A5677 Data Comparisons

Table D.3 and Figure 5.23 compare LRFR and LFR for Bridge A5677. This bridge had a span of 245 feet.

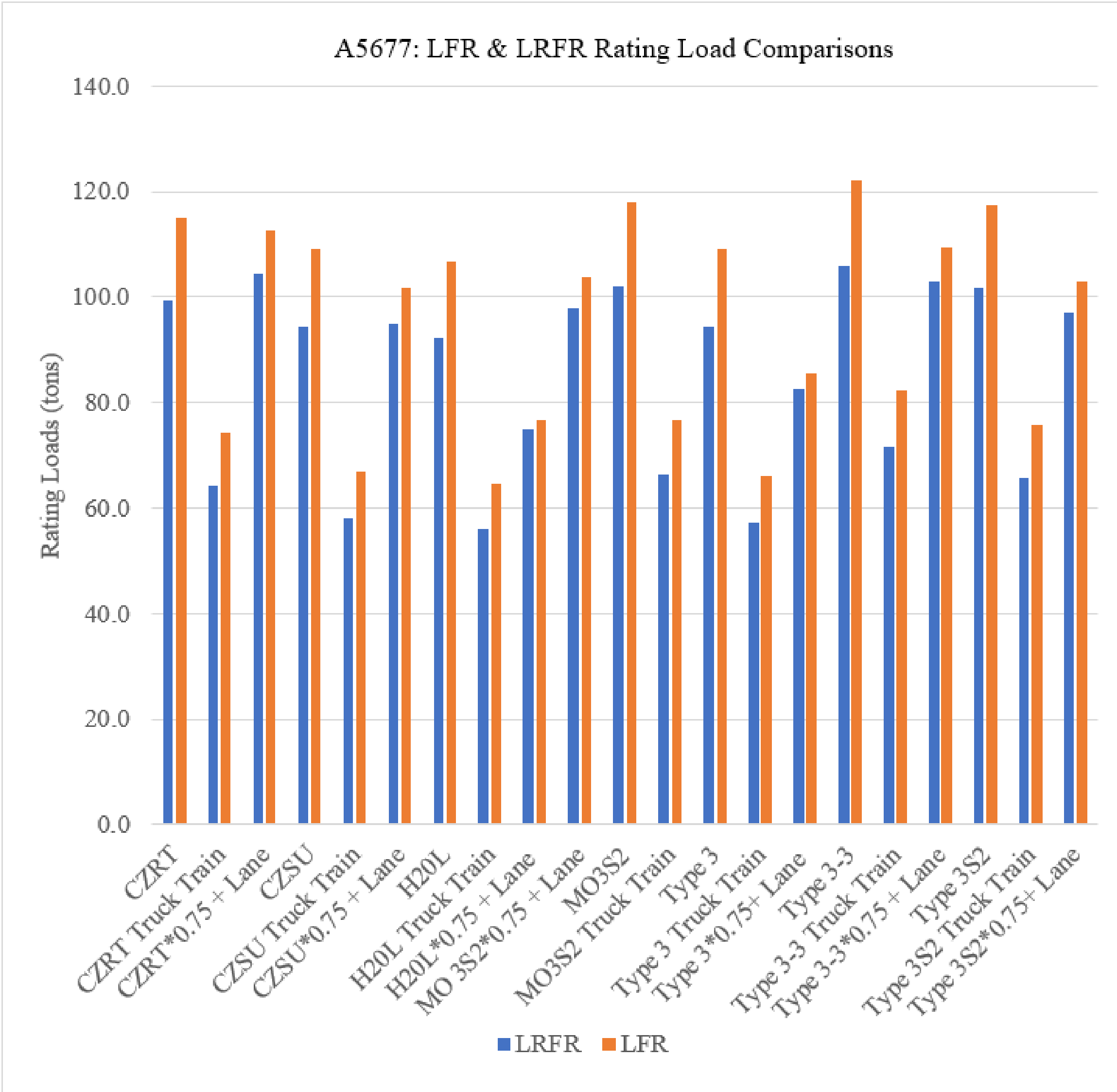


Figure 5.23: Column of A5677 for LFR & LRFR Rating Load Comparisons

5.8.4 Bridge A6723 Data Comparisons

Table D.4 and Figure 5.24 compare LRFR and LFR for Bridge A6723. This bridge had a span of 204 feet.

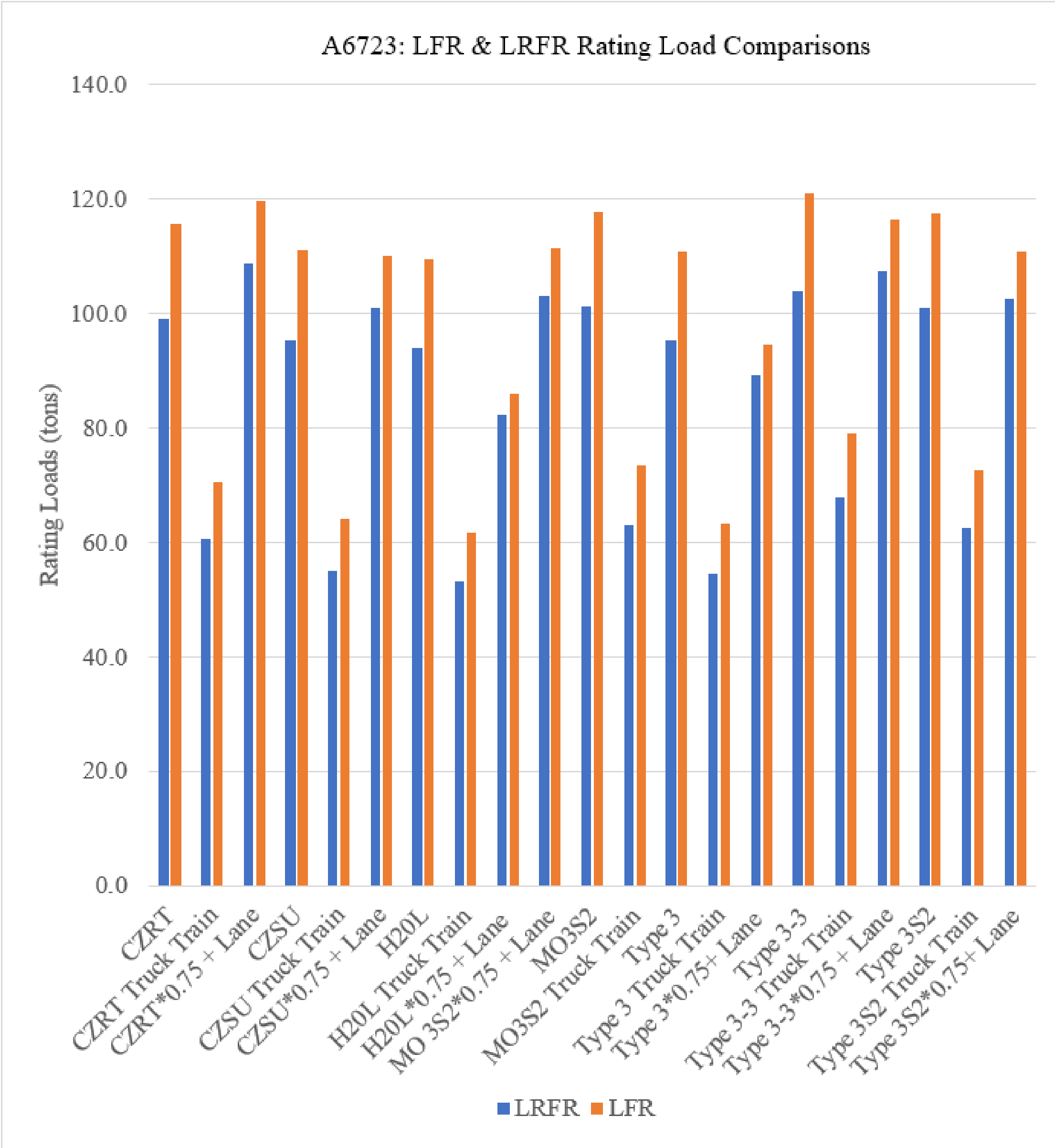


Figure 5.24: Column of A6723 for LFR & LRFR Rating Load Comparisons

5.8.5 Bridge A5910 Data Comparisons

Table D.5 and Figure 5.25 compare LRFR and LFR for Bridge A5910. This bridge had a span 248 feet.

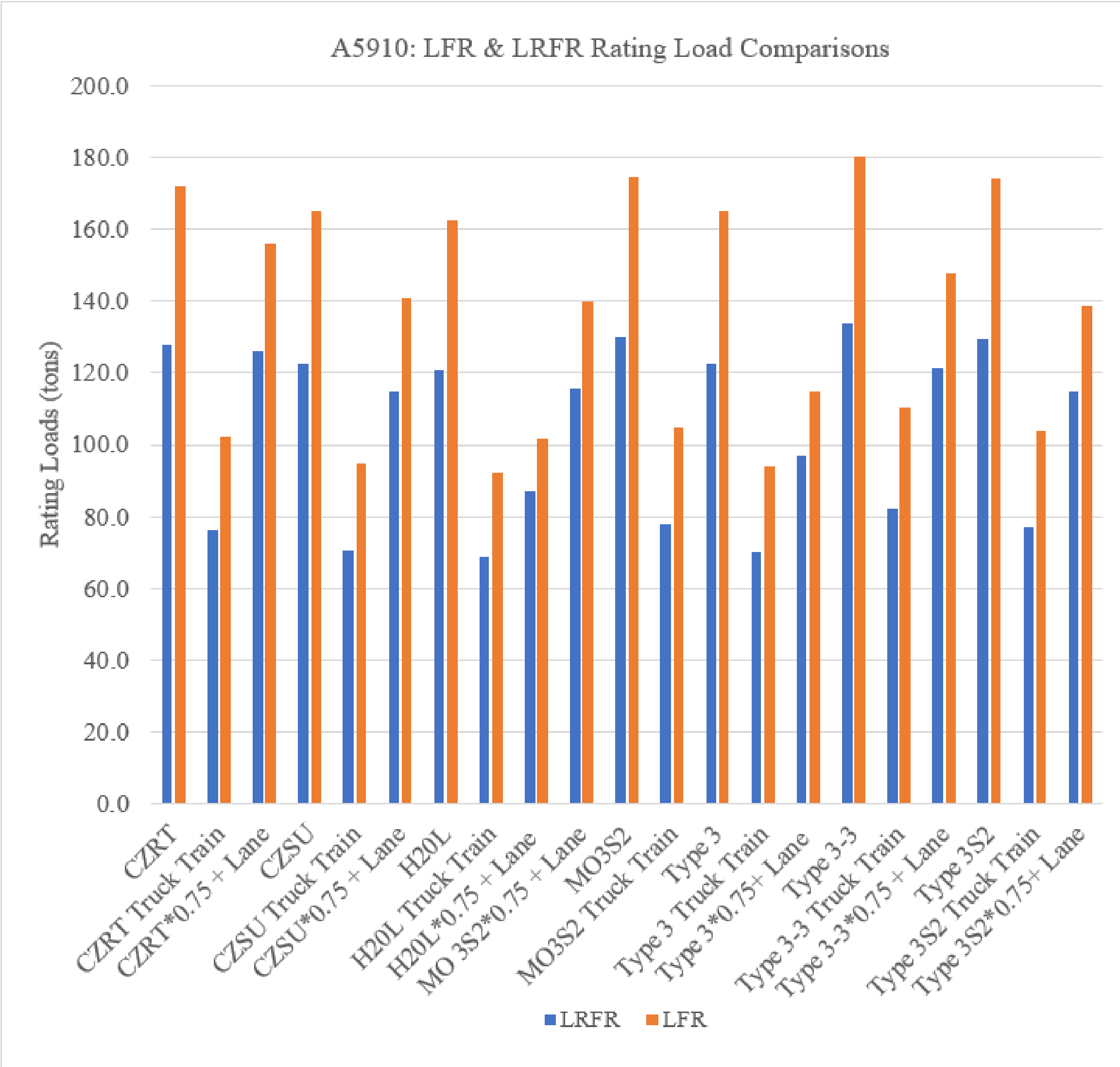


Figure 5.25: Column of A5910 for LFR & LRFR Rating Load Comparisons

The rating results from the five bridges listed above show that CZRT truck train vehicles have the lowest rating factor and Type 3 vehicles have the highest rating factors. When comparing the rating loads, Type 3-3 vehicles have the highest, while H20 truck train vehicles have the lowest when using either rating method. LFR has higher rating factors and rating loads than LRFR. Generally, truck train vehicles have the lowest rating loads and therefore govern by being the most conservative when using both LRFR and LFR.

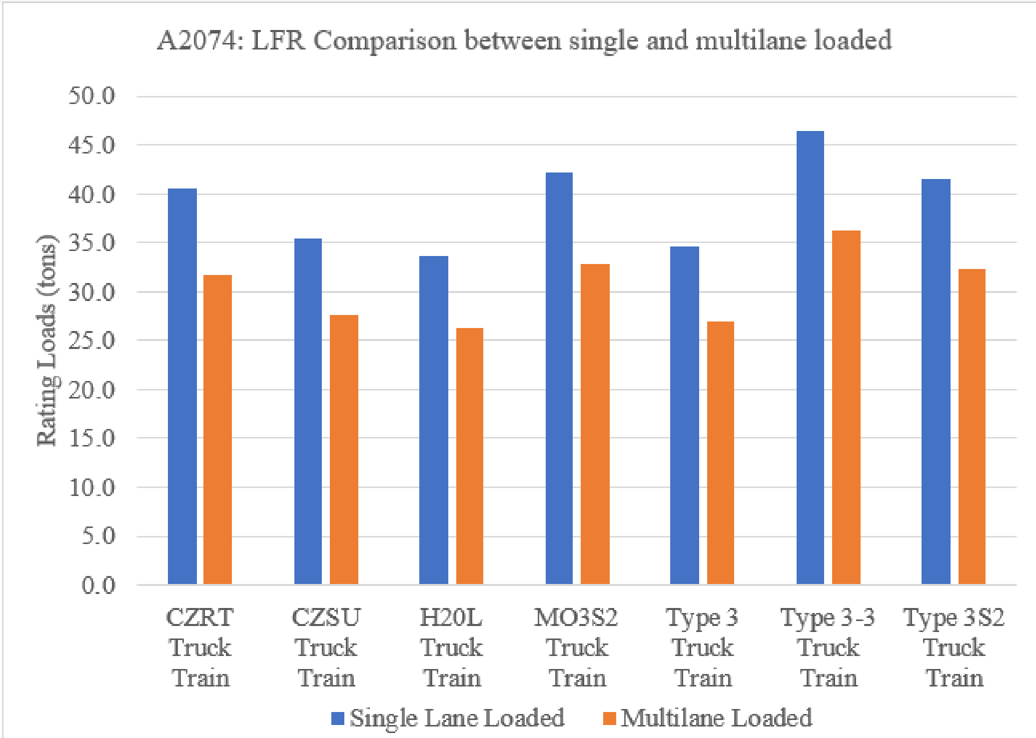
5.9 Comparison of Single Lane and Multilane Load Rating Methods for Train Trucks

5.9.1 Bridge A2074 Single Lane and Multilane Comparisons

Table 5.13 and Figure 5.26 compares single and multilane rating loads and factors for Bridge A2074.

Table 5.13: Comparison data for A2074 for Single and Multilane

	Single Lane Loaded (tons)		Multilane Loaded (tons)	
Live Load Type Model	LFR	LRFR	LFR	LRFR
CZRT Truck Train	40.59	12.95	31.63	12.10
CZSU Truck Train	35.41	12.07	27.59	11.28
H20L Truck Train	33.72	11.83	26.27	11.06
MO3S2 Truck Train	42.13	13.33	32.82	12.46
Type 3 Truck Train	34.60	11.97	26.95	11.19
Type 3-3 Truck Train	46.49	14.28	36.22	13.35
Type 3S2 Truck Train	41.50	13.20	32.33	12.34



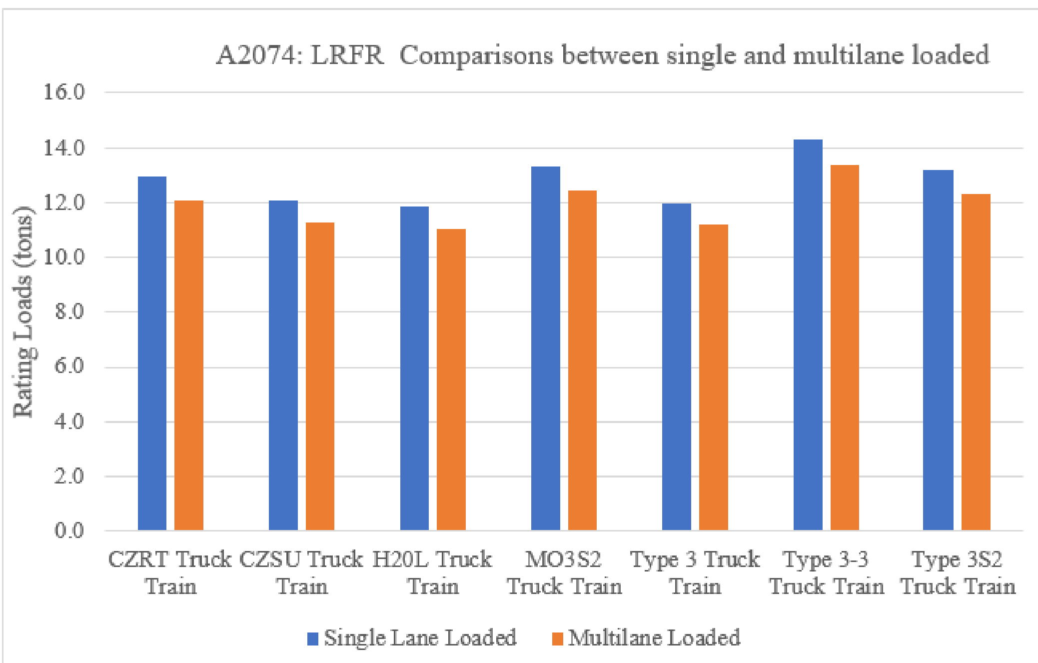


Figure 5.26: A2074 LFR and LRFR Comparison for Single Lane Loaded and Multilane Loaded

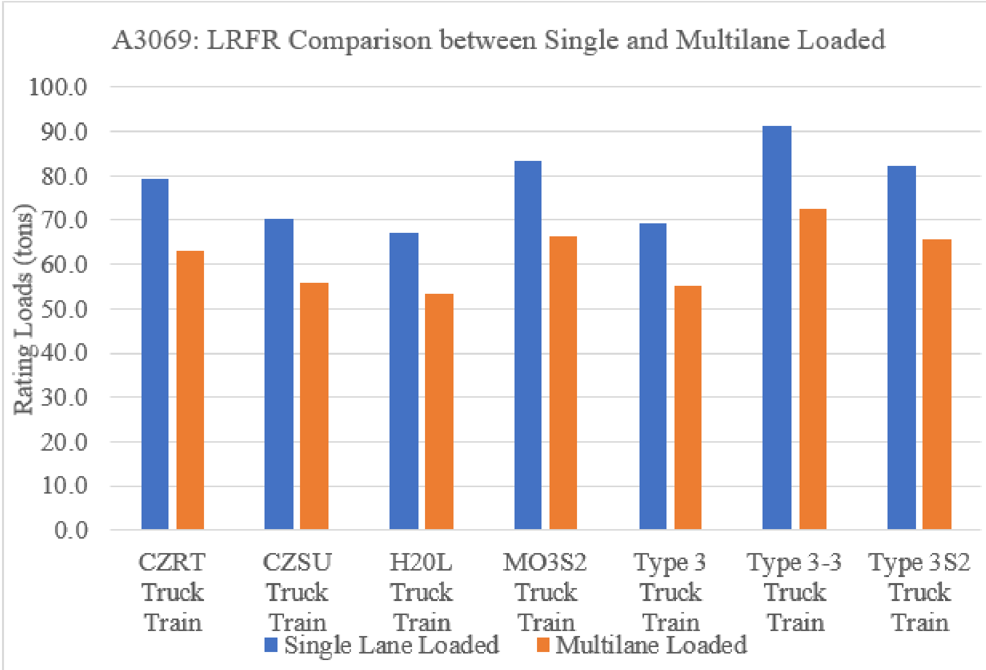
Table 5.13 and Figure 5.26 show that multilane loaded rating results are lower than when analyzed as single lane loaded when using both LFR and LRFR. Type 3-3 truck train vehicles have the highest rating load while H20L truck train vehicles show the lowest when using both methods.

5.9.2 Bridge A3069 Single and Multilane Comparisons

Table 5.14 and Figure 5.27 compares single and multilane rating loads and factors for Bridge A3069.

Table 5.14: Comparison Data for A3069 for Single and Multilane

	Single Lane Loaded (tons)		Multilane Loaded (tons)	
Live Load Type Model	LFR	LRFR	LFR	LRFR
CZRT Truck Train	103.98	79.30	72.12	63.14
CZSU Truck Train	92.06	70.19	63.85	55.89
H20L Truck Train	87.87	67.00	60.94	53.35
MO3S2 Truck Train	109.15	83.23	75.70	66.27
Type 3 Truck Train	90.71	69.16	62.91	55.07
Type 3-3 Truck Train	119.50	91.13	82.88	72.57
Type 3S2 Truck Train	107.99	82.35	74.90	65.57



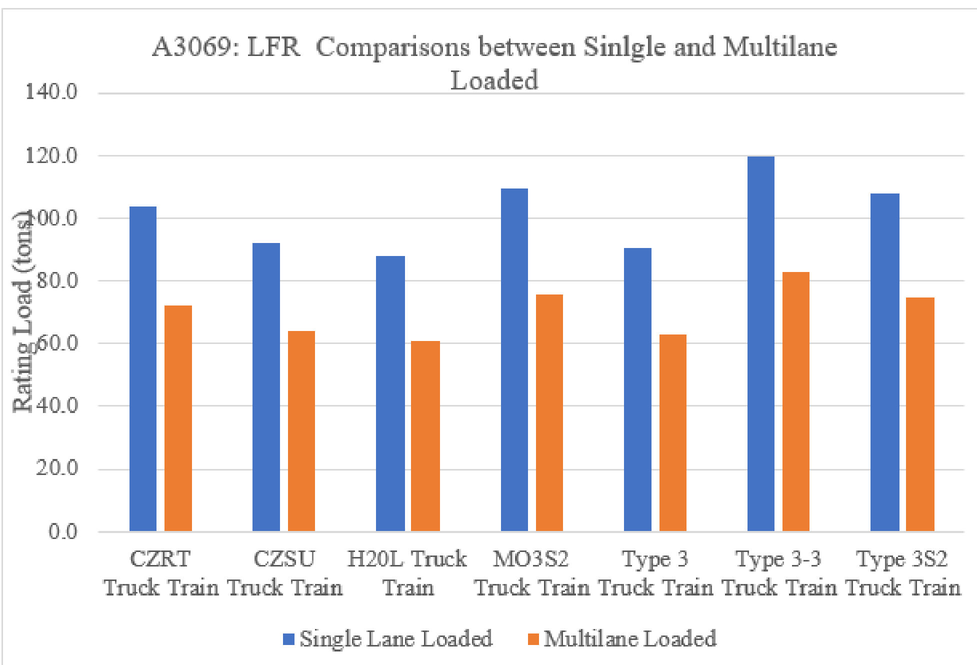


Figure 5.27: A3069 LFR and LRFR Columns Comparisons for Single Lane Loaded and Multi Lane Loaded

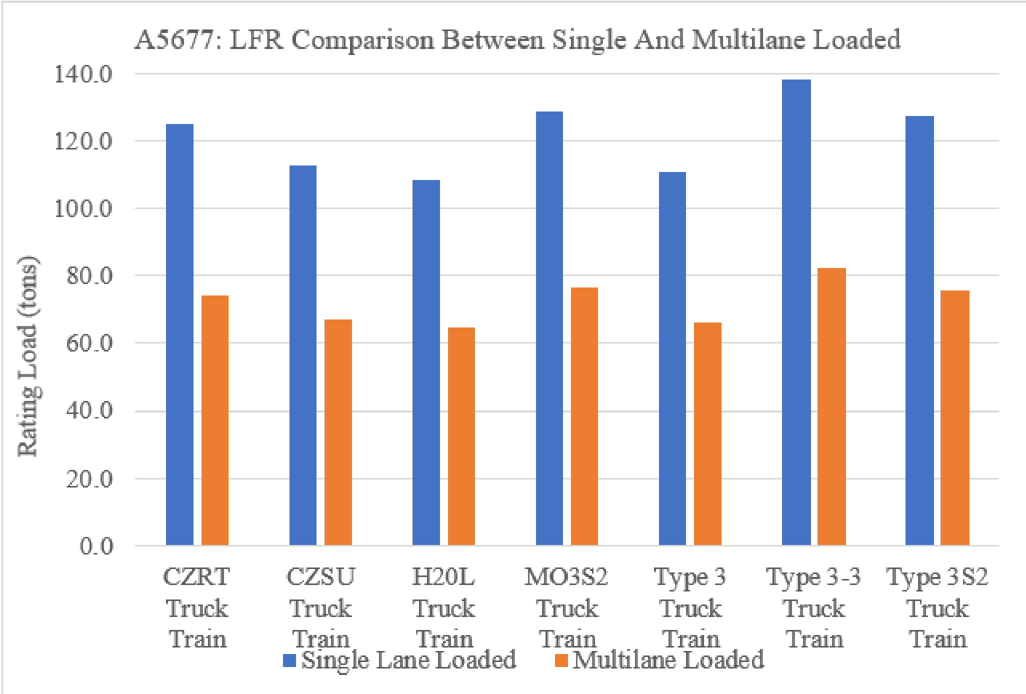
Table 5.14 and Figure 5.27 compare rating results from Bridge A3069, which show that multilane loaded rating results are lower than when analyzed as single lane loaded when using both LFR and LRFR. Type 3-3 truck train vehicles have the highest rating load while H20L truck train vehicles show the lowest when using both methods.

5.9.3 Bridge A5677 Single and Multilane Comparisons

Table 5.15 and Figures 5.28 compare single and multilane rating loads and factors for Bridge A5677.

Table 5.15: Comparison Data for A5677 for Single and Multilane

	Single Lane Loaded (tons)		Multilane Loaded (tons)	
Live Load Type Model	LFR	LRFR	LFR	LRFR
CZRT Truck Train	124.72	90.13	74.24	64.38
CZSU Truck Train	112.61	81.40	67.03	58.14
H20L Truck Train	108.48	78.40	64.57	56.00
MO3S2 Truck Train	128.63	92.97	76.57	66.41
Type 3 Truck Train	110.76	80.05	65.93	57.18
Type 3-3 Truck Train	138.44	100.12	82.41	71.52
Type 3S2 Truck Train	127.17	91.92	75.70	65.66



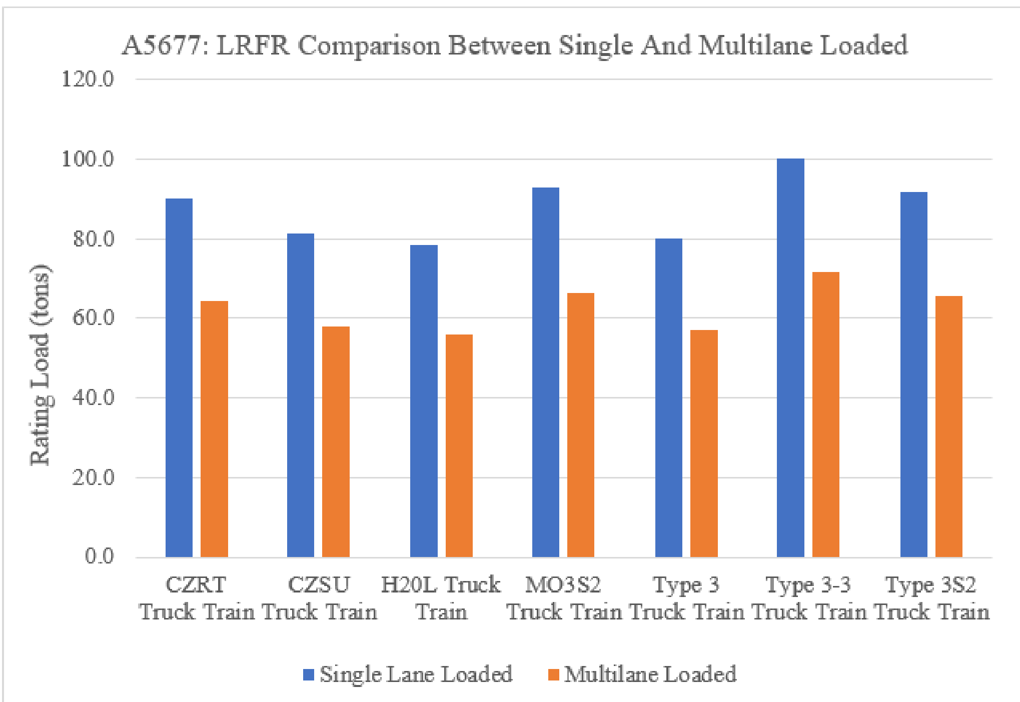


Figure 5.28: A5677 LFR and LRFR Columns Comparisons for SLL and MLL

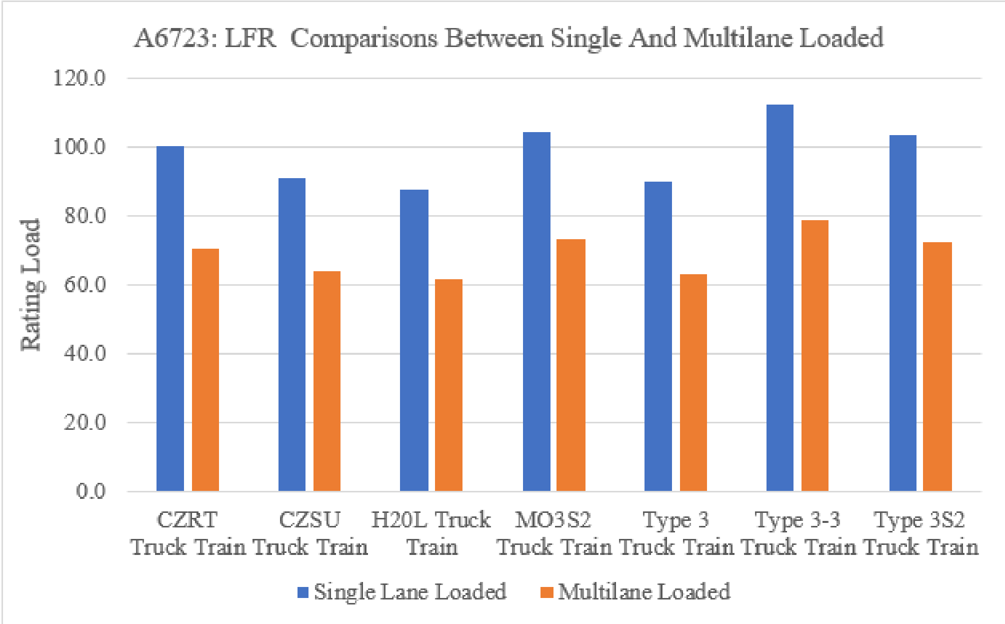
Table 5.15 and Figure 5.28 compare rating results from Bridge A5677 and show that multilane loaded rating results are less than single lane loaded when using both LFR and LRFR. Type 3-3 truck train vehicles have the highest rating load, while H20L truck train vehicles show the lowest load when using both rating methods.

5.9.4 Bridge A6723 Single and Multilane Comparisons

Table 5.16 and Figure 5.29 compares single and multilane rating loads and rating factors for Bridge A6723.

Table 5.16: Comparison Data for A6723 for Single and Multilane

	Single Lane Loaded (tons)		Multilane Loaded (tons)	
Live Load Type Model	LFR	LRFR	LFR	LRFR
CZRT Truck Train	100.53	75.38	70.54	60.57
CZSU Truck Train	91.28	68.44	64.05	54.99
H20L Truck Train	87.99	65.98	61.75	53.02
MO3S2 Truck Train	104.46	78.33	73.30	62.94
Type 3 Truck Train	90.22	67.65	63.31	54.36
Type 3-3 Truck Train	112.40	84.29	78.88	67.72
Type 3S2 Truck Train	103.56	77.66	72.68	62.40



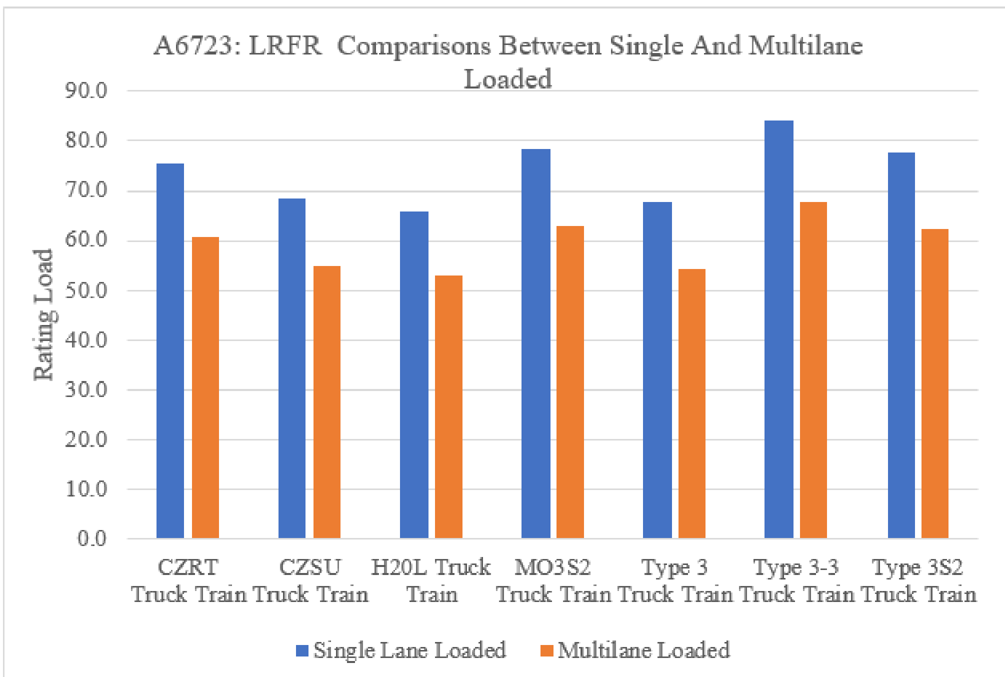


Figure 5.29: A6723 LFR and LRFR Columns Comparisons for SLL and MLL

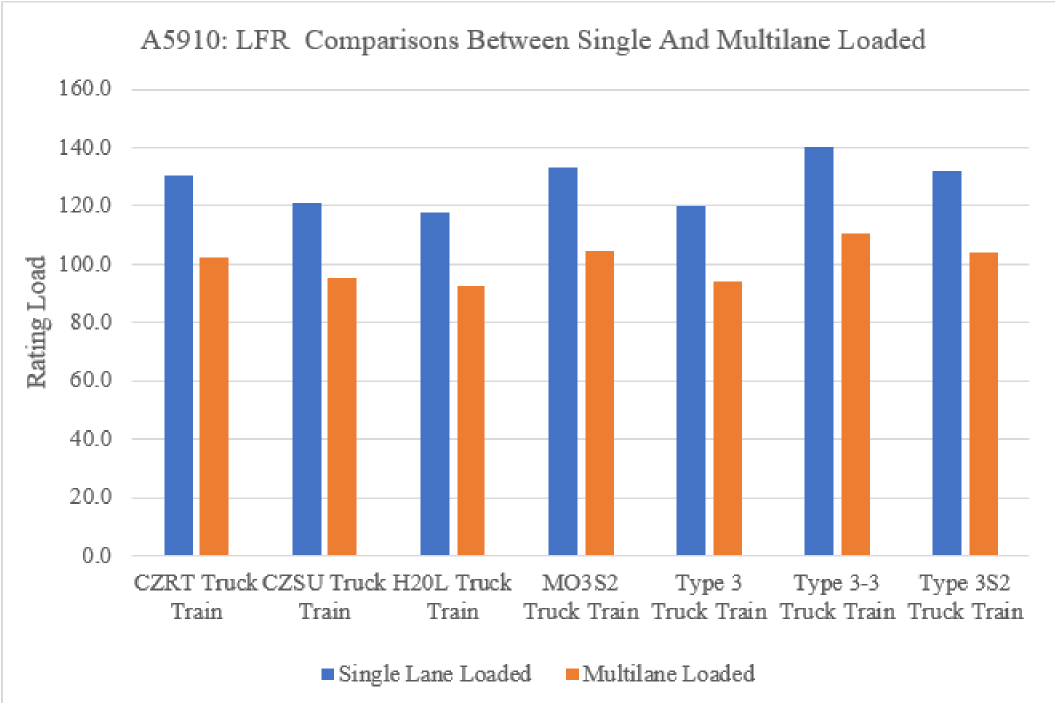
Table 5.16 and Figure 5.29 compares rating results from Bridge A6723 and shows that multilane loaded rating results are lower than single lane loaded when using both LFR and LRFR. Type 3-3 vehicles have the highest rating load while H20L vehicles show the lowest when using both methods. LFR is higher than LRFR for the truck train vehicles.

5.9.5 Bridge A5910 Single and Multilane Comparisons

Table 5.17 and Figure 5.30 compare single and multilane rating loads and rating factors for Bridge A5910.

Table 5.17: Comparison Data for A5910 for Single and Multilane

	Single Lane Loaded (tons)		Multilane Loaded (tons)	
Live Load Type Model	LFR	LRFR	LFR	LRFR
CZRT Truck Train	130.16	90.42	102.27	76.10
CZSU Truck Train	120.98	84.00	95.05	70.70
H20L Truck Train	117.65	81.68	92.44	68.74
MO3S2 Truck Train	133.16	92.50	104.63	77.84
Type 3 Truck Train	119.72	83.15	94.07	69.98
Type 3-3 Truck Train	140.52	97.60	110.41	82.13
Type 3S2 Truck Train	132.10	91.76	103.79	77.22



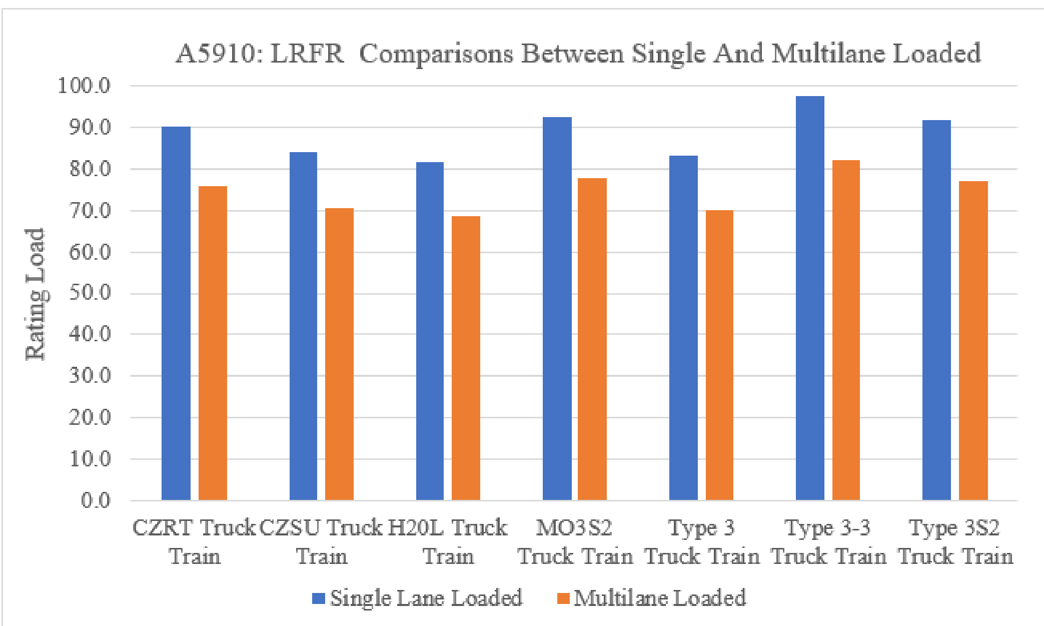


Figure 5.30: A5910 LFR and LRFR Single Lane and Multilane Comparisons

Table 5.16 and Figure 5.30 compare rating results from Bridge A5910 and show that multilane loaded rating results are lower than single lane loaded when using both LFR and LRFR. Type 3-3 vehicles have the highest rating load while H20L vehicles are the lowest when using both methods. LFR is higher than LRFR for the truck train vehicles.

5.10 MoDOT and AASHTO Vehicles Rating Comparisons for Bridges Greater Than 200 feet

MoDOT vehicles and AASHTO vehicles were compared for the five bridges that have span lengths greater than 200 feet. Vehicles selected included:

a) H20L and Type 3

b) MO3S2 and Type 3S2

c) CZRT and Type 3-3

When using both LFR and LRFR more MoDOT vehicles governed in postings than AASHTO vehicles. A division factor was used to compare groups of vehicles, and where the factor was greater than 1, the MoDOT vehicles governed, and where the factor was less than 1, the AASHTO vehicles governed. To ensure that the MoDOT vehicles generally governed, a factor identified as the lowest was recommended for posting for the MoDOT vehicles so they will envelop the AASHTO vehicles. Table D.6 compares LFR and LRFR for AASHTO and MoDOT vehicles for Bridge A2074. Figures 5.31 and 5.32 shows column comparisons.

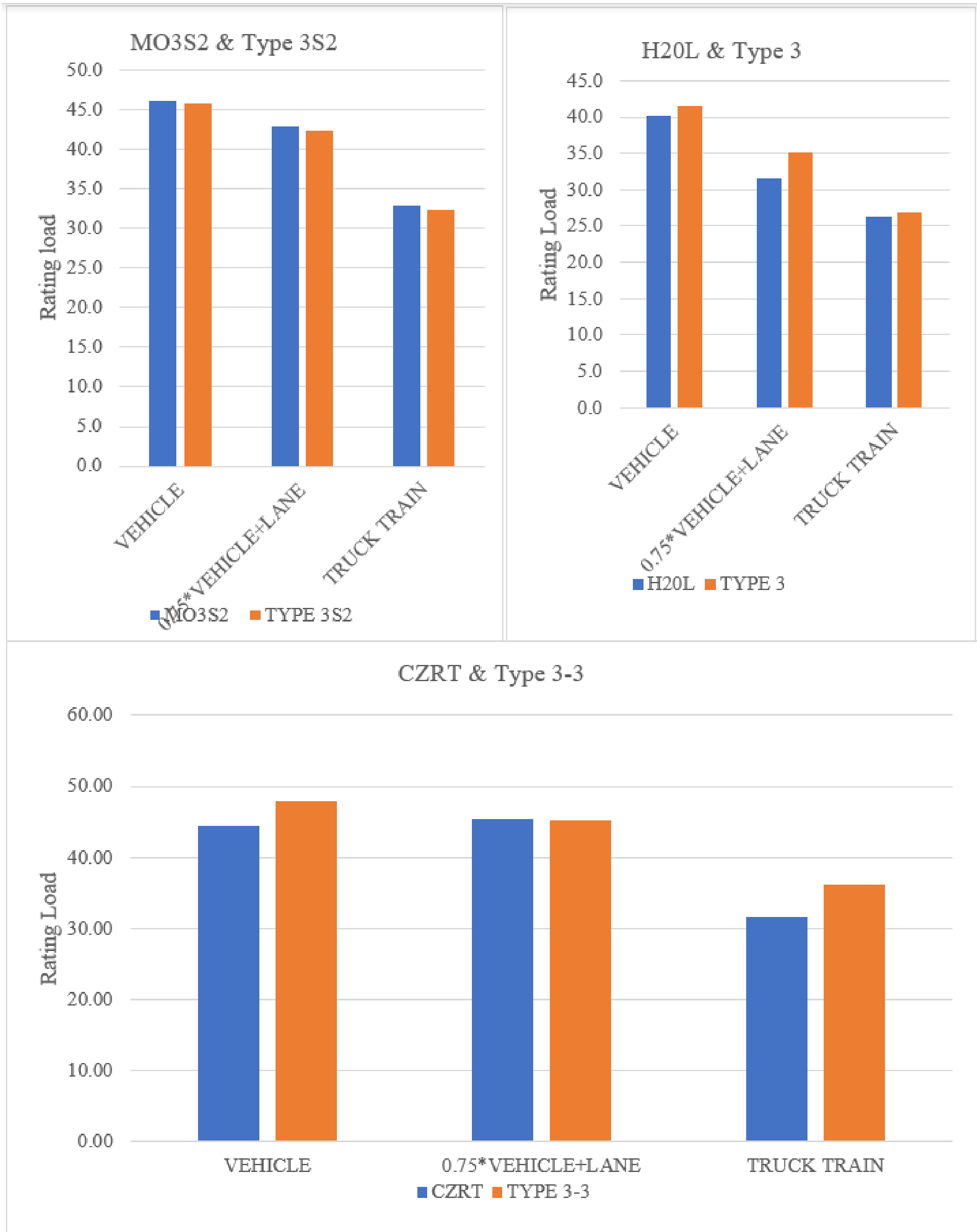


Figure 5.31: A2074 LFR Comparisons of MoDOT and AASHTO Vehicles

5.10.1 Bridge A2074 MoDOT and AASHTO Vehicles Comparisons

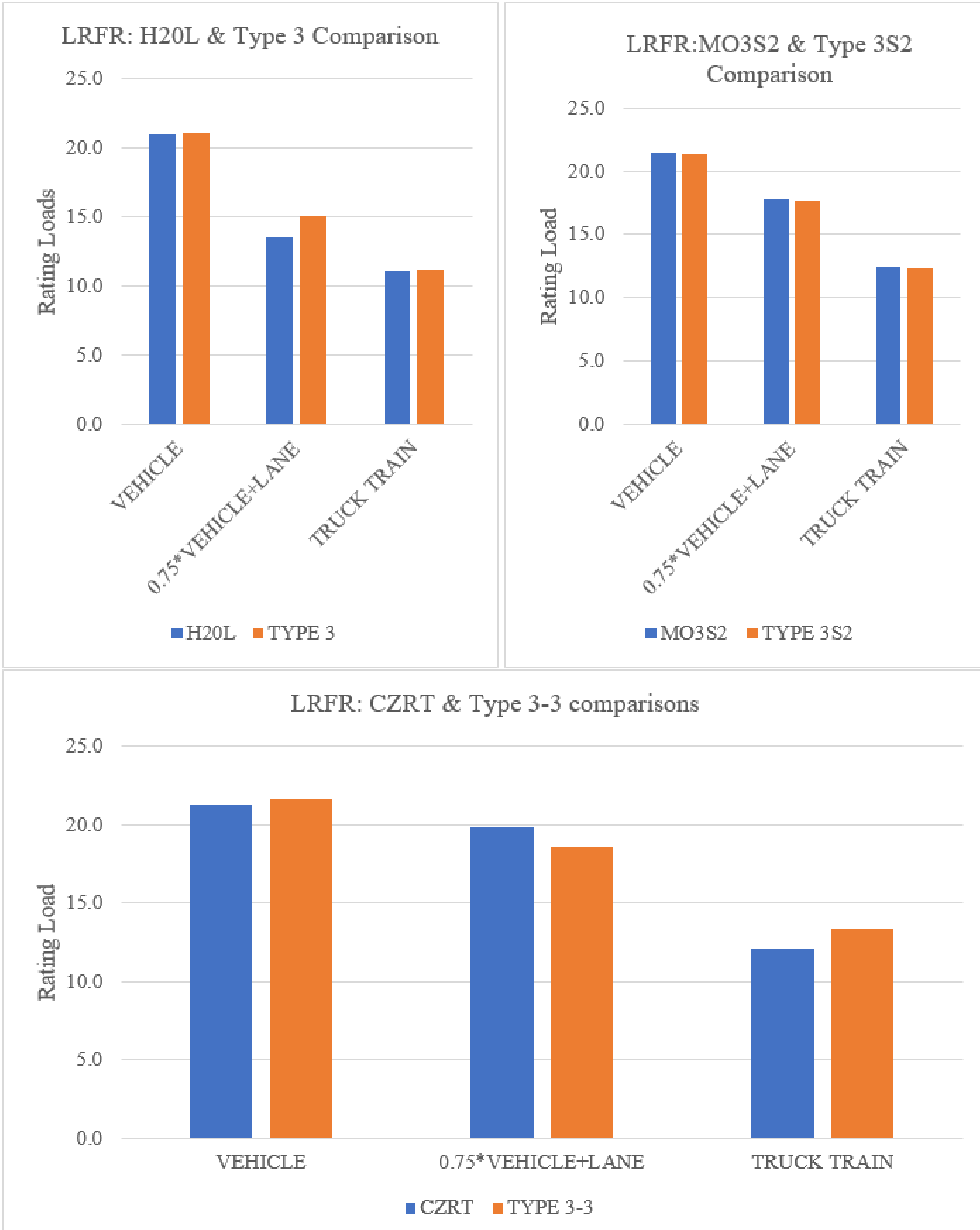


Figure 5.32: A2074 LRFR Comparisons of MoDOT and AASHTO Vehicles

The comparisons of rating loads and rating factors using LFR and LRFR for MoDOT and AASHTO vehicles for Bridge A2074 are summarized in Table D.6 and Figures 5.31 and 5.32. H20L vehicles govern against Type 3 vehicles and H20L truck train vehicles govern against Type

3 truck train vehicles. In addition, H20L *0.75 + 200 pounds per linear feet lane load governs against Type 3*0.75+ 200 pounds per linear feet lane load. When compared to Type 3S2 vehicles, MO3S2 governs only when not adjusted as a truck train or when the axles and lane load are adjusted as per MBE specifications. CZRT governs against Type 3-3 vehicles and CZRT truck train governs against Type 3-3 truck train.

5.10.2 Bridge A3069 MoDOT and AASHTO Vehicles Comparisons

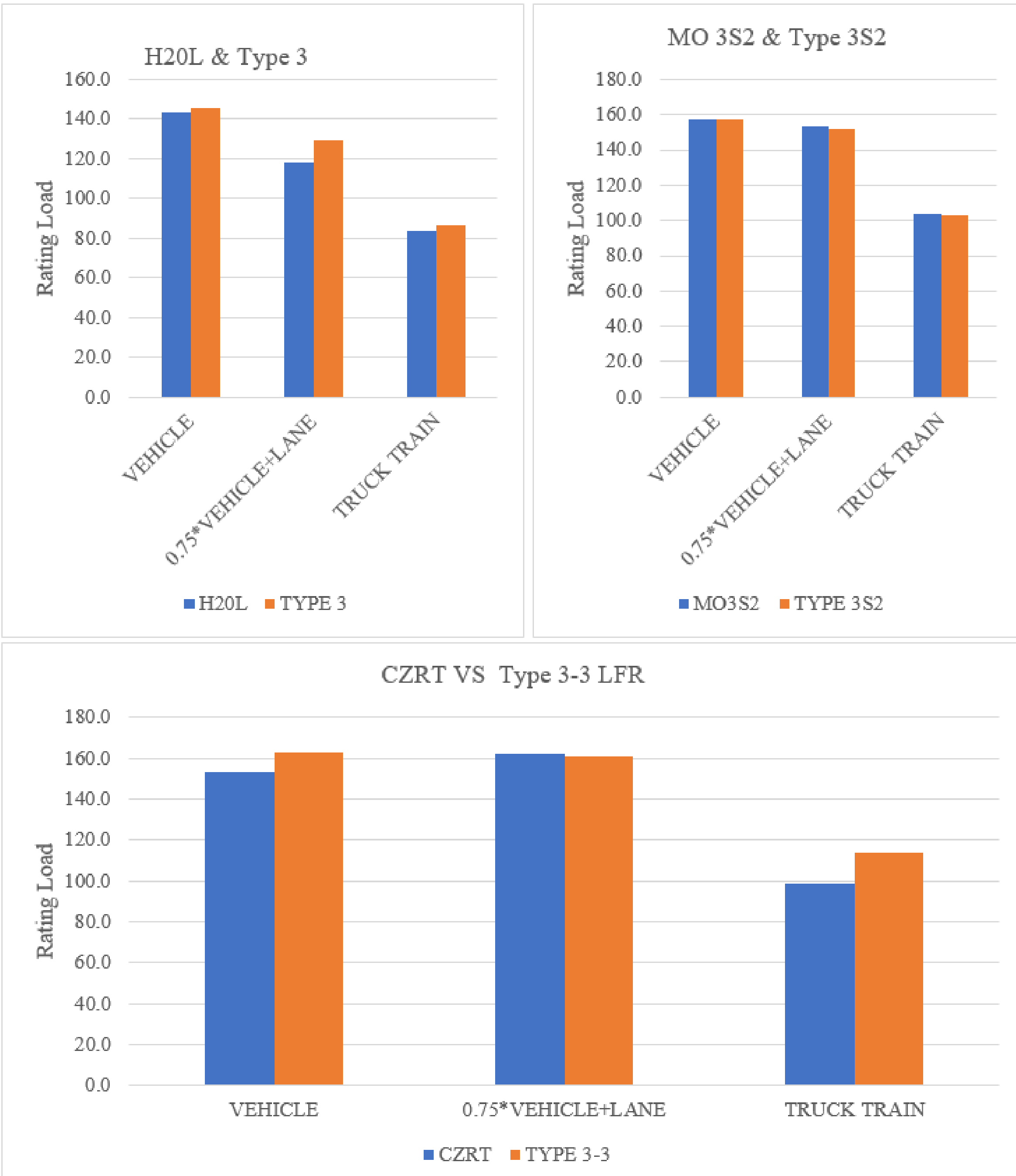


Figure 5.33: A3069 LFR Comparison of MoDOT and AASHTO Vehicles

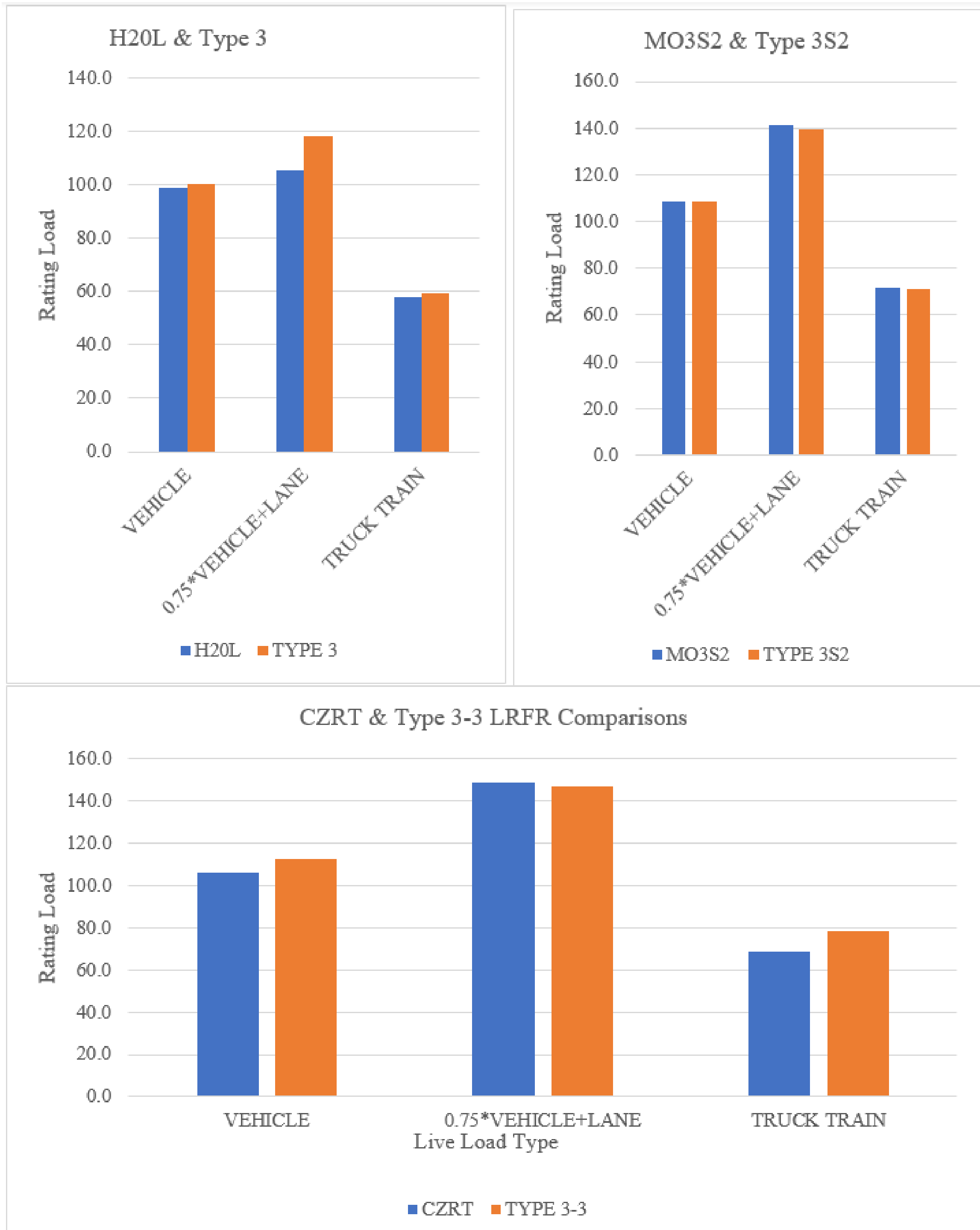


Figure 5.34: A3069 LRFR Comparisons of MoDOT and AASHTO Vehicles

The comparisons of rating loads and rating factors when using LFR and LRFR for MoDOT and AASHTO vehicles for Bridge A3069 are summarized in Table D.7 and Figures 5.33 and 5.34. H20L vehicles govern against Type 3 vehicles, and H20L truck train vehicles govern against Type 3 truck train vehicles. In addition, H20L*0.75 + lane and H20L truck train govern against

Type 3, Type 3*0.75 + lane, and Type 3 truck train. MO3S2 governs against Type 3S2 in LFR and shows almost equal values in LRFR. MO3S2*0.75 + lane requires a factor of 0.99 as shown in Table D.7 to envelop Type 3S2*0.75 + lane in LFR and LRFR. MO3S2 truck train envelops Type 3S2 truck train in both LFR and LRFR by using a scaling factor of 0.99 shown in Table D.7. CZRT vehicle envelops Type 3-3 with no scaling factor applied to it in both LFR and LRFR.

5.10.3 Bridge A5677 MoDOT and AASHTO Vehicles Comparisons

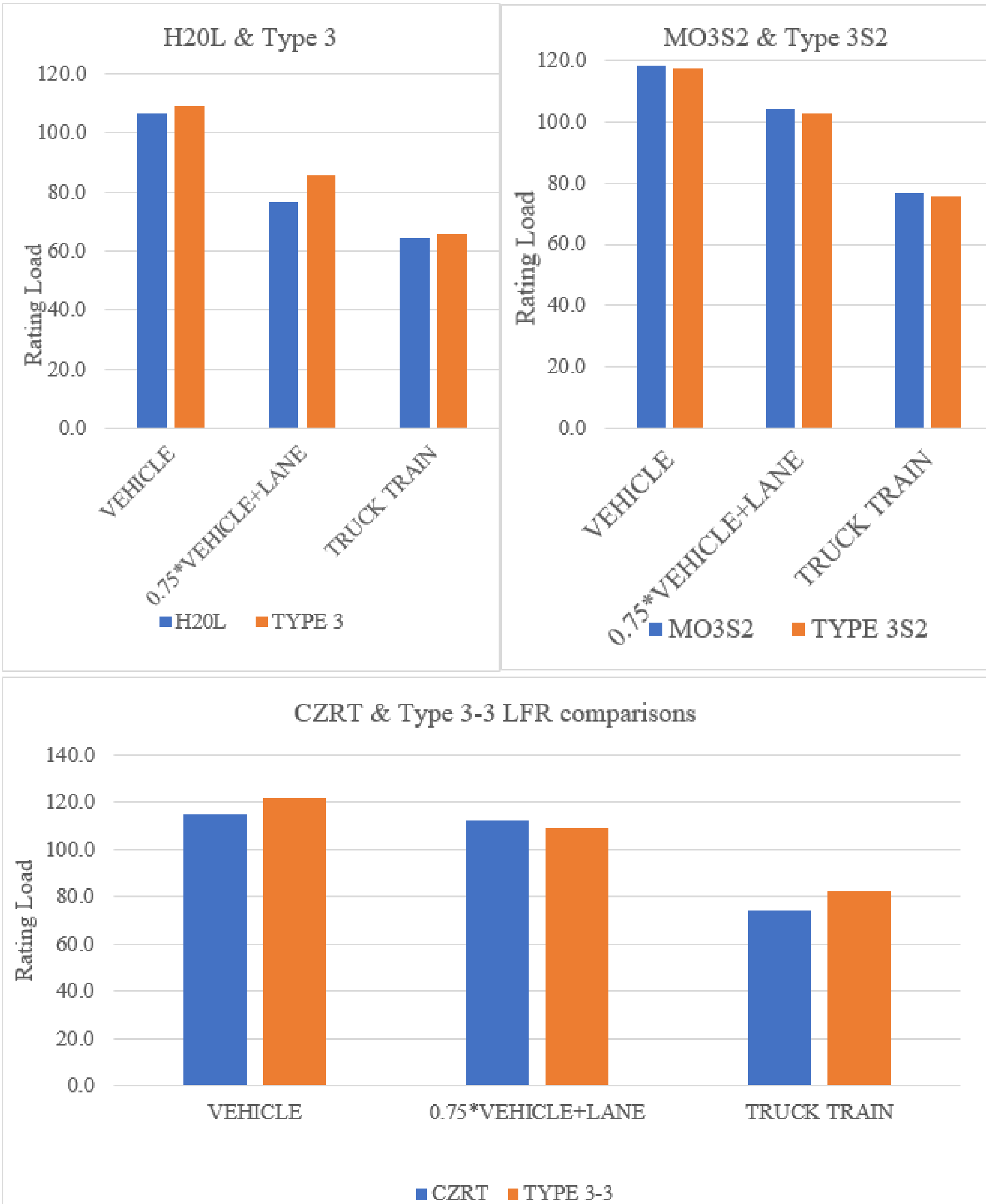


Figure 5.35: A5677 LFR Comparisons for MoDOT and AASHTO Vehicles

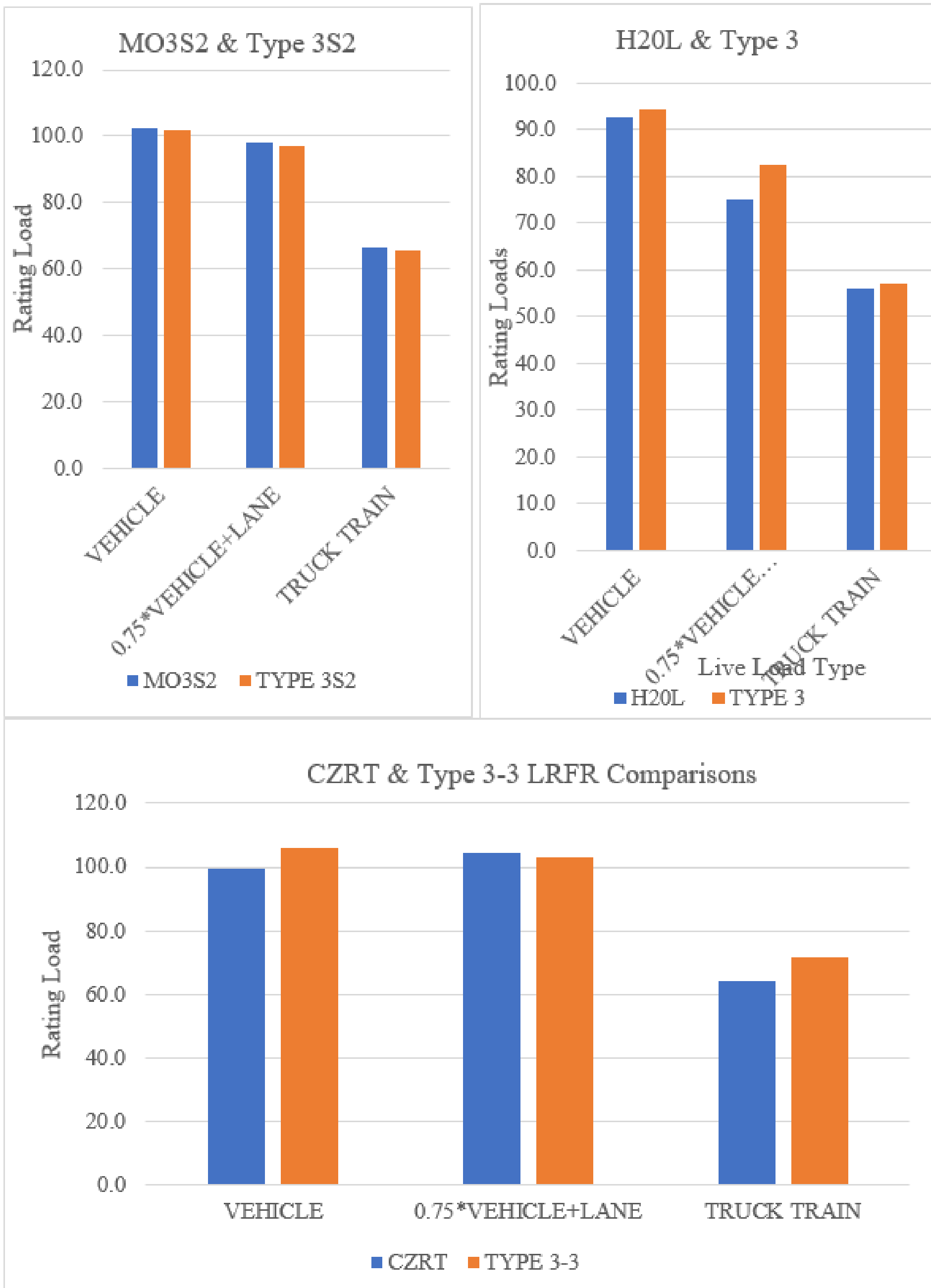


Figure 5.36: A5677 LFR Comparisons for MoDOT and AASHTO Vehicles

The comparisons of rating loads and rating factors when using LFR and LRFR for MoDOT and AASHTO vehicles for Bridge A5677 are summarized in Table D.8 and Figures 5.35 and 5.36. For this bridge, H20L, H20L*0.75 + lane and H20L truck train envelops Type 3, Type 3*0.75 + lane and Type 3 truck train. MO3S2, MO3S2*0.75 + lane and MO3S2 truck train require a scaling factor of 0.99 to envelop Type 3S2, Type 3S2*0.75 + lane and Type 3S2 truck train as shown in Table D.8. In addition, CZRT and CZRT truck train envelops Type 3-3 and Type 3-3 truck train without a scaling factor in both LFR and LRFR.

5.10.4 Bridge A6723 MoDOT and AASHTO Vehicles Comparisons

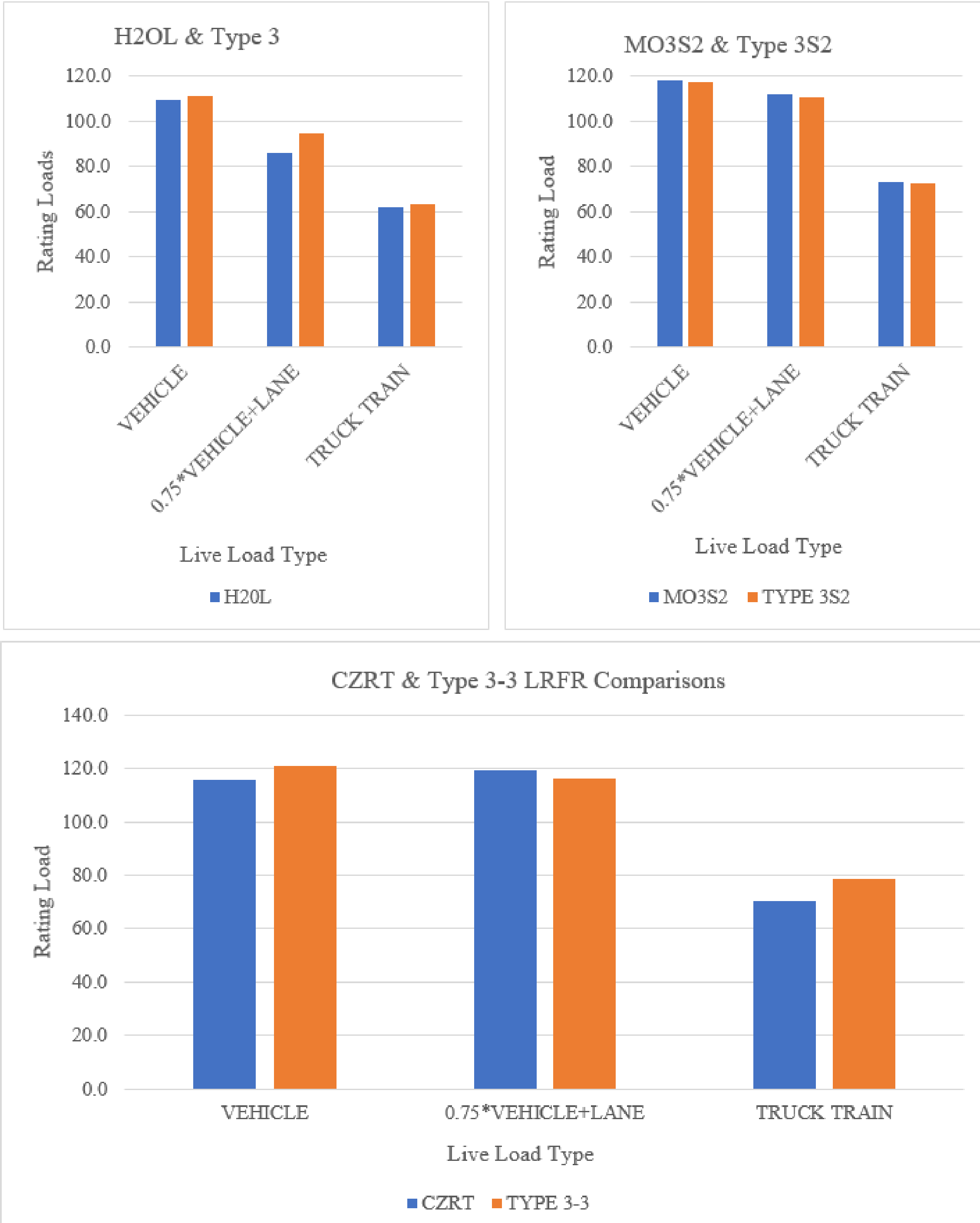


Figure 5.37: A6723 LFR Comparison of MoDOT and AASHTO Vehicles

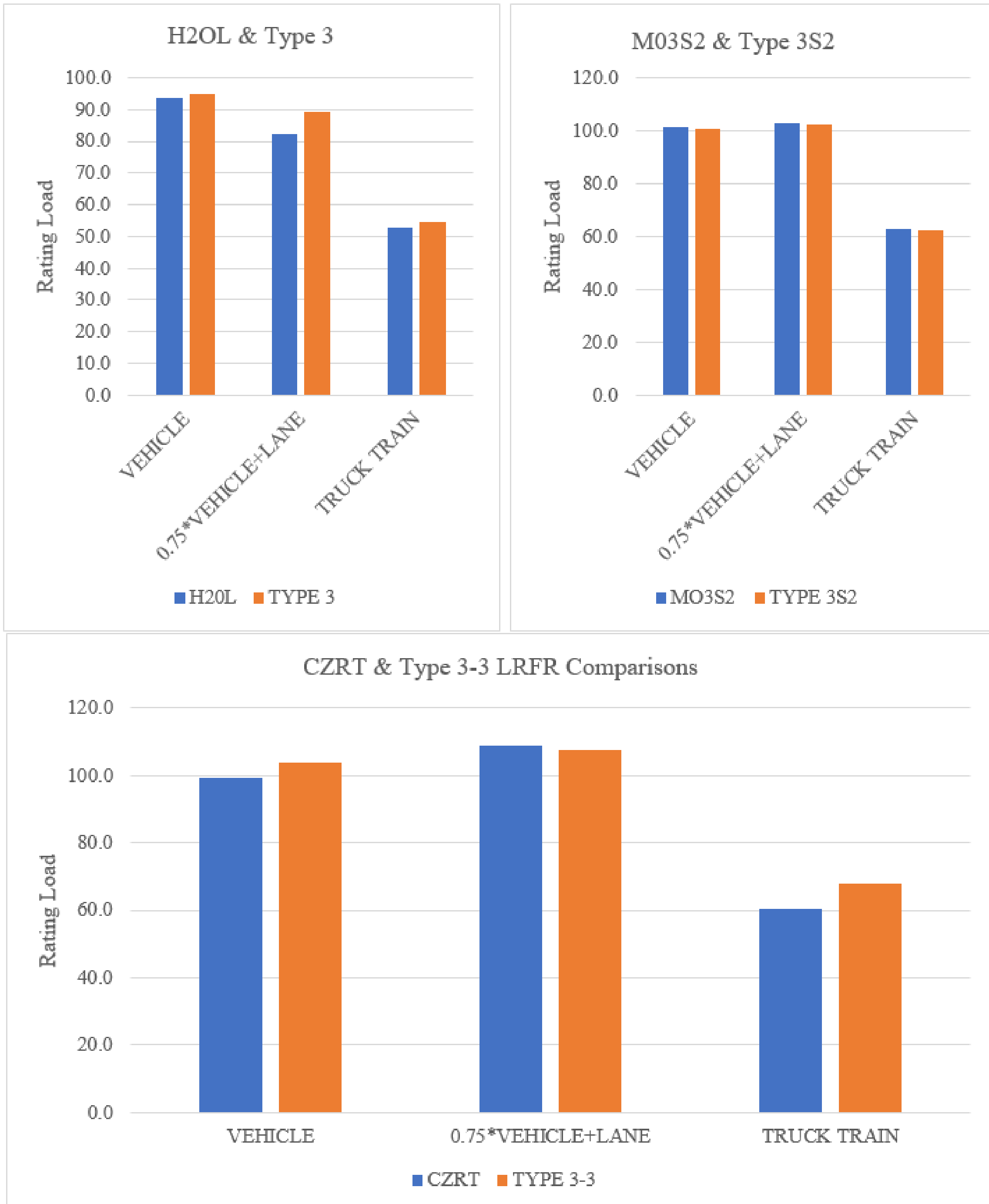


Figure 5.38: A6723 LRFR Comparison for MoDOT and AASHTO Vehicles

The comparisons of rating loads and rating factors when using LFR and LRFR for MoDOT and AASHTO vehicles for Bridge A6723 are summarized in Table D.9 and Figures 5.37 and 5.38. For this bridge, H20L, H20L*0.75 + lane and H20L truck train envelops Type 3, Type 3*0.75 + lane, and Type 3 truck train when using the two rating methods. MO3S2*0.75 + lane and MO3S2 truck train require a scaling factor of 0.99 to envelop Type 3S2*0.75 + lane and Type 3S2 truck train as shown in Table D.9. In addition, CZRT and CZRT truck train envelops Type 3-3 and Type 3-3 truck train without a scaling factor in both LFR and LRFR.

5.10.5 Bridge A5910 MoDOT and AASHTO Vehicles Comparisons

Figure 5.39: A5910 LFR Comparison for MoDOT and AASHTO Vehicles

Figure 5.40: A5910 LRFR Comparison for MoDOT and AASHTO Vehicles

The comparisons of rating loads and rating factors when using LFR and LRFR for MoDOT and AASHTO vehicles for Bridge A5910 are summarized in Table D.10 and Figures 5.39 and 5.40. For this bridge, H20L, H20L * 0.75 + lane and H20L truck train envelops Type 3, Type 3*0.75 + lane, and Type 3 truck train when using the two methods of rating. MO3S2*0.75+ lane and

MO3S2 truck train require a scaling factor of 0.99 to envelop Type 3S2*0.75 + lane and Type 3S2 truck train as shown in Table D.10. In addition, CZRT and CZRT truck train envelops Type 3-3 and Type 3-3 truck train without a scaling factor in both LFR and LRFR. CZRT*0.75 + lane requires a factor of 0.96 to envelop Type 3-3*0.75 + lane in LRFR, and 0.95 in LFR.

5.11 Summary of LRFR and LFR Comparisons for MoDOT and AASHTO Vehicles

Table 5.18 summarizes factors derived from comparing the AASHTO and MoDOT vehicles. They were obtained from the minimum factors from the five bridges used for this study with both LFR and LRFR. Tables 5.18, 5.19, and 5.20 show that the two methods of rating MoDOT and AASHTO vehicles produce similar scaling factors.

Table 5.18: Comparison of Scaling Factors for MoDOT and AASHTO Vehicles

	LFR Factors		
Live Load	Type 3	0.75*Type 3 + Lane	Type 3 Truck Train
H20L	1.014	-	-
0.75*H20L+Lane	-	1.096	-
H20L Truck Train	-	-	1.018

	LRFR Factors		
Live Load	Type 3	0.75*Type 3 + Lane	Type 3 Truck Train
H20L	1.003	-	-
0.75*H20L+Lane	-	1.084	-
H20L Truck Train	-	-	1.012

Table 5.18 shows that H20L, H20L*0.75 + lane and H20L truck train vehicles all envelop Type 3, Type 3*0.75 + lane and Type 3 truck train vehicles when using both methods of rating. The scaling factors for the rating loads for the two methods are almost equal.

Table 5.19: Comparison of Scaling Factors for MoDOT and AASHTO Vehicles

	LFR Factors		
Live Load	Type 3S2	0.75*Type 3S2 + Lane	Type 3S2 Truck Train
MO3S2	0.992	-	-
0.75*MO3S2+Lane	-	0.988	-
MO3S2 Truck Train	-	-	0.985

	LRFR Factors		
Live Load	Type 3S2	0.75*Type 3S2 + Lane	Type 3S2 Truck Train
MO3S2	0.994	-	-
0.75*MO3S2+Lane	-	0.989	-
MO3S2 Truck Train	-	-	0.989

Table 5.19 compares MO3S2 MoDOT vehicles and AASHTO Type 3S2 vehicles with various model adjustments and shows that MO3S2 will envelop Type 3S2 with a scaling factor of 0.992 in LFR and a factor of 0.994 in LRFR. MO3S2*0.75 + lane requires a scaling factor of 0.988 in LFR and 0.989 in LRFR to envelop Type 3S2*0.75 + lane. To completely envelop the AASHTO Type 3S2 vehicles, MO3S2 vehicles use a scaling factor similar to those shown in Table 5.19. Table 5.20 shows comparison factors for CZRT, CZRT*0.75 + lane, and CZRT truck train against Type 3-3, Type 3-3*0.75 + lane, and Type 3-3 truck trains.

Table 5.20: Comparison Factors for MoDOT and AASHTO Vehicles

	LFR Factors		
Live Load	Type 3-3	0.75*Type 3-3 + Lane	Type 3-3 Truck Train
CZRT	1.048	-	-
0.75*CZRT+ Lane	-	0.946	-
CZRT Truck Train	-	-	1.079

	LRFR Factors		
Live Load	Type 3-3	0.75*Type 3-3 + Lane	Type 3-3 Truck Train
CZRT	1.019	-	-
0.75*CZRT+ Lane	-	0.936	-
CZRT Truck Train	-	-	1.079

Table 5.20 shows that MoDOT CZRT vehicles govern against AASHTO Type 3-3 vehicles and that CZRT *0.75 + lane needs a factor of 0.946 in LFR and a factor of 0.936 in LRFR to envelop Type 3-3*0.75 + lane when using both methods of rating.

Comparing Tables 5.18, 5.19, and 5.20 shows that the factors for LRFR and LFR are very close, and therefore, the comparisons for these vehicles are the same for LFR and LRFR. In LRFR most MoDOT vehicles envelop AASHTO vehicles and SHVs. Some MoDOT vehicles need a scaling factor to envelop the rest of the AASHTO vehicles that show similar posting values. Tables 5.18, 5.19, and 5.20 along with Table D.6-Table D.10 in the appendix section show some factors which are less than 1, which can be used by MoDOT vehicles to envelop the rest of the AASHTO live loads like the Type 3, Type 3-3, Type 3S2 operating within the state of Missouri.

Practices in Other States: Below is some information on how other states address the rating of permit vehicles in LFR and LRFR both for simple spans and continuous spans greater or less than 200 ft.

Virginia (VDOT): The vehicles used in LFR and LRFR rating in BrR for Virginia DOT are shown below.

LFR

- Inventory: HS 20-44, NRL, NV-3, NV-4, SU4, SU5, SU6, SU7, VA TYPE 3, VA TYPE 3S2

- Operating: HS 20-44, NRL, NV-3, NV-4, SU4, SU5, SU6, SU7, VA TYPE 3, VA TYPE 3S2
- Legal operating: EV2 with adjacent vehicle SU7 and EV3 with SU7 adjacent vehicle

LRFR

- Design load rating Inventory: HL-93(US), HS 20-44
- Design load rating Operating: HL-93(US), HS 20-44
- Legal load rating /Routine: EV2, EV2 One_lane, EV3, EV3 One_lane, VA TYPE 3, VA TYPE 3S2
- Legal load rating /Specialized Hauling: NRL, SU4, SU5, SU6, SU7
- Permit load rating: NV-3 with no adjacent vehicle, NV-4 with no adjacent vehicle.

NV-3 and the NV-4 are their permit vehicles. In LFR, they do NOT have a lane load or an adjacent vehicle. They rely solely on the live load factor (1.3 for LFR) and the single-lane and multi-lane LLDFs to represent the maximum load effect. In LRFR, they do add a lane load of 0.266 klf (0.200 klf * 1.33 Str. II load factor) for their permit vehicles for simple spans greater than 200' or continuous bridges. In all cases, they run their permit vehicles as "unlimited crossings" or "mixed with traffic" which results in a larger load factor than specifying "single trip" and/or "escorted" permit load case. BrR applies load factors based on inputs according to Table 6A.4.5.4.2a-1 of the MBE for all permit vehicles. MBE has a good explanation for how the permit vehicles should be analyzed (and what BrR defaults to). When specifying unlimited crossings accurate ADTT info must be input into BrR.

Colorado (CDOT): CDOT follows a process similar to VDOT with the below exception.

- For LFR, bridges constructed before 1985 (i.e., the time when design switched from ASD to LFD) have legal and permit vehicles run as "single lane loaded" unless the structure is non-redundant/fracture critical. Otherwise, CDOT functions similarly to VDOT.
- For LRFR, spans greater than 200' a lane load is added similar to VDOT.

For LRFR, BrR defaults to the MBE but relies on proper inputs for the vehicle and analysis settings. For VDOT and CDOT, this means adding the lane load and load factor for simple spans greater than 200' or continuous spans. This also means selecting the appropriate "Frequency" such as Unlimited Crossings. These steps generate acceptable results per the MBE so long as the permit vehicle axle loading, and weights are tuned appropriately by MoDOT to envelope any "real" permit vehicle configuration and loading. From there, the load factors and lane loading per the MBE and AASHTO account for potential adjacent lane loading or "train-type" loading in a single lane.

For LFR, if MoDOT is looking for a more simplified approach they could follow what VDOT and CDOT do so long as they have an enveloping permit vehicle definition. In that case, no lane load or "vehicle train" would be needed even for spans greater than 200' or continuous.

5.12 Conclusions and Recommendations

The research conducted to compare the two rating methods shows that LFR and LRFR differ in several ways. Comparing LFR and LRFR shows that most bridges rated in LFR govern in interior girders, while when using LRFR, most bridges will govern in the exterior girders, and this is summarized in Table 5.1. Generally, ratings are lower when using LRFR than when using LFR, and therefore this will affect the number of bridges that require posting. Table 5.3 shows that posted bridges increased by 22% for H20L, 14.3 % for CZSU, 23.8% for CZRT, and 30.5% for MO3S2, indicating that bridges requiring posting increases when using LRFR.

The posting threshold MoDOT currently uses needs to conform with the use of the LRFR. The research indicates posting thresholds used for CZSU (45 tons) and CZRT (70 tons) within the commercial zones need to be reduced to their GWTs of 40.8 tons and 51 tons, respectively. With the reductions, CZSU will be able to envelop SU4, SU5, SU6, and SU7, while CZRT will be able to envelop Type 3-3 and Type 3S2 as shown in Table 5.8. The use of the current thresholds for the two vehicles seems conservative and leads to more bridges being posted. H20L, which in the current live load model for LFR has a posting threshold of 30 tons, needs to be revised to 31 tons in LRFR. The posting load factors also need to be revised to meet the requirements of LRFR. A factor of 0.94 can be used for H20L, 0.96 for MO3S2, 0.97 for CZRT, and 0.91 for CZSU. The minimum factor of 0.91 obtained from Table 5.8 can be used conservatively for posting just as a factor of 0.86 is currently used in LFR.

Service II limit state factor changes from 1.3 to 1.0 significantly reduced the number of bridges that required posting. Also, most rating loads and rating factors improved by up to 30% of their initial values. Hopefully, the data produced from this study can help MoDOT decide whether to make any changes concerning the revision of Service II limit state factors.

For bridges that have spans greater than 200 feet, most MoDOT vehicles envelop AASHTO vehicles, though some will require a factor in posting. Table D.6-Table D.10 in the appendix shows that for the sample of bridges used, H20L, H20L*0.75 + lane and H20L truck train envelops Type 3, Type 3*0.75 + lane and Type 3 truck train when using LFR and LRFR. MO3S2, MO3S2*0.75 + lane, and MO3S2 truck train require a scaling factor of 0.98 to envelop Type 3S2, Type 3*0.75 + lane, and Type 3S2 truck train. CZRT and CZRT truck trains can envelop Type 3-3 and Type 3-3 truck trains without a scaling factor in both LFR and LRFR. CZRT*0.75 + lane requires a scaling factor of 0.93 to envelop Type 3-3*0.75 + lane when using both methods of rating.

The rating results for bridges with spans greater than 200 feet showed that Type 3-3 has the highest rating loads while the H20 truck train has the lowest rating loads when using both rating methods. LFR has higher rating factors and rating loads than LRFR. Generally, truck trains have the lowest rating loads and therefore govern by being the most conservative in both LRFR and LFR.

When single-lane loaded and multilane loaded bridges were compared, ratings for multilane loaded bridges were more conservative than the single-lane loaded bridges when using both LFR and LRFR.

From a practice perspective, using BrR Jacobs Engineering has completed the rating of a Truss-Floorbeam-Stringer bridge that has a span length of 200 feet and a three-span continuous steel girder (11 steel girders) bridge with span lengths 112 feet – 210 feet – 112 feet. The results seemed to make sense for both the bridges and the rating report has been accepted by the client. BrR defaults to rating structures according to the current AASHTO LRFD (if selected for analysis) and the associated AASTHO and MBE code at the time of the BrR version release. The user has the option to change the code type, but that would have to be done manually and can be checked to make sure it is correctly assigned. In most cases, any discrepancies from AASHTO LRFD or the MBE code would be due to an error in that version of BrR.

5.13 Effect of Lateral Torsional Buckling

A study was conducted to determine if the steel bridges rating was controlled by the lateral torsional buckling mode. Seventy-one steel bridges were rated using BrR AASHTOWare by the LRFR rating methodology using HL-93 (US) (Truck + lane) at the operating rating level. The results are shown in Table 5.21.

Table 5.21 LRFR Rating of Steel Bridges using HL-93 at the Operating Rating Level

	BRIDGE ID	Limit State	R.F (LRFR) (HL-93 Operating)	Flexure Type	LTB Check PASS/FAIL
1	R0531	STRENGTH-I Steel Flexure	0.00	Neg	FAIL
2	A0001	STRENGTH-I Steel Flexure Stress	1.913	Neg	PASS
3	A0172	STRENGTH-I Steel Flexure Stress	1.188	Neg	PASS
4	A0258	SERVICE-II Steel Flexure Stress	1.105	Neg	PASS
5	A0467	STRENGTH-I Steel Flexure Stress	0.867	Neg	FAIL
6	A0476N	STRENGTH-I Steel Flexure Stress	1.048	Neg	PASS
7	A0611	STRENGTH-I Steel Flexure Stress	0.371	Neg	FAIL
8	A0723	STRENGTH-I Steel Flexure Stress	0.643	Neg	FAIL
9	A0764	STRENGTH-I Steel Flexure Stress	0.883	Neg	FAIL
10	A0812	STRENGTH-I Steel Flexure Stress	0.646	Neg	FAIL

	BRIDGE ID	Limit State	R.F (LRFR) (HL-93 Operating)	Flexure Type	LTB Check PASS/FAIL
11	A0872	STRENGTH-I Steel Flexure Stress	0.562	Neg	FAIL
12	A0996	STRENGTH-I Steel Flexure Stress	0.520	Neg	FAIL
13	A01031	STRENGTH-I Steel Flexure Stress	1.349	Neg	PASS
14	A1066	STRENGTH-I Steel Flexure Stress	0.50	Neg	FAIL
15	A1096	STRENGTH-I Steel Flexure Stress	0.333	Neg	FAIL
16	A1144S	STRENGTH-I Steel Flexure Stress	1.390	Neg	PASS
17	A1149	SERVICE-II Steel Flexure Stress	1.411	Neg	PASS
18	A1159N	STRENGTH-I Steel Flexure Stress	1.188	Neg	PASS
19	A1166	STRENGTH-I Steel Flexure Stress	1.331	Neg	PASS
20	A1167	STRENGTH-I Steel Flexure Stress	1.205	Neg	PASS
21	A1272	STRENGTH-I Steel Flexure Stress	0.604	Neg	FAIL
22	A1293N	STRENGTH-I Steel Flexure Stress	0.498	Neg	FAIL
23	A1466N	STRENGTH-I Steel Flexure	0.207	Neg	FAIL
24	A1608E	STRENGTH-I Steel Flexure Stress	0.556	Neg	FAIL
25	A1836	STRENGTH-I Steel Flexure	0	Neg	FAIL
26	A1866	STRENGTH-I Steel Flexure Stress	0.400	Neg	FAIL
27	A1918	STRENGTH-I Steel Shear	0.710	Neg	PASS
28	A1961	STRENGTH-I Steel Flexure Stress	0.444	Neg	FAIL
29	A1990	STRENGTH-I Steel Flexure Stress	0.479	Neg	FAIL
30	A2014W	STRENGTH-I Steel Flexure Stress	0.626	Neg	PASS
31	A2035	STRENGTH-I Steel Flexure Stress	0.412	Neg	FAIL
32	A2140	STRENGTH-I Steel Flexure Stress	0.472	Neg	FAIL

	BRIDGE ID	Limit State	R.F (LRFR) (HL-93 Operating)	Flexure Type	LTB Check PASS/FAIL
33	A2075	STRENGTH-I Steel Flexure Stress	0.368	Neg	FAIL
34	A2126	STRENGTH-I Steel Shear	2.590	Neg	PASS
35	A2207	STRENGTH-I Steel Flexure Stress	0.853	Neg	PASS
36	A2223S	STRENGTH-I Steel Flexure Stress	1.743	Neg	PASS
37	A2334	STRENGTH-I Steel Flexure Stress	0.815	Neg	FAIL
38	A2336	STRENGTH-I Steel Flexure Stress	1.303	Neg	PASS
39	A2350W	STRENGTH-I Steel Flexure Stress	0.919	Neg	FAIL
40	A2364	STRENGTH-I Steel Flexure Stress	0.902	Neg	FAIL
41	A2497	STRENGTH-I Steel Flexure Stress	0.708	Neg	FAIL
42	A2522	SERVICE-II Steel Flexure Stress	1.464	Neg	PASS
43	A2569	STRENGTH-I Steel Flexure Stress	1.320	Neg	PASS
44	A2606	STRENGTH-I Steel Flexure Stress	0.698	Neg	PASS
45	A2903	STRENGTH-I Steel Flexure Stress	0.582	Neg	FAIL
46	A2929	STRENGTH-I Steel Flexure Stress	0.541	Neg	FAIL
47	A2933	SERVICE-II Steel Flexure Stress	1.274	Neg	PASS
48	A2956	STRENGTH-I Steel Shear	1.234	Neg	PASS
49	A2992	STRENGTH-I Steel Flexure Stress	1.183	Neg	PASS
50	A3050	STRENGTH-I Steel Flexure Stress	0.372	Neg	FAIL
51	A3342	STRENGTH-I Steel Flexure Stress	1.127	Neg	PASS
52	A3813	STRENGTH-I Steel Flexure Stress	0.667	Neg	FAIL
53	A4142	STRENGTH-I Steel Shear	2.084	Neg	PASS

	BRIDGE ID	Limit State	R.F (LRFR) (HL-93 Operating)	Flexure Type	LTB Check PASS/FAIL
54	A5458	STRENGTH-I Steel Shear	2.029	Neg	PASS
55	A20501	STRENGTH-I Steel Flexure Stress	0.078	Neg	FAIL
56	F0604	STRENGTH-I Steel Flexure Stress	0.684	Neg	PASS
57	JO344	STRENGTH-I Steel Flexure Stress	0.941	Neg	PASS
58	L0158	SERVICE-II Steel Flexure Stress	1.253	Neg	PASS
59	L0597	STRENGTH-I Steel Flexure Stress	0.944	Neg	PASS
60	L0598	STRENGTH-I Steel Flexure Stress	1.503	Neg	PASS
61	L0791	STRENGTH-I Steel Flexure Stress	1.739	Neg	PASS
62	N0038	STRENGTH-I Steel Flexure Stress	0.524	Neg	FAIL
63	N0047	STRENGTH-I Steel Flexure Stress	0.439	Neg	FAIL
64	N0145	STRENGTH-I Steel Flexure Stress	0.354	Neg	FAIL
65	N0388	STRENGTH-I Steel Flexure Stress	0.463	Neg	FAIL
66	N0447	STRENGTH-I Steel Flexure Stress	0.135	Neg	FAIL
67	N0631	STRENGTH-I Steel Flexure Stress	0.324	Neg	FAIL
68	N0706	STRENGTH-I Steel Flexure Stress	0.312	Neg	FAIL
69	P0581	STRENGTH-I Steel Flexure Stress	0.000	Neg	FAIL
70	R0091	STRENGTH-I Steel Flexure Stress	0.580	Neg	FAIL
71	R0232	STRENGTH-I Steel Flexure Stress	0.193	Neg	FAIL

Table 5.21 shows that all the bridges with a rating factor above 1 passed the Lateral Torsional Buckling (LTB) check. When the rating factor goes below 1, we observed that some bridges also failed the Lateral Torsional Buckling check. The lowest rating factor for a bridge that had a pass in LTB was 0.626, while the rest of the bridges with ratings below 0.5 failed in LTB.

5.13.1 Graphical Comparisons

The rating loads from the LFR and LRFR were compared for the bridges that passed the lateral torsional buckling check. The vehicles live loads used for this comparison study are CZSU, H20L, MO3S2, SU5, and CZRT. A factor was then generated from the comparisons of data from the two methodologies of rating. The second comparison was done with the posting loads generated from LFR based on MoDOT LFR posting guidance of using a factor of 0.86 for posting loads. The LFR posting thresholds based on MoDOT guidance and the gross vehicle weights are shown in Table 5.22.

Table 5.22 MoDOT LFR posting Threshold and Gross Weight of the Vehicles

Vehicle	Threshold (Tons)	GVW (Tons)
H20L	30	20
CZSU	45	40.8
MO 3S2	45	36.64
CZRT	70	51
SU5	NA	31

CZSU and CZRT had a considerable number of bridges posted in LFR and therefore posted ratings for bridges in LFR using the MoDOT LFR posting policy were compared to corresponding LRFR legal rating loads without using any factor and ignoring the MBE LRFR posting equation. Due to a lack of data points or fewer bridges requiring posting in LFR for H20L, MO3S2, and SU5 to make comparisons, even if the bridge was not required to be posted according to MoDOT LFR policy, an assumption is made that the bridge was required to be posted and therefore the rating load is multiplied by a factor of 0.86 and compared with the corresponding rating loads in LRFR. The MBE posting equation for LRFR was ignored and therefore LRFR rating loads are used for comparison. SU5 is posted only if the rating factor is less than 1.0 as it has no LFR posting threshold.

Two types of graphical comparisons were done in this study to generate the factors.

i) The first graphical comparison was done between the LFR and LRFR rating loads.
ii) The second graphical comparison was between LFR posted loads and LRFR legal loads, with assumptions applied where necessary.

5.13.1.1 Graphical Comparison of LFR and LRFR Rating Loads

Figures 5.41 to 5.45 shows the comparison of the LFR .vs. LRFR rating loads for H20L, MO3S2, SU5, CZSU and CZRT respectively.

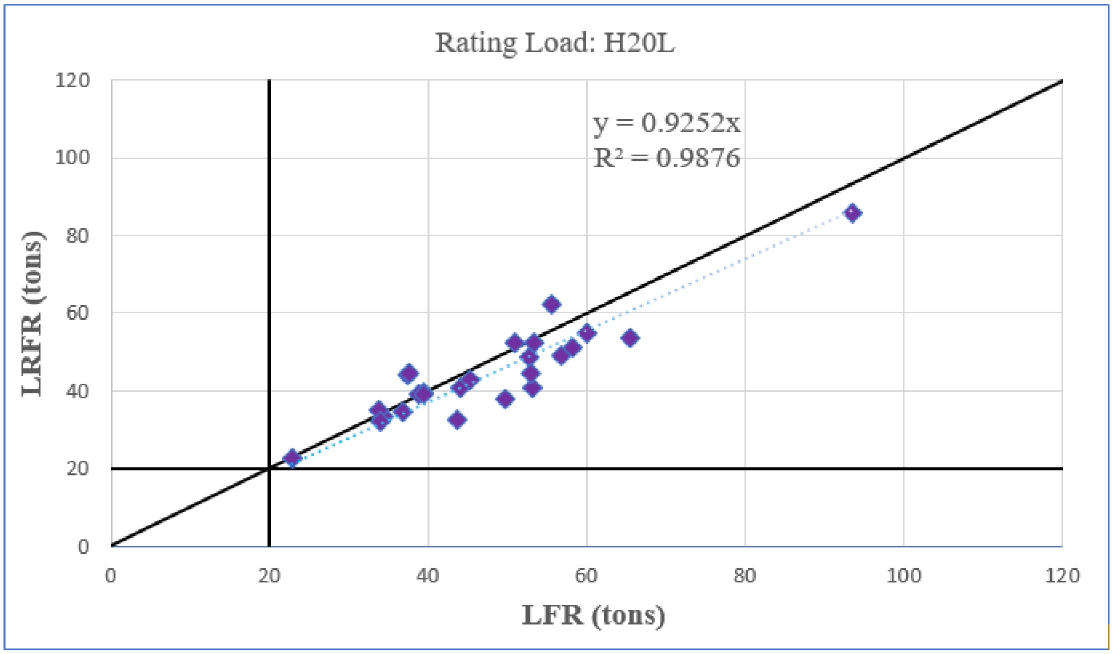


Figure 5.41 Rating Load Comparison for H20L

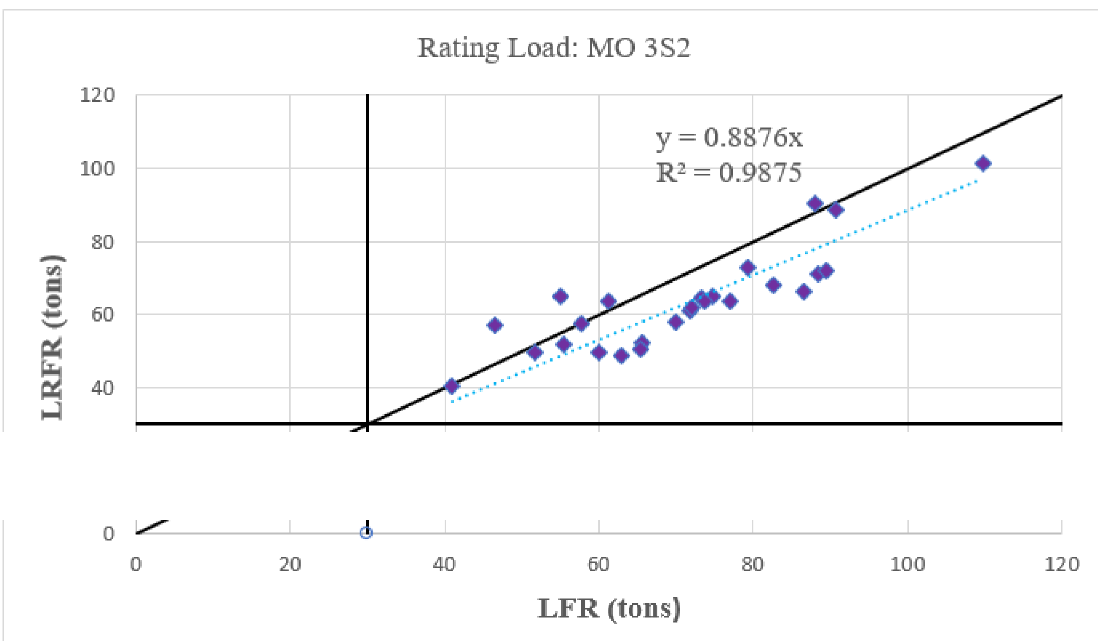


Figure 5.42 Rating Load Comparison for MO3S2

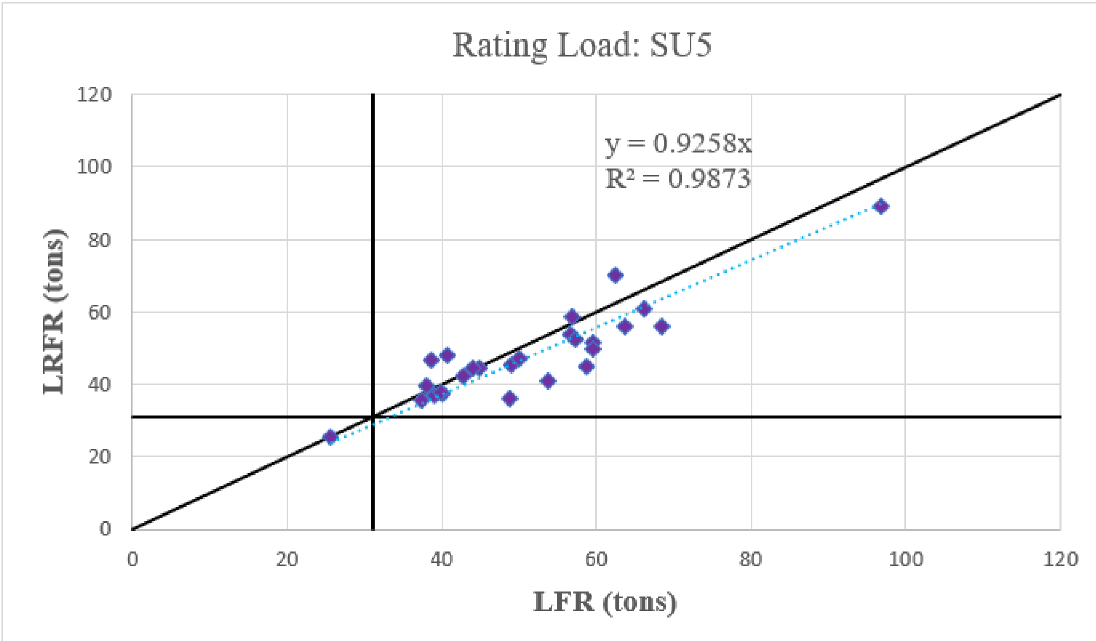


Figure 5.43 Rating Load Comparison for SU5

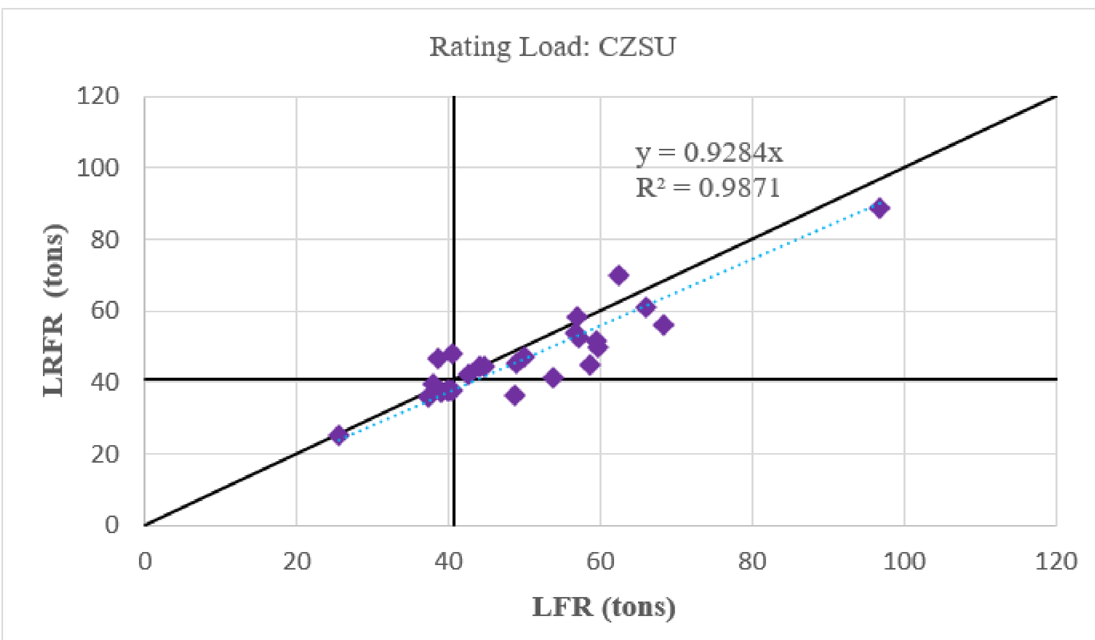


Figure 5.44 Rating Load Comparison for CZSU

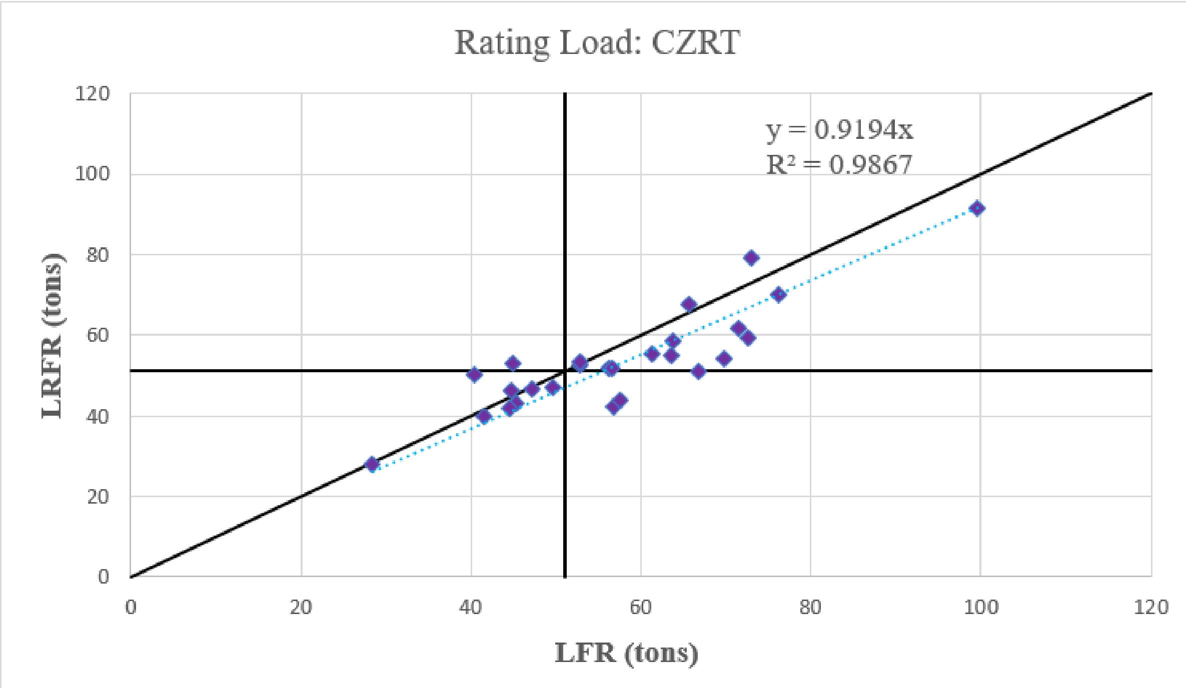


Figure 5.45 Rating Load Comparison for CZRT

The graphical data is summarized in Table 5.23 which shows the ratio of the rating loads for the five vehicles.

Table 5.23 Rating Load Comparison for CZRT

Live Load	CZSU	H20L	MO3S2	SU5	CZRT
Factor	0.93	0.93	0.89	0.93	0.91

5.13.1.2 Graphical Comparison Between LFR Posted Loads and LRFR Legal Loads,

Figures 5.46 to 5.50 show the comparison of the LFR posted and LRFR legal loads for live load vehicles H20L, MO3S2, SU5, CZSU, and CZRT, respectively.

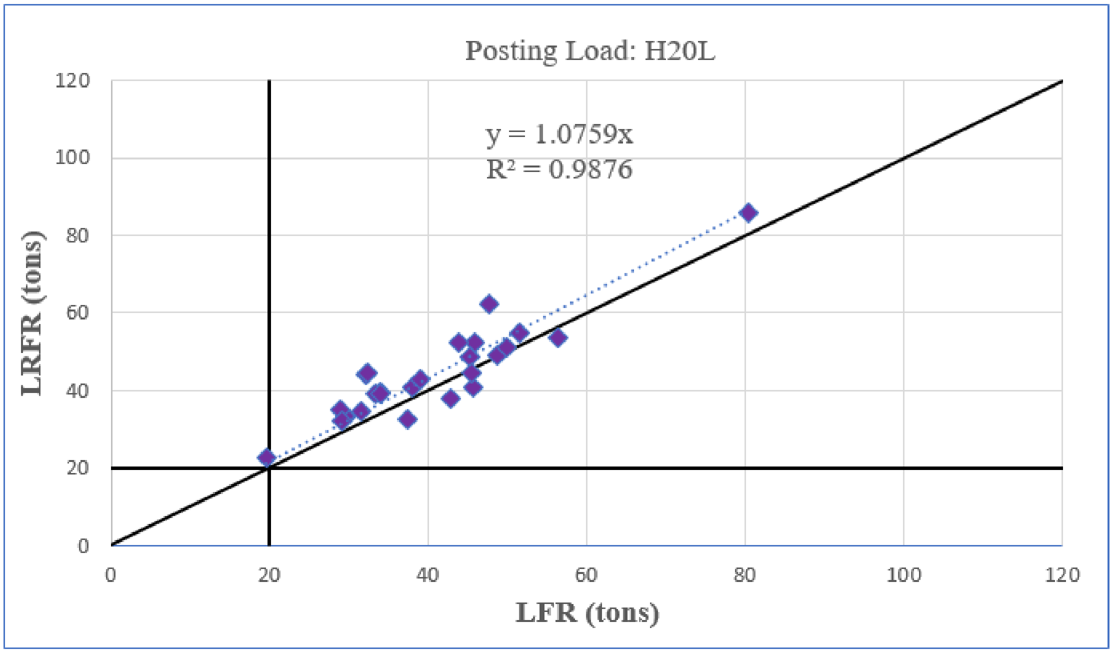


Figure 5.46 Posting Load Comparison for H20L

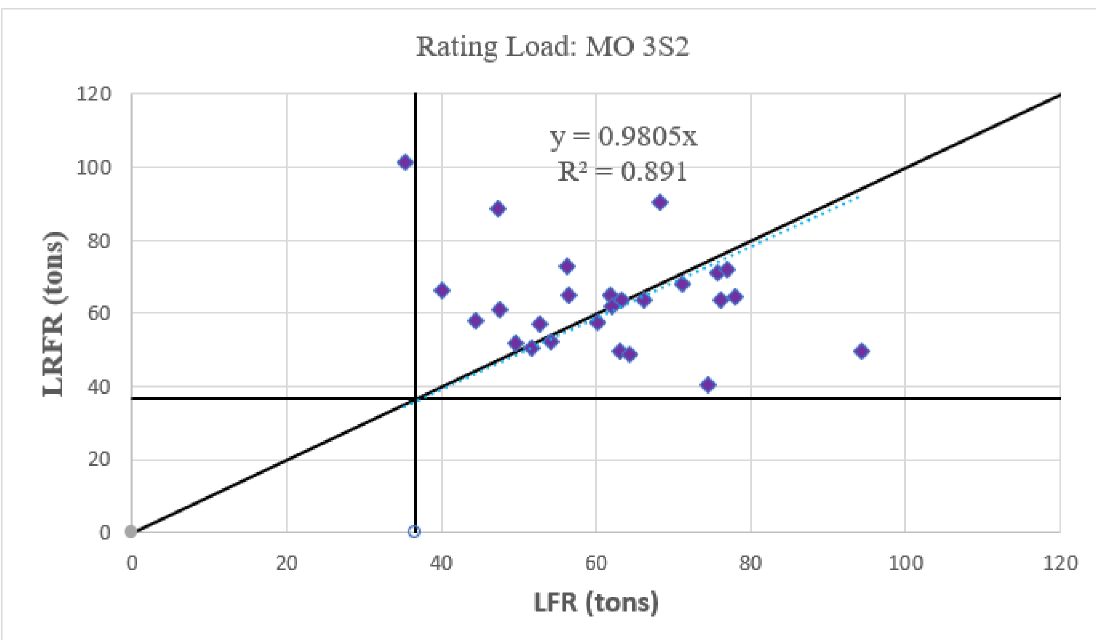


Figure 5.47 Posting Load Comparison for MO3S2

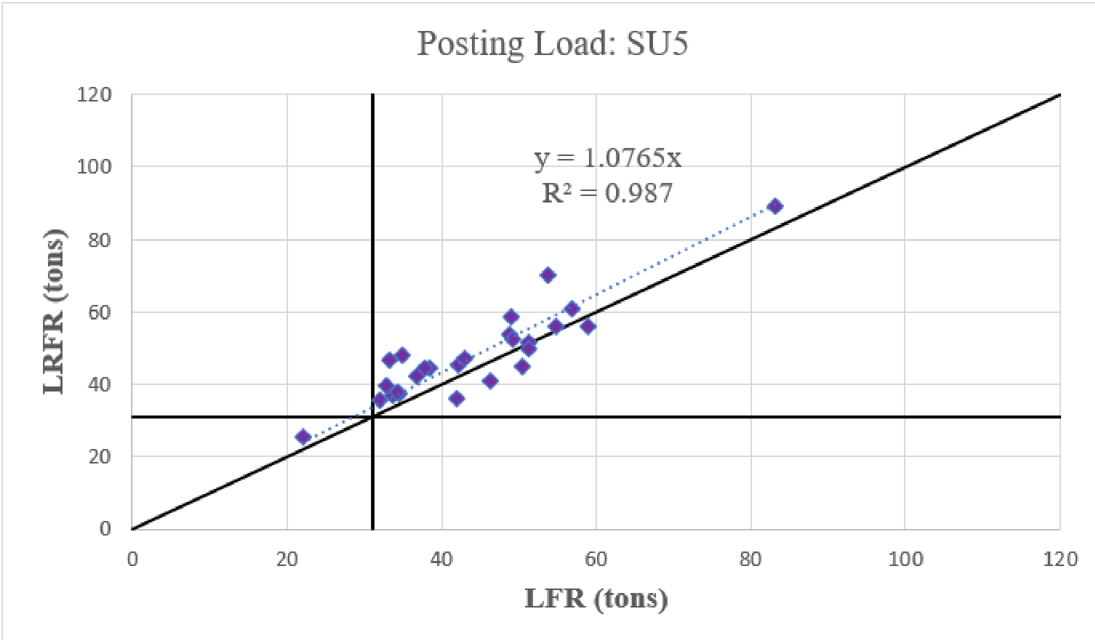


Figure 5.48 Posting Load Comparison for SU5

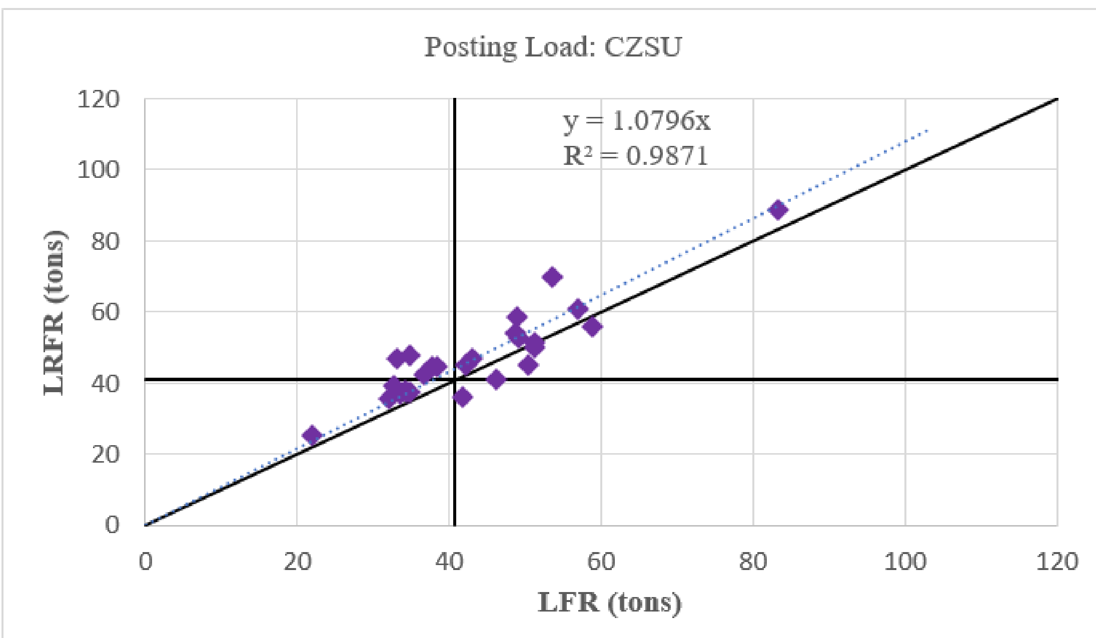


Figure 5.49 Posting Load Comparison for CZSU

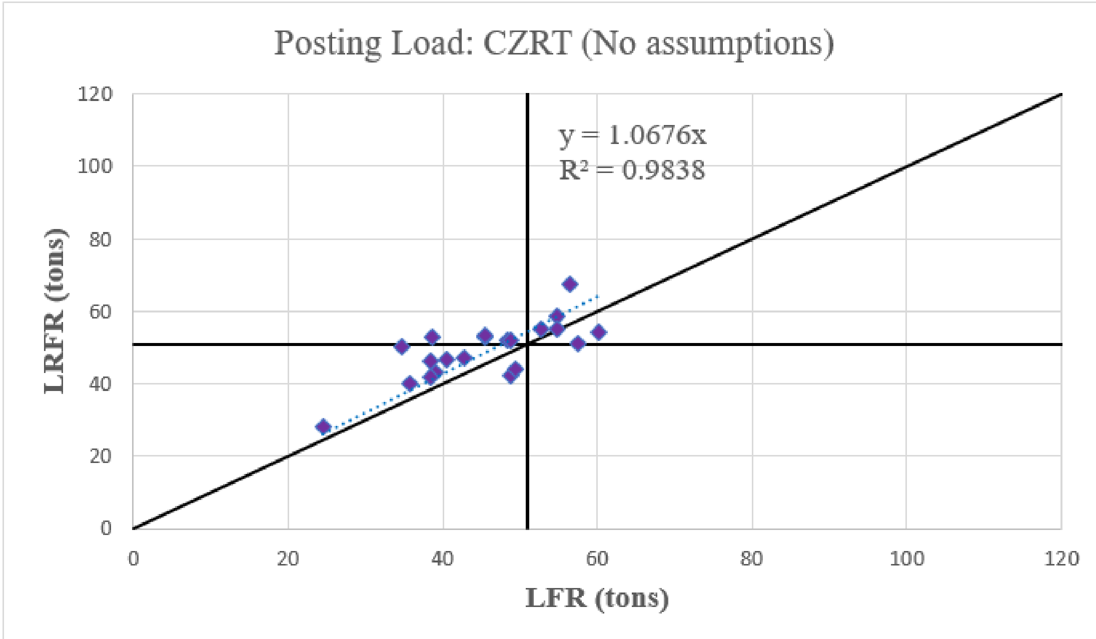


Figure 5.50 Posting Load Comparison for CZRT

Table 5.24 shows average ratios of the LRFR legal rating load and LFR posting loads for the five legal vehicles.

Table 5.24 Ratio of LRFR Legal Rating Load and LFR Posting Loads

Live Load	CZSU	H20L	MO 3S2	SU5	CZRT
Factor	1.08	1.08	0.98	1.08	1.07

Conclusion of the LTB Study

The comparison of LFR and LRFR rating load factors generated a consistent factor of 0.93 with the lowest factor of 0.89 from the MO3S2 comparison. The comparison of the posting loads in LFR and the LRFR rating legal loads generated a consistent factor of 1.08, with the lowest being CZRT, with a factor of 0.98 corresponding to MO3S2.

$$\frac{LRFR\ RL}{LFR\ RL} = 0.93$$

$$\frac{LRFR\ Legal\ RL}{LFR\ Posting\ Load} = 1.08$$

The results generated from the comparison of posted ratings for CZRT showed that the assumptions made did not affect the outcome in cases where enough data is available to make comparisons.

Chapter 6: Results for Prestressed Concrete Bridges

6.1 Comparison Between LFR and LRFR

This chapter compares the rating factor and rating load plots between LFR and LRFR for 100 prestressed concrete bridges. Since prestressed bridges are mostly new and have greater capacity, bridges of this type that require load posting are rare. In Figure 6-1 below, the x-axis represents the LFR rating factor, and the y-axis represents the LRFR rating factor. If the plots are below the 45-degree line, it implies that the bridges have a rating factor in LFR greater than one in LRFR and vice-versa. If plots are concentrated along the line, it implies that the two rating methods yield similar results with minimal variance.

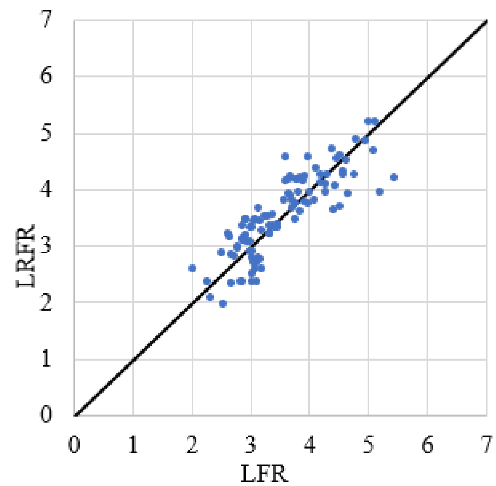


Figure 6.1: Example Comparative Graph of LFR and LRFR Rating Factor

Rating load plots are like the rating factor plots, with LFR loads represented on the x-axis and the y-axis representing LRFR loads. However, in addition to the diagonal line, rating load plots have horizontal and vertical lines. The vertical line represents the BIRM LFR threshold for the vehicle being compared. BIRM does not have thresholds for the AASHTO vehicles, so in this case the vertical line represents the maximum GWT for vehicles. The horizontal line represents the GWT of the vehicles for LRFR loads. Plots to the right of the vertical line have rating loads greater than the threshold and vice versa. Plots above the horizontal line have rating loads greater than vehicles GWT, and vice versa. Posting for LFR is required when the rating load is on the left of the vertical line. Posting is required for LRFR when rating load plots fall below the horizontal line. The maximum GWT of vehicles is used as a threshold to determine the posting requirement when using LRFR based on the recommendation in MCE (AASHTO, 2017) for this comparative study.

The add-on equation on the chart region is the regression line and R-squared value (equal to 1 – sum squared regression). The regression line, also known as a best-fit line, is a straight line that represents the relationship between LFR and LRFR in a regression analysis. It is commonly used in statistics and data analysis to understand the nature of the relationship between a dependent variable and one or more independent variables. Figure 6-2 shows a sample plot representing the load rating and load posting comparison between LFR and LRFR.

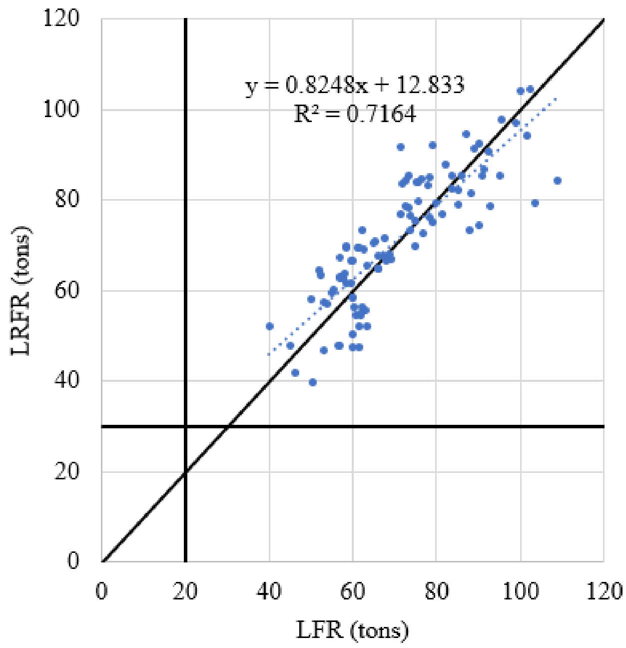


Figure 6.2: Example Comparative Graph of LFR and LRFR Rating Load

6.1.1. H20 Legal Load Comparison

Figures 6-3 show two comparative plots between LFR and LRFR for rating factors and rating loads respectively. The two plots are similar in terms of data distribution but proportional in magnitude since the rating load is maximum GWT multiplied by the rating factor. The H20L ratings between LFR and LRFR are similar. The data in the plot are moderately scattered along the 45-degree line with some data points below the line and some data points above the line. The average ratio between LRFR rating factor over LFR is 1.01 with a standard deviation of 0.12. The linear regression line is y = 0.8248 x + 12.833 with a R-square value of 0.7164.

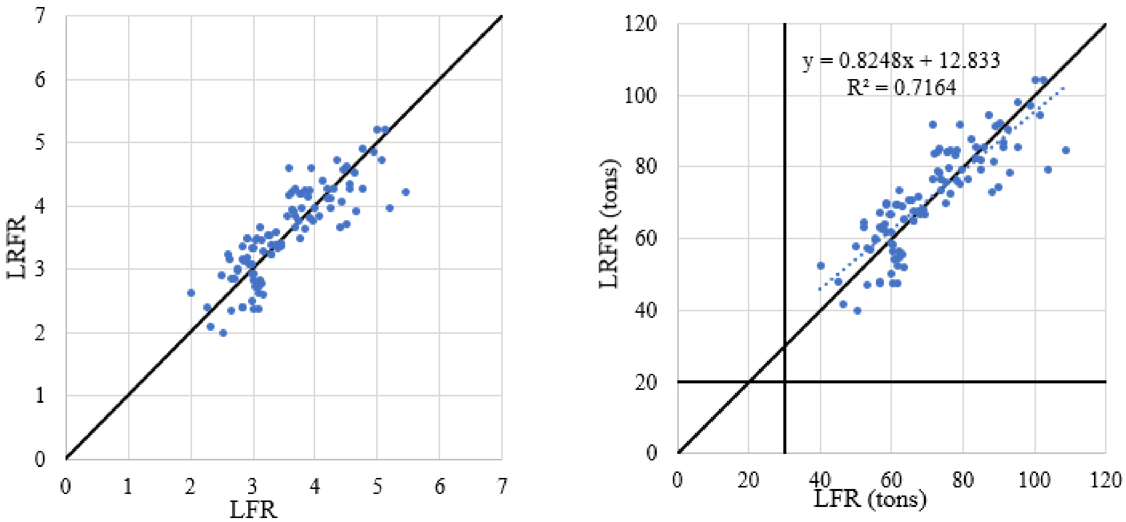


Figure 6.3: Example Comparative Graph of LFR and LRFR Rating Load

The two graphs show that none of the prestressed concrete bridges are required to be load-posted for H20L based on LFR load-posting requirements in BIRM and a rating factor greater than 1 in LRFR. Table 6-1 shows the comparison of the mean and standard deviation of rating factors for different types of prestressed concrete bridges for both LFR and LRFR. In addition, it shows the ratio of the mean and standard deviation of the two rating factors. Overall, the ratio of the rating load of LRFR to LFR is 1.01 with a standard deviation of 0.12 indicating that load rating results between the two methods are similar. Simply supported bridges have load ratings of LRFR less than LFR (average ratio of rating factor LRFR/LFR = 0.97), while in bridges with continuous spans, the trend is the opposite (average ratio of rating factor LRFR/LFR = 1.05). Among all the girder types, multiple box beam bridges have the lowest ratio of rating factor LRFR/LFR (ratio of 0.93) and stringer girder type bridges have the largest ratio of 1.08. Bridges using ASD have the largest ratio of rating factor between LRFR and LFR (ratio of 1.05) while LRFD bridges have the lowest of 0.96. Commercial and non-commercial zone bridges have similar rating loads.

Table 6. 1: Comparison Rating LFR vs. LRFR for H20 Legal Load

Type		# of bridges	LFR		LRFR		Ratio LRFR/LFR	
			Mean	STD	Mean	STD	Mean	STD
All		100	3.54	0.74	3.56	0.72	1.01	0.12
Span	Continuous	54	3.53	0.77	3.68	0.71	1.05	0.11
	Simply supported	46	3.56	0.72	3.43	0.72	0.97	0.11
Girder Type	Stringer	51	3.35	0.66	3.57	0.58	1.08	0.11
	Box Beam Single	12	3.87	0.49	3.82	0.48	0.99	0.10
	Box Beam Multiple	18	3.18	0.34	2.97	0.57	0.93	0.09
	Tee Beam	17	4.42	0.68	4.18	0.75	0.95	0.08
	Slab	2	2.41	0.14	2.04	0.07	0.85	0.08
Design Method	ASD	10	2.74	0.38	2.87	0.55	1.05	0.19
	LFR	76	3.67	0.72	3.71	0.70	1.02	0.11
	LRFD	14	3.42	0.68	3.27	0.61	0.96	0.11
Zone	Commercial	41	3.84	0.81	3.86	0.70	1.02	0.12
	Non-commercial	59	3.33	0.62	3.36	0.67	1.01	0.12

6.1.2 Vehicle MO3S2

Figure 6-4 compares the rating factor and rating loads for MO3S2. The plotted data points are lightly scattered along the 45-degree line, with some points falling below and others above the line. The average ratio of LRFR rating factor over LFR is 0.99, with a standard deviation of 0.10. The linear regression line is represented by the equation y = 0.9316x + 6.1589, with an R-square value of 0.6943. In this regression, LRFR data serves as the dependent variable (y-axis) while LFR data serves as the independent variable (x-axis).

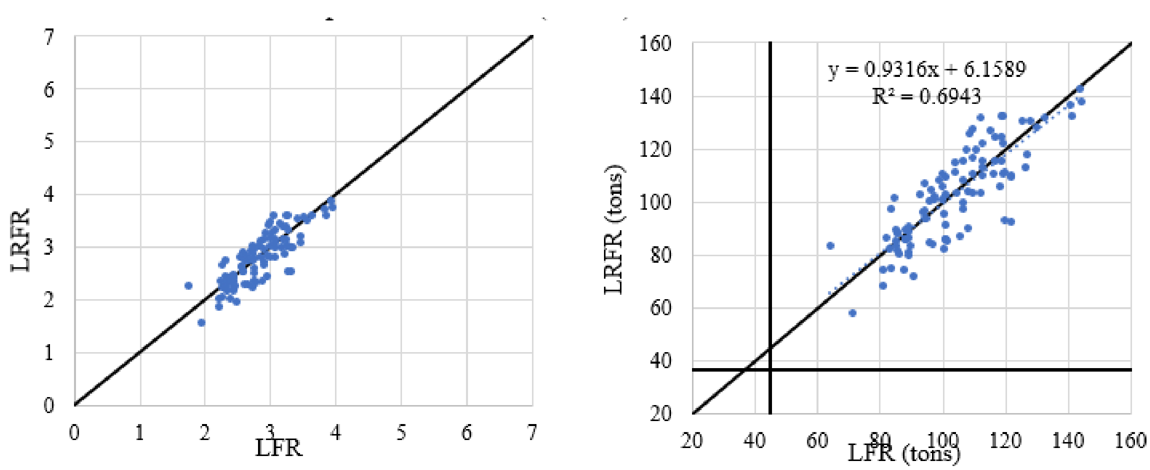


Figure 6.4: Rating Factor and Rating Load of MO3S2 Plots

The two graphs show that none of the prestressed concrete bridges are required to be load-posted for MO3S2 based on LFR requirements in BIRM and rating factors greater than 1 in LRFR. In addition, it shows the ratio of the mean and standard deviation of the two rating factors. Table 6-2 shows the average rating factor of MO3S2 is 2.83 in LFR and 2.80 in LRFR, which implies that prestressed bridges have sufficient capacity to carry live load vehicle MO3S2. In addition, it is evident that the disparity in the rating outcomes between the two methods is minimal. The average rating factor ratio LRFR compared to LFR is 0.99, with a standard deviation of 0.10. As with the H20 legal load comparison case, the simply supported girder bridges have LFR average rating factors greater than LRFR, while the continuous girder bridges have LFR average ratings less than the LRFR ratings. Slab bridges have the lowest ratio of rating factor LRFR/LFR among other types, with a ratio of 0.85 and a standard deviation of 0.08. Considering that the entire sample comprises only two slab bridges, it is important to note that the data might not be comprehensive enough to accurately represent the entirety of the inventory. Commercial zone and non-commercial zone results show no significant difference in rating factor.

Table 6.2: Comparison Rating LFR vs. LRFR for MO3S2

Type		# of Bridge	LFR		LRFR		Ratio LRFR/LFR	
			Mean	STD	Mean	STD	Mean	STD
All		100	2.83	0.44	2.80	0.49	0.99	0.10
Span	Continuous	54	2.82	0.39	2.85	0.45	1.01	0.10
	Simply	46	2.84	0.50	2.75	0.54	0.97	0.09
Girder Type	Stringer	51	2.76	0.34	2.83	0.39	1.03	0.10
	Box Beam Single	12	3.44	0.45	3.37	0.50	0.98	0.09
	Box Beam Multiple	18	2.50	0.19	2.41	0.22	0.97	0.06
	Tee Beam	17	3.01	0.43	2.83	0.54	0.93	0.09
	Slab	2	2.37	0.14	2.01	0.06	0.85	0.08
Design Method	ASD	10	2.37	0.34	2.31	0.47	0.98	0.17
	LFR	76	2.89	0.42	2.88	0.45	1.00	0.09
	LRFD	14	2.81	0.44	2.73	0.54	0.97	0.10
Zone	Commercial	41	2.99	0.49	2.93	0.51	0.98	0.10
	Noncommercial	59	2.71	0.36	2.71	0.46	1.00	0.10

6.1.3 Vehicle CZSU (Commercial Zone Bridges)

The CZSU vehicle configuration (GWT of 40.8 tons) is a variation of a special haul vehicle, close to the SU5 vehicle. It is used by MoDOT to rate bridges that are within the commercial zone, according to BIRM. Vehicles allowed in commercial zones can weigh up to 90,000 pounds, while non-commercial zone bridges are limited to 80,000 pounds vehicles. 41 prestressed concrete bridges in the research bridges inventory are in the commercial zone. Thus, a comparison of ratings for CZSU can only be conducted on those bridges. Figure 6-5 shows the comparison of the rating factor and rating load for CZSU. Only one bridge required posting when using LFR, but no bridge required load posting when using LRFR. Data points on the comparative graph line up along the diagonal line but are more scattered than in two previous comparison plots of H20L and MO3S2. The regression line represents the data as y = 0.7163x + 23.27 with R-squared value of 0.6578.

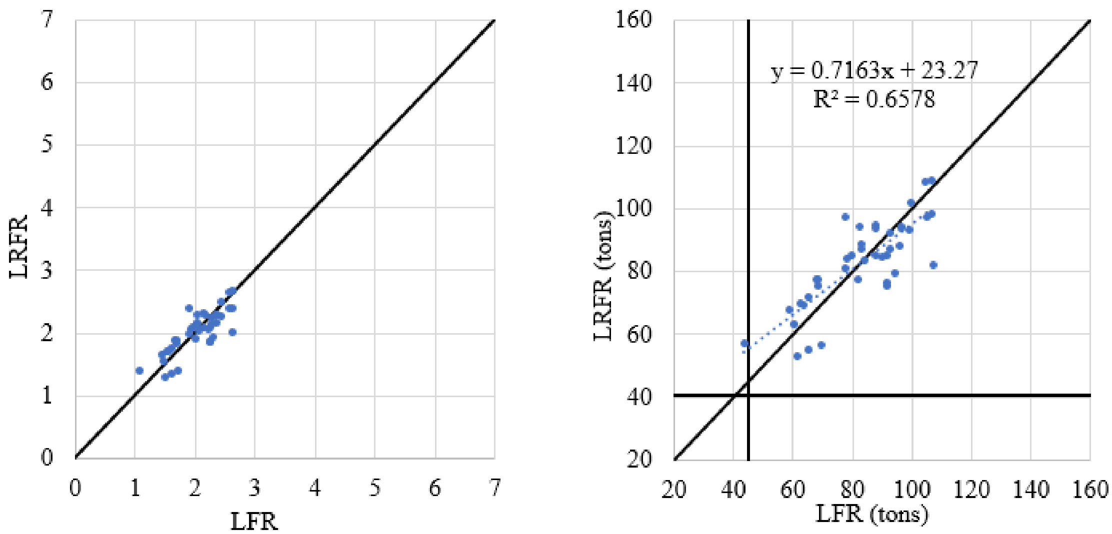


Figure 6.5: Rating Factor and Rating Load of CZSU Plots

Table 6-3 shows the comparison of the mean and standard deviation of rating factors for different types of prestressed concrete bridges for both LFR and LRFR. In addition, it shows the ratio of the mean and standard deviation of the two rating factors. The mean of the ratio rating factor between LRFR and LFR is 1.01, with a standard deviation of 0.12.

Table 6.3: Comparison Rating LFR vs. LRFR for CZSU

Type		# of bridges	LFR		LRFR		Ratio LRFR/LFR	
			Mean	STD	Mean	STD	Mean	STD
All		41	2.04	0.38	2.03	0.34	1.01	0.12
Span	Continuous	37	2.04	0.35	2.03	0.32	1.00	0.11
	Simply	4	2.05	0.68	2.05	0.54	1.04	0.20
Girder Type	Stringer	24	1.89	0.37	1.95	0.30	1.05	0.13
	Box Beam Single	5	2.22	0.14	2.15	0.11	0.97	0.03
	Box Beam Multiple	0	-	-	-	-	-	-
	Tee Beam	12	2.26	0.35	2.13	0.44	0.94	0.09
	Slab	0	-	-	-	-	-	-
Design Method	ASD	4	1.50	0.30	1.59	0.23	1.08	0.20
	LFR	36	2.10	0.35	2.08	0.32	1.00	0.11
	LRFD	1	2.06	-	2.05	-	1.00	-

6.1.4 Vehicle CZRT (Commercial Zone Bridges)

CZRT is the rating model of combination vehicle that MoDOT uses to rate bridges in commercial zones. Figure 6-6 compares the rating factors and rating loads for CZRT. With 51 tons of maximum GWT and a 70-ton threshold according to BIRM, there is only one bridge that requires posting when using LFR, and no bridge needed posting when using LRFR. As it was when looking at other vehicles, LFR and LRFR had similar ratings for most of the bridges. As shown in Table 6-4, the mean of ratio LRFR rating factor/LFR rating factor is 0.99 with standard deviation of 0.11. The regression line represents the data is y = 0.8068x + 19.601 with R-squared value of 0.5319. Most of the bridges in the commercial zone area are continuous (37/41) span girder bridges. The average of rating ratio LRFR/LFR is 0.99 with standard deviation of 0.10, while the average ratio value for simply supported girder bridges is 1.04 with standard deviation of 0.2. Among girder structure type, T-beam girder bridges have the smallest rating factor.

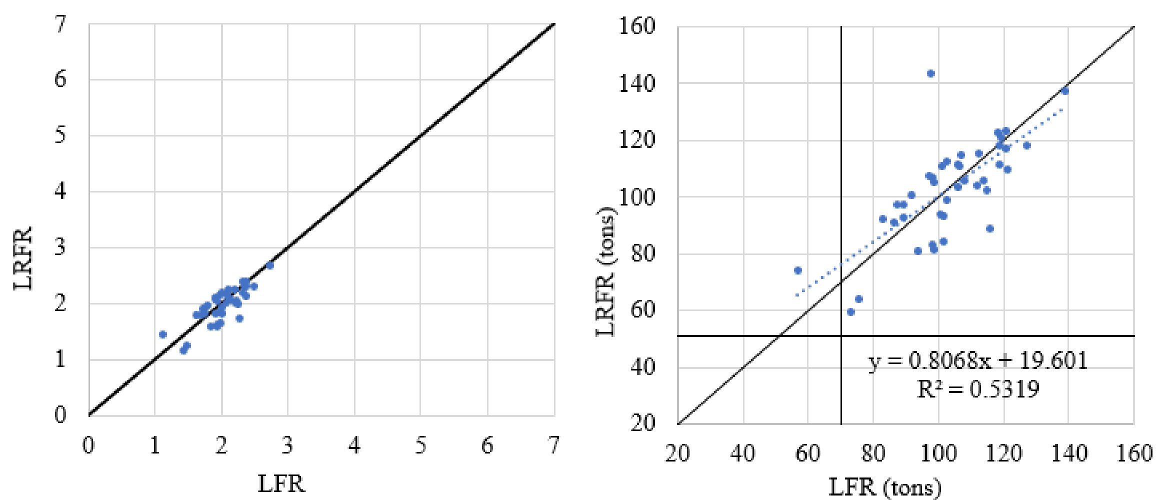


Figure 6.6: Rating Factor and Rating Load of CZRT Plots

Table 6.4: Comparison Rating LFR vs. LRFR for CZRT

Type		# of bridges	LFR		LRFR		Ratio LRFR/LFR	
			Mean	STD	Mean	STD	Mean	STD
All		41	2.02	0.31	1.99	0.32	0.99	0.11
Span	Continuous	37	2.02	0.26	1.98	0.29	0.99	0.10
	Simply	4	2.05	0.69	2.06	0.59	1.04	0.20
Girder Type	Stringer	24	1.94	0.26	1.96	0.23	1.03	0.12
	Box Beam Single	5	2.45	0.17	2.38	0.19	0.98	0.03
	Box Beam Multiple	0	-	-	-	-	-	-
	Tee Beam	12	2.02	0.31	1.90	0.41	0.93	0.09
	Slab	0	-	-	-	-	-	-
Design Method	ASD	4	1.51	0.31	1.63	0.38	1.08	0.20
	LFR	36	2.07	0.26	2.02	0.29	0.98	0.10
	LRFD	1	2.34	-	2.38	-	1.02	-

6.1.5 Vehicle SU5

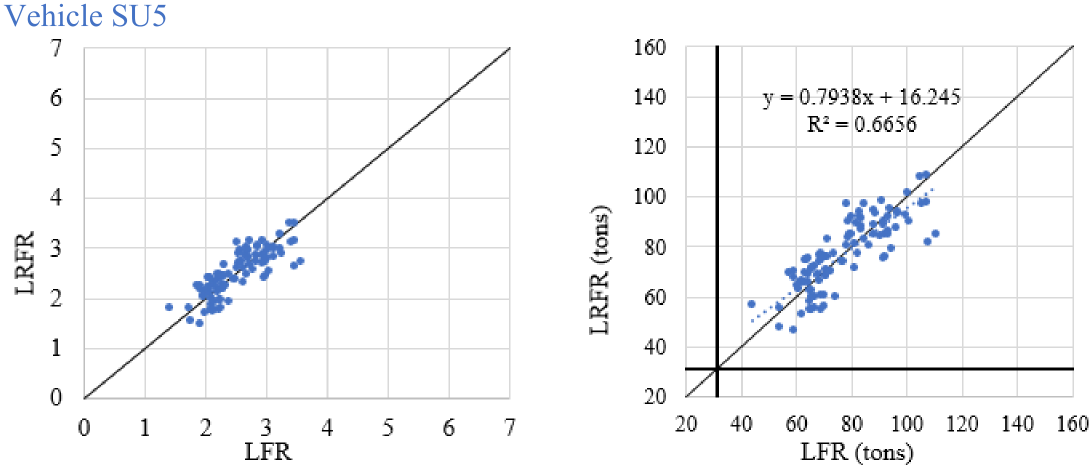


Figure 6.7: Rating Factor and Rating Load of SU5 Plots

SU5 is a special hauling vehicle that has five axles and a GWT of 31 tons that is used in commercial zones. MoDOT currently does not have SU5 in its rating practices, so this study will provide a better look at the differences between ratings for this vehicle in LFR and LRFR, even though results show SU5 rating factors are similar. Figure 6-6 shows that none of the bridges have a rating factor under 1 and that the data points are distributed close to the 45-degree line. The regression line shows the data is y = 0.7938x + 16.245 with an R-squared value of 0.6656. Table 6-7 shows the mean of the ratio LRFR rating factor/LFR rating factor is 1.01 with a standard deviation of 0.12. Slab and T-beam have the lowest rating factor ratio LRFR/LFR among other structure type bridges with values of 0.85 and 0.94 respectively.

Table 6.5: Comparison Rating LFR vs. LRFR for SU5

Type		# of bridges	LFR		LRFR		Ratio LRFR/LFR	
			Mean	STD	Mean	STD	Mean	STD
All		100	2.48	0.47	2.49	0.45	1.01	0.12
Span	Continuous	54	2.47	0.48	2.56	0.44	1.05	0.11
	Simply	46	2.49	0.45	2.41	0.46	0.97	0.11
Girder Type	Stringer	51	2.35	0.41	2.50	0.36	1.07	0.11
	Box Beam Single	12	2.79	0.31	2.74	0.30	0.99	0.10
	Box Beam Multiple	18	2.21	0.20	2.10	0.32	0.95	0.07
	Tee Beam	17	2.99	0.41	2.81	0.49	0.94	0.09
	Slab	2	1.81	0.11	1.54	0.04	0.85	0.07
Design Method	ASD	10	1.98	0.28	2.05	0.36	1.05	0.19
	LFD	76	2.56	0.45	2.58	0.43	1.02	0.10
	LRFD	14	2.40	0.39	2.33	0.42	0.97	0.11
Zone	Commercial	41	2.68	0.51	2.67	0.45	1.01	0.12
	Non-commercial	59	2.34	0.38	2.37	0.42	1.02	0.11

6.1.6 Observation and Discussion

With LFR, about 7.4% of the sampled bridges are found to have exterior girders governing the rating. However, when applying LRFR, the number of bridges where exterior girders govern the rating increases significantly to around 61.9% as seen in Table 6-6.

Table 6.6: Exterior Girder Governing Rating

Vehicle	LFR	LRFR
H20L	8/100	61/100
MO3S2	9/100	58/100
CZSU	2/41	26/41
CZRT	3/41	27/41
SU5	8/100	61/100
Average	7.4%	61.9%

Table 6.7 shows that there are no significant differences in posting between LFR and LRFR across the sample of 100 prestressed bridges. The ratio of the rating factor between the methods is from 0.99 to 1.01 with a standard deviation from 0.11 to 0.12. H20 legal load truck has the highest average rating factor and CZRT has the lowest due to the vehicle's GWT. Overall, slab bridges have the smallest ratio between LRFR and LFR (about 0.85), and the stringer bridges have the largest ratio (around 1.3 - 1.08). Simple support girders bridges and ASD type of bridges have the most scattered data (the greatest standard deviation).

Table 6.7: Summary of Rating Factor and Load Posting of LFR and LRFR

	Posting Required			Rating Factor LFR		Rating Factor LRFR		LRFR/LFR Ratio	
Vehicle	LFR	LRFR	Both	Average	STD	Average	STD	Average	STD
H20L	0	0	0	3.54	0.74	3.56	0.72	1.01	0.12
MO3S2	0	0	0	2.48	0.47	2.49	0.45	1.01	0.12
CZSU	1	0	0	2.04	0.38	2.03	0.34	1.01	0.12
CZRT	1	0	0	2.02	0.31	1.99	0.32	0.99	0.11
SU5	0	0	0	2.48	0.47	2.49	0.45	1.01	0.12

6.2 AASHTO Vehicles Envelop Study

6.2.1 Comparison Between State Vehicles with Special Hauling Vehicles (SHVs)

There are two single-unit truck vehicles included in MoDOT's current load rating practices, i.e., H20 legal load and commercial zone truck CZSU. According to BIRM Section 15.11.1, H20L has a maximum GWT of 20 tons and CZSU has a maximum GWT of 40.8 tons and both will require posting if rating tonnage is less than 30 tons and 45 tons, respectively. The threshold is higher than GWT to help envelop other single-unit trucks traveling across the state. The posting values will be set to no greater than 86% of rating tonnage if rated within the LFR methodology.

According to information on load rating of specialized hauling vehicles from NCHRP Report 700, SHVs create higher force effects and thus result in lower load ratings for certain bridges, especially those with shorter spans or shorter loading lengths such as transverse floor beams, when compared to AASHTO Type 3, Type 3S2 and Type 3-3 legal loads and HS20 design load. Therefore, SHVs are to be included in rating and posting analyses by Article 6A.2.3 and Article 6B.9.2 of the 1st Edition of the MBE (Article 6B.7.2 of the 2nd Edition of the MBE). If the state verifies that the use of SHV is precluded in state laws or the state has its rating vehicle models for legal loads that envelop the applicable AASHTO SHV, including SHV vehicles in the state rating policy is not necessary.

Considering the potential for increased SHV travel within the state, this study helps determine if the state legal loads envelop AASHTO SHV vehicles, or if not, what threshold and posting practice should the state adopt other than the posting load equation specified in MBE 3rd edition.

This section compares plots of rating loads and rating factors for H20 legal load and CZSU versus SHV and AASHTO Type 3 legal loads when using LRFR. The purpose of this comparison was to observe the correlation in rating results between statewide legal loads, SHVs and AASHTO Type 3 legal loads. In addition, the current load posting threshold was examined along with the factor of 86% which is the existing LFR rating practice and load posting policy of BIRM. From there, the new posting threshold and factor (if valid) will be recommended with the new rating methodology (LRFR) with the primary criteria that the statewide legal load would "envelop" the SHV and AASHTO legal load. This implies that establishing load posting practices for MoDOT vehicles would be inclusive for all the vehicles that travel through the state without the need to rate all the vehicles. Only bridges in commercial zone areas are used for comparison within CZSU and SHV vehicles. Both bridges in non-commercial and commercial zones are used for comparison between H20L and SHV vehicles.

6.2.2 Example of Comparative Graphs

Rating load data using LRFR across a 100-bridge sample inventory were graphed, with the x-axis representing the MoDOT rating loads and the y-axis representing the SHV and AASHTO rating loads as shown in Figure 6-8. Data that fall in the region above the diagonal line have SHV vehicle rating loads greater than MoDOT vehicle rating loads. The horizontal and vertical lines represent the maximum GWT for SHVs and MoDOT vehicles respectively.

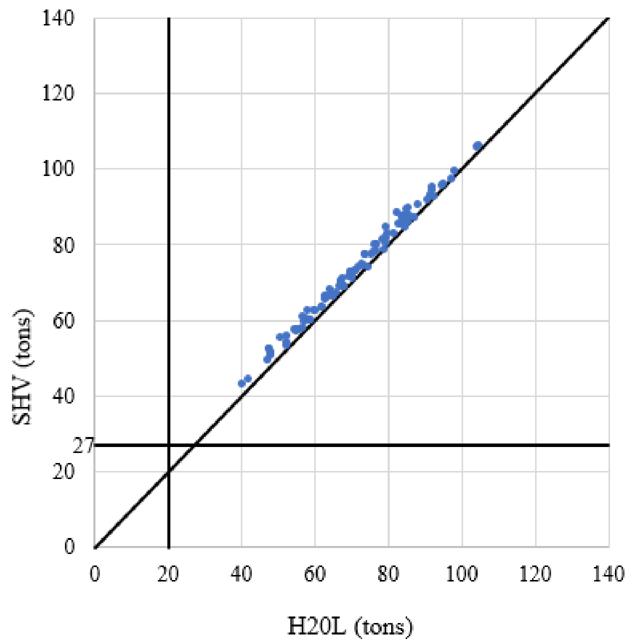


Figure 6.8: Example of Comparison Graph

6.2.3 Setting Threshold and Factor

MoDOT's current load rating and load posting practices examine two conditions to determine load posting. According to BIRM chapter 15.11, a bridge is required to be posted if its rating load is less than the threshold and the posting load is 0.86 multiplied by the rating load. In the context of this project, 0.86 is the posting factor. The threshold and posting factor are applied to the posting load to ensure that the posting load is sufficient to envelop other similar configuration vehicles that are not included in the rating vehicles template.

For MoDOT vehicles to be able to envelop the SHV and AASHTO vehicles, two conditions must be met. The first condition for enveloping is that the threshold of MoDOT vehicles must be at least equal to the GWT of SHV and AASHTO vehicles. This ground setting ensures that bridges that are required to be posted for SHV and AASHTO vehicles are also required to be posted for MoDOT vehicles. Second, the MoDOT vehicle rating load must be less than the SHV and AASHTO vehicle rating load across all the bridges in the sample. If the MoDOT vehicle rating load is greater than the SHV and AASHTO loads, load posting calculations will be performed based on the adjusted rating load value. The adjusted rating load is calculated by multiplying the state legal load rating load with a factor less than 1 (a posting factor will be used in the context of this study). The reason for using adjusted rating load for posting load calculations is to ensure that the posting load for state vehicles would envelop SHV and AASHTO vehicles. The adjusted rating loads are less than or equal to SHV and AASHTO vehicle's rating loads at any given bridge. More than 100 sample bridges were analyzed, and the factor was determined by using the smallest ratio between rating loads of SHV and AASHTO versus state legal loads.

6.2.4 LRFR Comparison Between H20 Legal Load and SHV Vehicles

The four graphs below show rating loads using LRFR between H20 legal load and SU4, SU5 (Figure 6.9), SU6 and SU7 (Figure 6.10).

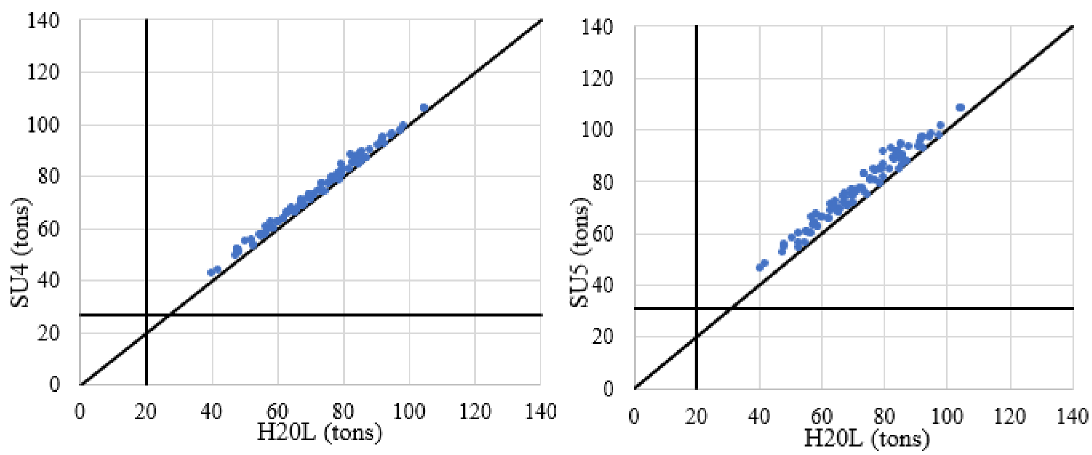


Figure 6.9: Rating Load Comparisons Between H20L and SU4, SU5

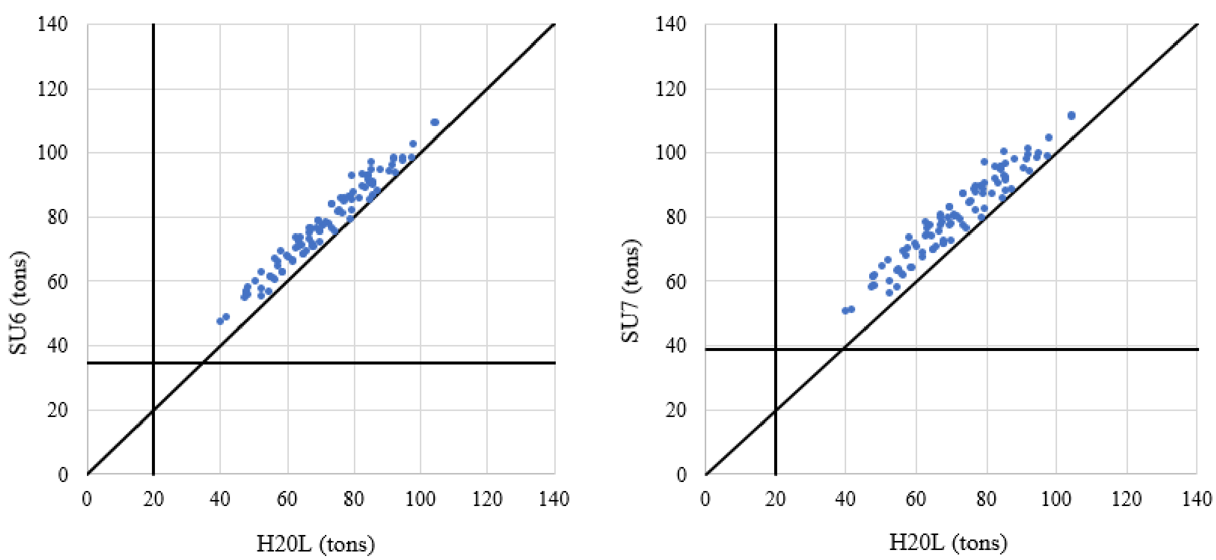


Figure 6.10: Rating Load Comparisons Between H20L and SU6, SU7

The rating load data distribution is linear and consistently parallels the 45-degree line in all the graphs comparing H20L and SHVs. All the data points are above the 45-degree line, which means the H20 legal load has a rating load less than the SHV vehicles (SU4, SU5, SU6, SU7). This is numerically represented in Table 6-8 below with rating load ratio H20L/SHVs all less than 1 with a small standard deviation from 0.02 to 0.05.

SU4 has a load effect of less than H20L across all the sample bridges (all the data points are above the 45-degree line). This would satisfy the first condition of the enveloping requirements. To envelop SU4, H20L must have a posting threshold equal or greater than SU4's maximum GWT of 27 tons. Similarly, SU5 must have a load effect less than H20L, but its GWT must be greater (31 tons > 20 tons). H20L must have a threshold equal or greater than 31 tons to envelop SU5. Lastly, SU6 and SU7 are considered heavy truck and would not commonly operate within a non-commercial zone.

Table 6.8: Rating Load Ratio Between H20 Legal Load and SHVs in LRFR

Rating Load Ratio	**Mean**	**Standard Deviation**
H20L/SU4	0.96	0.02
H20L/SU5	0.92	0.04
H20L/SU6	0.91	0.04
H20L/SU7	0.88	0.05

6.2.5 LRFR Comparisons Between CZSU and SHV Vehicles

The below graphs compare four plots of rating load using LRFR for CZSU and SU4, SU5 (Figure 6.11), SU6, SU7 (Figure 6.12).

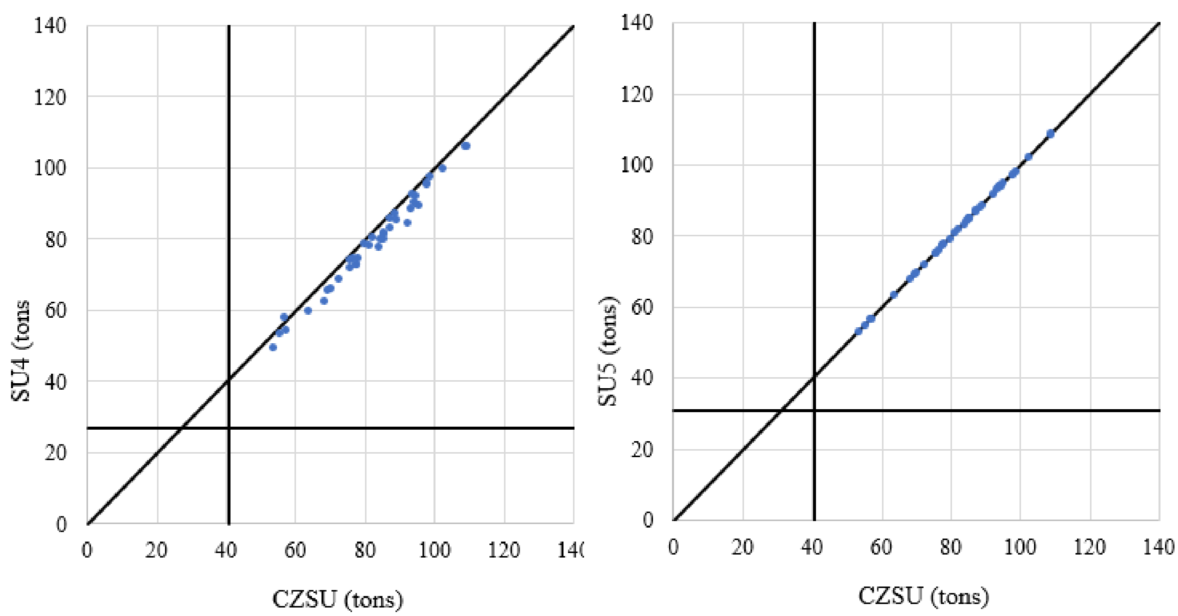


Figure 6.10: Rating Load Comparisons Between CZSU and SU4, SU5

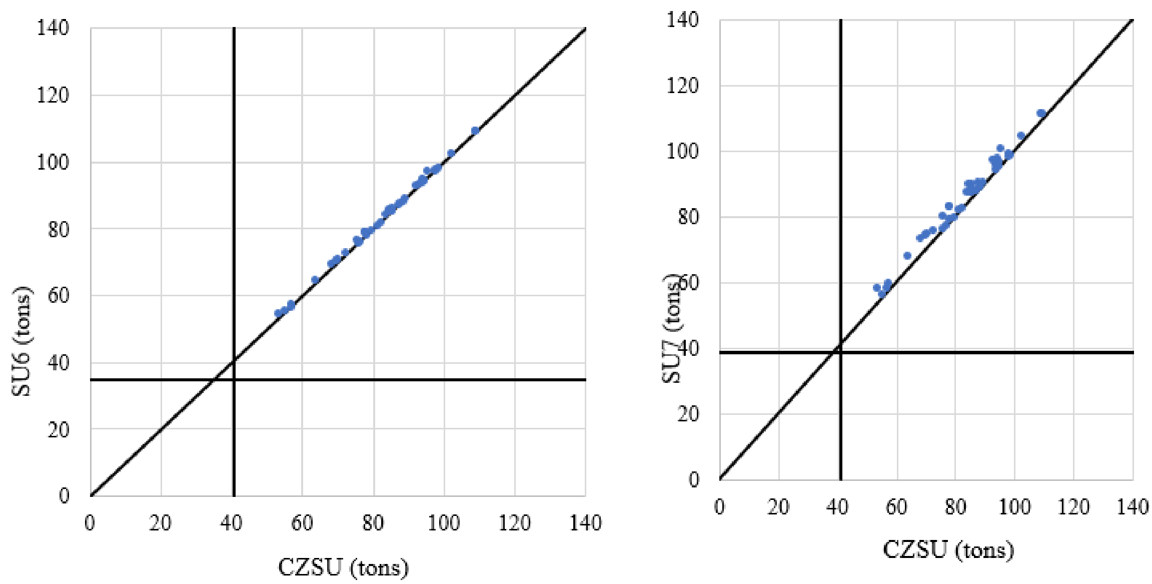


Figure 6.11: Rating Load Comparisons Between CZSU and SU6, SU7

The plots in the graphs comparing CZSU and SHVs vehicles are consistently linear and close to the 45-degree line, suggesting a correlation between the performance of CZSU and SHVs vehicles. As seen in Table 6-9, SU5 and SU6 have rating loads most similar to CZSU. SU7 has rating loads greater than CZSU, while SU4 has rating loads less than CZSU across all 41 commercial zone bridges.

CZSU has a maximum GWT (40.8 tons) greater than SU4. Therefore, the threshold for CZSU to envelop SU4 is the gross weight of CZSU. Since SU4 has a rating load less than CZSU, an adjusted CZSU rating load is needed for posting load calculations. The adjusted CZSU rating load is calculated by multiplying the CZSU rating load by a factor less than one. The adjusted CZSU rating load is established to ensure that the rating load used for posting calculations would be less than the SU4 rating load, thereby enveloping SU4. A factor of 0.92 is obtained by taking the minimum rating load ratio SU4/CZSU. Figure 6.13 shows that plots are all above the 45-degree line after applying the factor of 0.92 in the CZSU verses SU4 comparison graph. Hence, by applying a factor of 0.92 on load posting policy (posting load = 0.92 * rating load), load rating of SU4 does not have to be performed if load rating using CZSU is done. CZSU envelops SU5, SU6, SU7 without applying a threshold or a factor since all the data is above the 45-degree line and the CZSU GWT is higher than the GWT of SU5, SU6, and SU7.

Table 6.9: Rating Load Ratio Between CZSU and SHVs in LRFR

Rating Load Ratio	Mean	Standard Deviation
CZSU/SU4	1.04	0.02
CZSU/SU5	1.00	0.00
CZSU/SU6	0.99	0.01
CZSU/SU7	0.96	0.02

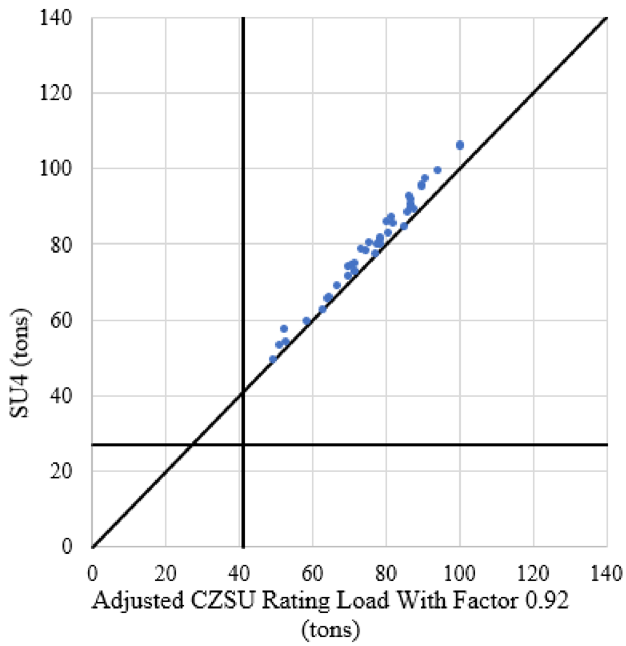


Figure 6.12: Comparison of CZSU vs SU4 With Factor of 0.92

6.2.6 Observation and Discussion

Table 6-10 shows that all SHV vehicles ratings are greater than H20L ratings when using LRFR. SU5, SU6, and SU7 rating loads are also greater than CZSU. Only SU4's rating load is less than CZSU for almost all the commercial zone bridges (40/41). The summary threshold and factor table (Table 6-11) is based on a sample of 100 bridges across different types of structure, continuity, and design methods, and suggests that if the threshold of H20L is 31 tons, and a factor equal to 1.0 is used, SU4 and SU5 will be enveloped by H20L.

Similarly, SU6 and SU7 are enveloped by CZSU in commercial zones with a CZSU threshold equal to CZSU maximum GWT of 40.8 tons, and a factor of 1.0. Within the non-commercial zone, it is suggested that SU6 and SU7 be included in the load rating process to determine if bridges have sufficient capacity to carry those vehicles. The recommendation considers the numerical analysis of rating results across bridge samples provided by MoDOT and notes that the final load rating policy will be determined by MoDOT.

Table 6.10: Number of Bridges That Have MoDOT Rating Load Greater Than SHVs

	SU4	SU5	SU6	SU7
H20L	0/100	0/100	0/100	0/100
CZSU	40/41	0/41	0/41	0/41

Table 6.11: Threshold and Factor Required for H20L and CZSU to Envelop SHV

SHV	**H20L – 20T Threshold**	**H20L – 20T Factor**	**CZSU (commercial zone) - 40.8T Threshold**	**CZSU (commercial zone) - 40.8T Factor**
SU4	27	1	-	0.92
SU5	31	1	-	1
SU6	34.75	1	-	1
SU7	38.75	1	-	1

6.3. Comparison Between State Vehicles with AASHTO Vehicles

The AASHTO legal vehicles (Type 3, Type 3S2, and Type 3-3) are used for load rating bridges for routine legal commercial traffic, according to MBE 3rd edition Section 6A.4.4.2.1. AASHTO legal vehicles are sufficiently representative of average truck configuration in use today. These vehicles are also suitable for bridge posting purposes; however, they do not always represent the regular traffic across the state. Missouri has its own state legal vehicles similarly to AASHTO vehicles (single unit truck H20L, combination truck MO3S2, commercial zone vehicles CZSU and CZRT). In lieu of bridge rating and posting using AASHTO legal vehicles, a goal of this project is to compare Missouri vehicle rating results with AASHTO vehicle models and determine steps to allow Missouri vehicles to envelop AASHTO vehicles.

6.3.1 LRFR Load Rating Comparison Between MO3S2 and AASHTO Combination Vehicles

Figure 6-14 shows that Type 3-3 rating loads across 100 prestressed bridges are greater than those of MO3S2. The data points exhibit a consistent and upward linear trend, aligning parallel to the 45-degree line, with a minor scattering of values. To envelop Type 3-3, MO3S2 must have a threshold no less than the GWT of Type 3-3(40 tons). The mean of the rating load ratio between MO3S2/Type 3-3 is 0.88 with standard deviation of 0.05 as shown in Table 6-12.

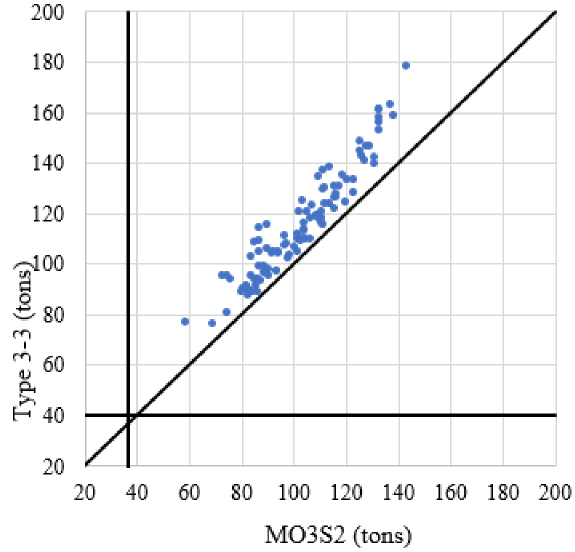


Figure 6.13: Comparison of Rating Load Between MO3S2 and Type 3-3

Figure 6-15 shows that AASHTO legal load Type 3S2 has rating loads slightly less than MO3S2. The mean of rating load ratio between MO3S2/Type 3S2 is 1.01 with standard deviation of 0.01 as seen in Table 5-12. Data points in figure 6-15 are slightly below the 45-degree line with significantly reduced scattering compared to the MO3S2/Type 3-3 plot. To be able to envelop Type 3S2, there is no need to apply a posting threshold since MO3S2 has a GWT (36.64 tons) that is greater than Type 3S2 (36 tons), a factor of 0.97 is applied to scale down the MO3S2 rating load for posting load calculations. A factor of 0.97 is produced by taking the minimum rating load ratio Type3S2/MO3S2 (see appendix A for Type 3S2 and MO3S2 load rating data). Figure 6-16 shows the adjusted MO3S2 rating load used for load posting versus Type 3S2 rating load. MO3S2 adjusted rating loads are now less than Type 3S2 rating load.

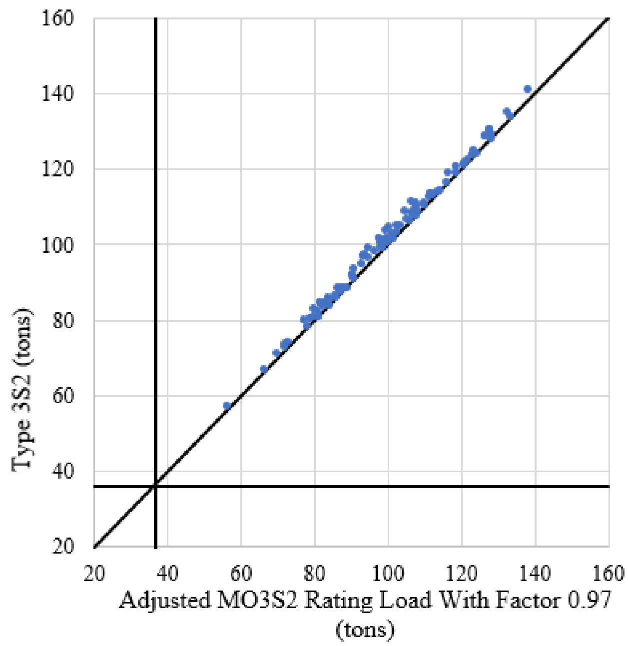


Figure 6.14: Compare Rating Load Between MO3S2 and Type 3S2

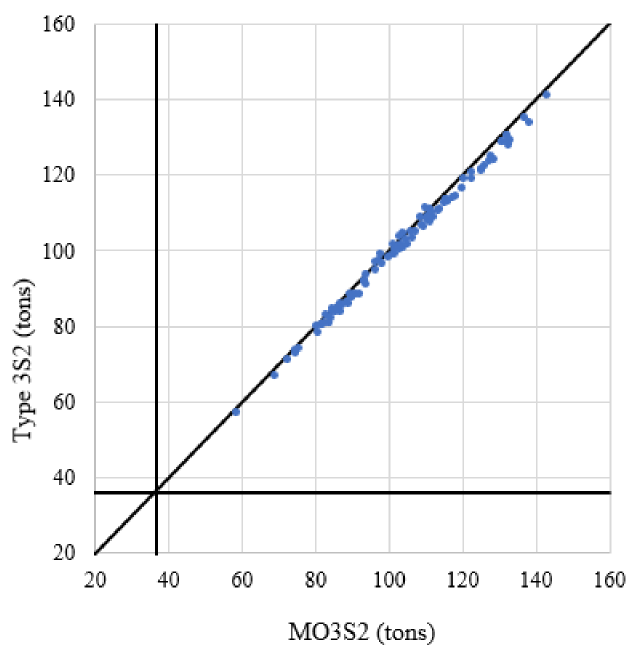


Figure 6.15: Comparison of MO3S2 and Type 3S2 With Factor of 0.97

Table 6.12: Rating Load Ratio Between MO3S2 and AASHTO Vehicles in LRFR

Rating Load Ratio	Mean	Standard Deviation
MO3S2/Type 3-3	0.88	0.05
MO3S2/Type 3S2	1.01	0.01

6.3.2 LRFR Load Rating Comparison Between CZRT and AASHTO Combination Vehicles

Graphs comparing CZRT rating loads verses those of Type 3-3 and Type 3S2 when using LRFR are shown in Figures 6-17 and 6-18. Both graphs show significantly increased scatter compared to all other MoDOT vehicles. The majority of the data points are above the 45-degree line, which means that CZRT places higher in rating load compared to Type 3-3 and Type 3S2 in most of the commercial zone bridges. Since CZRT maximum GWT (50 tons) is higher than AASHTO Type 3-3 (40 tons) and Type 3S2 (36 tons), there is no need to set the threshold for CZRT. To envelop Type 3-3, a posting factor of 0.96 will be applied. The factor of 0.96 is obtained by using the lowest rating load ratio between CZRT and AASHTO Type 3-3. Similarly, to envelop Type 3S2, the lowest rating load ratio between CZRT and Type 3S2 is used as the posting factor. Figure 6-19 and Figure 6-20 show that CZRT rating loads are reduced by the posting factor results for all the data points that are now above the 45-degree line. Table 6-13 shows average ratio of CZRT versus Type 3-3 and Type 3S2 are 0.84 (standard deviation of 0.09) and 0.96 (standard deviation of 0.06) respectively.

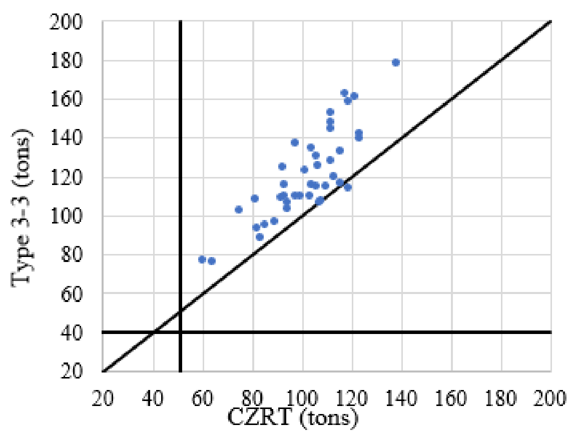


Figure 6.16: Rating Load Comparison of CZRT vs Type 3-3

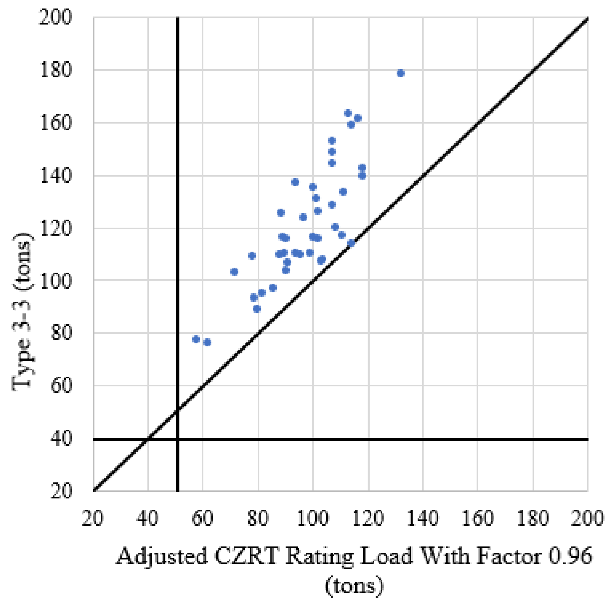


Figure 6.17: Rating Load Comparison of CZRT vs Type 3S2

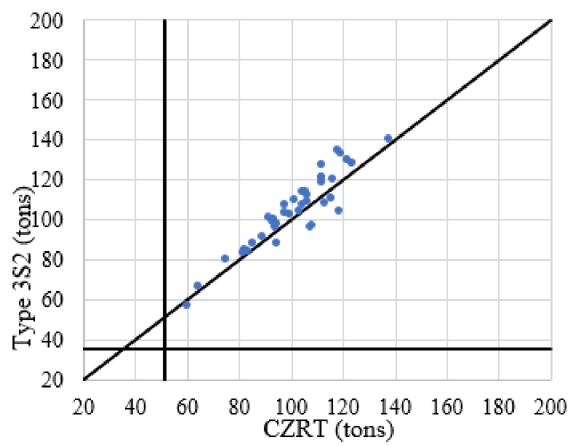


Figure 6.18: Comparison of CZRT and Type 3-3 with Factor of 0.96

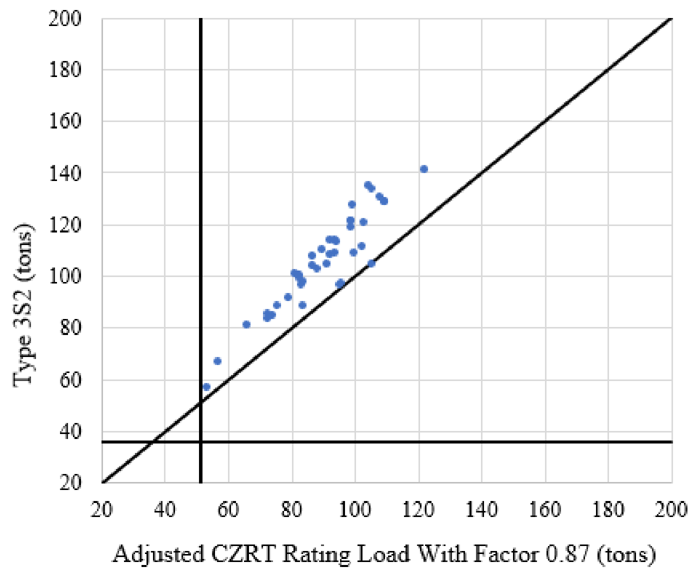


Figure 6.19: Comparison of CZRT and Type 3S2 with Factor of 0.87

Table 6.13: Rating Load Ratio Between CZRT and AASHTO Vehicles in LRFR

Rating Load Ratio	**Mean**	**Standard Deviation**
CZRT/Type 3-3	0.84	0.09
CZRT/Type 3S2	0.96	0.06

6.3.3 LRFR Load Rating Comparison Between H20L and AASHTO Type 3

AASHTO legal load Type 3 and MoDOT legal load H20L are both single unit truck vehicles. The graph, shown in Figure 6-21, comparing H20L and Type 3 rating loads shows that there is strongly linear correlation between the two vehicle rating results. All the data points are above 45-degree line, implying that H20L has a lower rating load than Type 3 across all prestressed bridges. If H20L has a threshold no less than Type 3 gross weight (25 tons), H20L will envelop AASHTO Type 3.

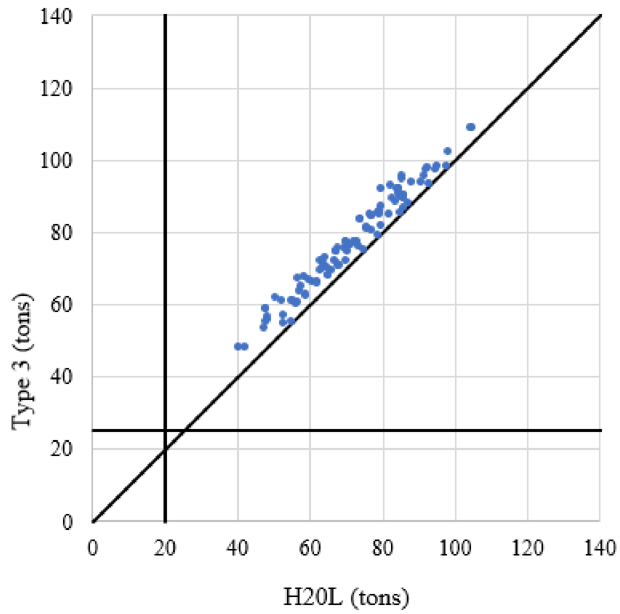


Figure 6.20: Rating Load Comparison of H20L and Type 3

6.3.4 Observation and Discussion

Table 6-14 and Table 6-15 highlight the main observations made from the load rating analysis of 100 prestressed bridge samples.

- Type 3-3 vehicles envelop MO3S2 vehicles if MO3S2 has a posting threshold no less than 40 tons.
- When using LRFR within commercial zone bridges, Type 3-3 vehicles are enveloped by CZRT with a factor of 0.96 and no threshold greater than the CZRT GWT is required.
- Type 3S2 vehicles are enveloped by MO3S2 when using a factor of 0.97, but no threshold greater than MO3S2 is required.
- When using LRFR within commercial zone bridges, Type 3S2 vehicles are enveloped by CZRT with a posting factor of 0.87 and without raising posting thresholds.
- Since MO3S2 already envelops Type 3-3 and Type 3S2, CZRT does not need any conditions to envelop Type 3S2 and Type 3-3. Because of this, the posting factor of CZRT will be 1.
- Type 3 vehicles are enveloped by H20L if H20L threshold are no less than 25 tons.

Table 6.14: Number of Bridges That Have MoDOT Rating Loads Greater Than AASHTO

	Type 3	**Type 3-3**	**Type 3S2**
H20L	0/100	-	-
MO3S2	-	0/100	13/100
CZRT	-	1/41	7/41

Table 6.15: Summary of Threshold and Posting Factor for H20L, MO3S2 and CZRT

	H20L Threshold	**H20L Factor**	**MO3S2 Threshold**	**MO3S2 Factor**	**CZRT (commercial zone) Threshold**	**CZRT (commercial zone) Factor**
Type 3	25	1				
Type 3-3			40	1	-	0.96
Type 3S2			-	0.97	-	1

6.3. Serviceability Limit State Consideration for Legal Load Rating

Service limit states consider the condition of a bridge under normal service conditions, including factors like fatigue, deformation, and long-term durability. MoDOT has asked whether service limit state should be included in its legal load rating for bridges. Answering this question is a project objective and this study hopes to give a recommendation based on the rating results of the prestressed bridges sample. When bridges are being evaluated with load and resistance factor ratings, MoDOT requires (according to BIRM Chapter 15) that “the limit state shall be provided for the controlling load rating that is being reported” (AASHTO, 2022). In the manual, there is no specific guidance on whenever service limit state might or might not be evaluated.

The Service III limit state is used for prestressed concrete superstructures and looks at the tension of prestressed concrete girders to provide crack control. The research article “Evaluation of Serviceability Requirements for Load Rating Prestressed Concrete Bridges” (Wood, 2007) found that prestressed bridges designed in the 1950s and 1960s showed no distress or signs of deterioration despite load rating results implying the opposite.

LRFR results for the 100 prestressed bridges from this study contain six bridges controlled by Service III – tensile stress concrete. A summary of those bridges is shown in Table 6.16 below.

Table 6.16: Service III Bridges Structure Type

Bridge	NBI	Description	Structure	Girder Type
B0272	33353	3 Span	Simple	Single Box Beam
B0226	33445	2 Span	Simple	Single Box Beam
B0057	33443	1 Span	Simple	Multiple Box Beam
B0290	33475	1 Span	Simple	Multiple Box Beam
B0267	33538	3 Span	Simple	Multiple Box Beam
A7647	32839	3 Span	Continuous	Tee Beam

Table 6-16 shows bridges that have one to three spans. Most of them are simply supported, box beam/girder structures, but there is one continuously supported tee beam bridge.

Table 6.17: Service III Bridges Design Information

Bridge	NBI	Year Built	Design Method	Commercial Zone?
B0272	33353	2011	LFD	N
B0226	33445	2011	LFD	Y
B0057	33443	2011	LFD	N
B0290	33475	2011	LRFD	N
B0267	33538	2011	LRFD	N
A7647	32839	2009	LFD	Y

According to Table 6-17, most of the bridges that are LRFR Service III controlled are built in recent years (five were built in 2011 and one was built in 2009). Four out of six were designed using LFD specifications and two others with LRFD specifications. There are two bridges within commercial zone and four outside.

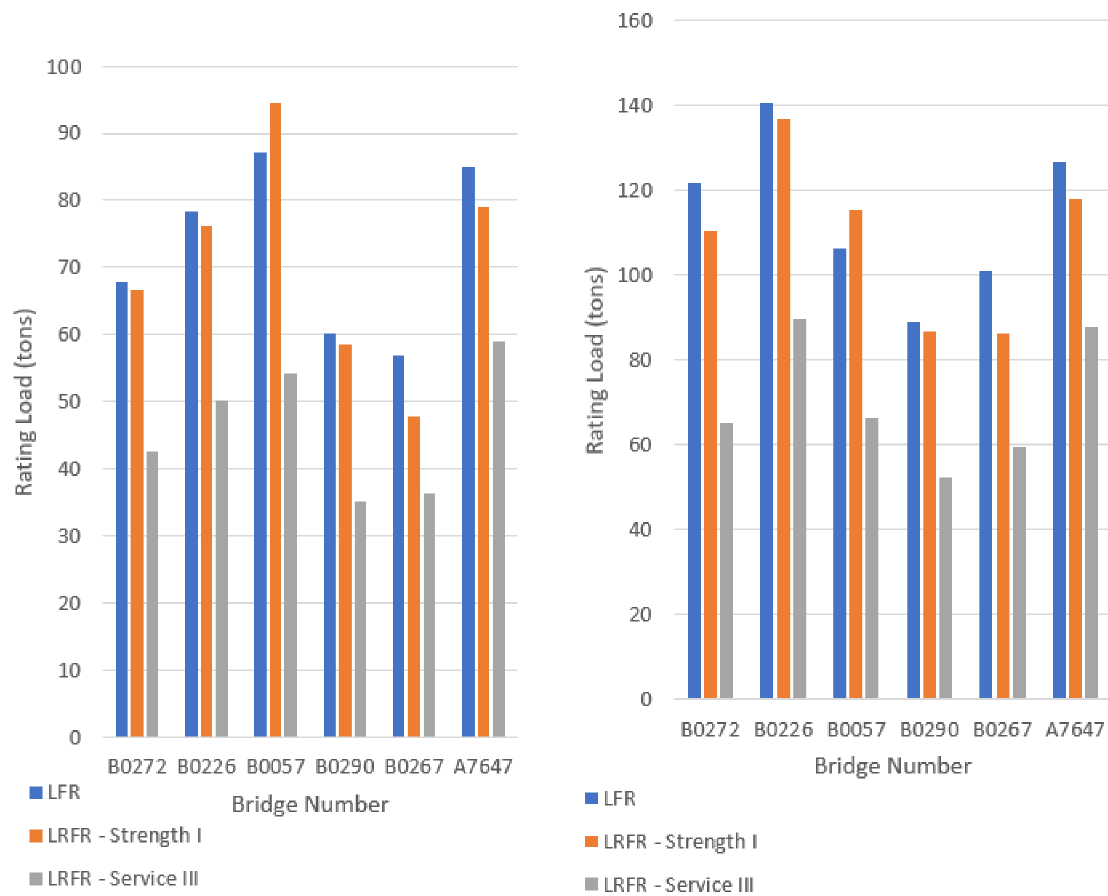
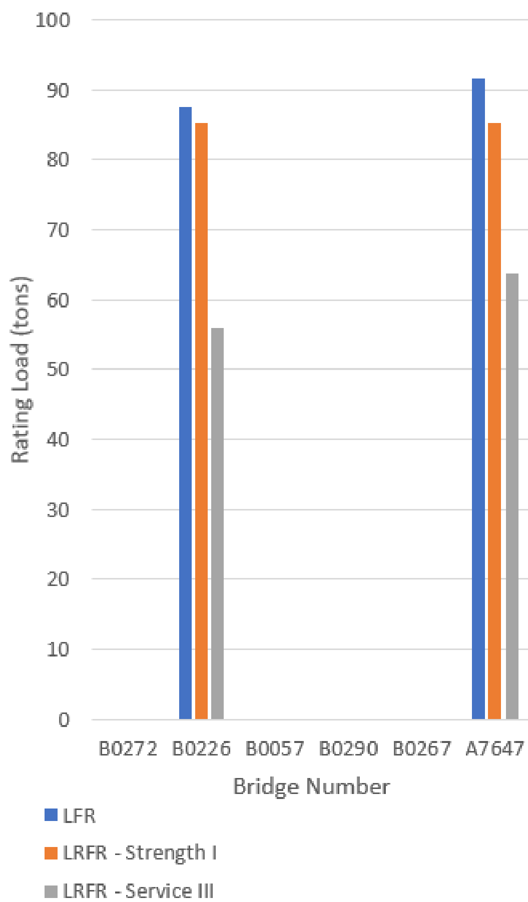


Figure 6.21. Comparison of Rating Load for H20L (left) and MO3S2 (right)



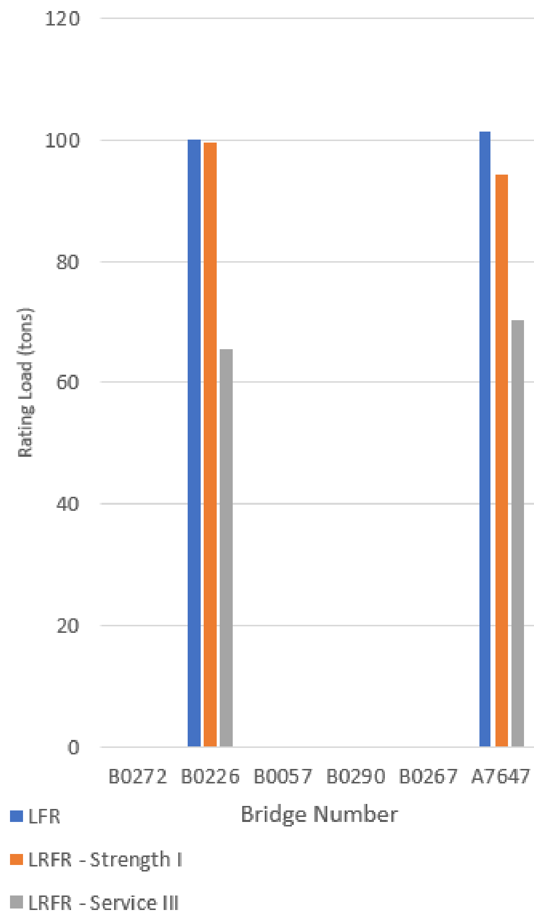


Figure 6.22. Comparison of Rating Load for CZSU (left) and CZRT (right)

Figure 6-20 and Figure 6-21 compare rating loads for H20L, MO3S2, CZSU, and CZRT vehicles within the LFR flexural limit state, LRFR strength I limit state, and LRFR Service III limits state. The LFR flexural and LRFR strength I limit state rating results are similar in terms of rating load and none are required for load posting. However, the LRFR Service III rating results show much lower results. Despite the rating load decrease with LRFR Service III, none of the bridges require load posting since LRFR rating factors are greater than 1.0. Rating data is shown in Table 6-18.

Table 6.18: Comparison of Legal Load Rating Between LRFR Service III, Strength I, and LFR

	Service III		Strength I		LFR		Ratio	
Bridge	Rating Factor	Rating Load	Rating Factor	Rating Load	Rating Factor	Rating Load	Ser. III/Str. I	Ser. III/LFR
H20 Legal load								
B0272	2.13	42.6	3.337	66.74	3.392	67.84	0.64	0.63
B0226	2.5	50.06	3.81	76.2	3.915	78.29	0.66	0.64
B0057	2.72	54.32	4.733	94.65	4.356	87.13	0.57	0.62
B0290	1.76	35.22	2.921	58.41	3.007	60.14	0.6	0.59
B0267	1.81	36.27	2.391	47.81	2.837	56.74	0.76	0.64
A7647	2.95	59.02	3.953	79.05	4.254	85.07	0.75	0.69
MO3S2								
B0272	1.78	65.26	3.013	110.39	3.324	121.79	0.59	0.54
B0226	2.45	89.86	3.733	136.79	3.836	140.56	0.66	0.64
B0057	1.81	66.22	3.149	115.4	2.899	106.22	0.57	0.62
B0290	1.43	52.2	2.363	86.59	2.433	89.15	0.6	0.59
B0267	1.62	59.36	2.351	86.15	2.757	101.01	0.69	0.59
A7647	2.4	88	3.217	117.88	3.462	126.86	0.75	0.69
CZSU								
B0226	1.37	56.02	2.09	85.28	2.148	87.63	0.66	0.64
A7647	1.56	63.63	2.089	85.23	2.248	91.73	0.75	0.69
CZRT								
B0226	1.65	65.65	2.503	99.62	2.516	100.13	0.66	0.66
A7647	1.77	70.41	2.37	94.31	2.55	101.49	0.75	0.69

Table 6.19: Ratio of Rating Load Between LRFR Strength I and LFR/ LRFR Service III

	Ratio (LRFR Service III/Strength I)		Ratio (LRFR Service III/LFR Flexure)	
	Mean	STD	Mean	STD
H20L	0.66	0.08	0.63	0.03
MO3S2	0.64	0.07	0.61	0.05
CZSU	0.70	0.06	0.67	0.04
CZRT	0.70	0.06	0.67	0.03

Table 6-19 shows rating loads of LRFR Service III are about 64% to 70% compared to LRFR strength I rating loads, and about 61% to 67% compared to LFR flexure rating loads for four state legal load ratings. However, inspection information from MoDOT indicates that those bridges are in good condition (NBI rating >= 6), and they show no distress in the concrete girders (Table 6-20). All of Service III limit state-controlled bridges are currently not required to have load posting or other restrictions. Thus, it would be appropriate not to include Service III limit state in MoDOT's legal load rating for LRFR.

Table 6.20: Superstructure Rating and Current Posting Required for Service Limit State Load Rating-Controlled Bridges

Bridge	NBI	Superstructure Rating	Current Posting Required
B0272	33353	9	Not Required
B0226	33445	8	Not Required
B0057	33443	6	Not Required
B0290	33475	7	Not Required
B0267	33538	8	Not Required
A7647	32839	9	Not Required

6.4. Conclusions and Recommendations

There appears to be no significant difference in rating loads and the number of bridges requiring posting when using LFR and LRFR for prestressed bridges according to this study's examination of 100 such structures in Missouri. Prestressed girders are usually used in short span bridges, and most prestressed bridges were built recently (compared to reinforced concrete slab and steel bridges). Thus, results showed high ratings for all the vehicles (about 3.5 for H20L, 2.5 for MO3S2 and SU5, and 2.04 for CZSU and CZRT).

When using LFR in MoDOT's current load rating practices, all vehicles use a posting factor of 0.86. This is applied to different types of bridges throughout the state, but this portion of the study focused on a sample of 100 prestressed bridges. The selection of vehicles to be enveloped was held to SU4, SU5, SU6, SU7, Type 3, Type 3-3, and Type 3S2. Based on these criteria, recommendations on thresholds and posting factors for the LRFR method are summarized in table 6-15. Vehicles will have different posting factors based on the need to envelop SHVs and AASHTO vehicles. These suggestions hope to assist MoDOT implement a new LRFR load posting policy. They include:

H20L (threshold 31T, factor = 1.0) will envelop SU4, SU5, Type 3.

MO3S2 (threshold 40T, factor = 0. 97) will envelop Type 3-3, Type 3S2.

CZSU (threshold = GWT, factor = 1) will envelop SU6, SU7.

Table 6.21: Summary of Threshold and Posting Factor Proposals for MoDOT's Vehicles

	BIRM (LFR)		Proposal (LRFR)	
MoDOT Vehicles	Threshold (tons)	Posting Factor	Threshold (tons)	Posting Factor
H20L	30	0.86	31	1
MO3S2	45	0.86	40	0.97
CZSU	45	0.86	40.8	1
CZRT	70	0.86	50	1

Six prestressed sample bridges have Service III limit state-controlled load rating when using LRFR. Serviceability rating loads are about 64% to 67% compared to the strength limit state. However, all these bridges are in good condition after 10 years of service, which would suggest excluding the service limit state when using LRFR at the legal load level.

Chapter 7: Reinforced Concrete Bridges – Research Study

MoDOT provided samples of 107 reinforced concrete bridges to be analyzed in AASHTOWare v7.1 for a load rating study focusing on procedures when using the LFR and LRFR methods. The study examined 99 bridges because eight of the sample files would not run in the required BrR v7.1 software.

7.1 Classification of RC Bridges

The bridges are categorized below by year built (Table 7.1), by number of spans (Table 7.2) and the length of the structure (Table 7.3). MoDOT provided the bridge models.

Table 7.1 summarizes the number of bridge models by year built and indicates that most of the concrete bridges were constructed from 1920 to 1960. Only five bridges were built after 1980.

Table 7.1: Number of Concrete Bridge Samples Against the Year Built

Year Built	Concrete
1920-1929	25
1930-1939	23
1940-1949	15
1950-1959	22
1960-1969	15
1970-1979	2
1980-2009	0
2010-2019	5
TOTAL	107

Number of Spans: The samples had varying numbers of spans, as seen in Table 7.2. There were 64 three-span models provided for this study.

Table 7.2: Number of Bridge Types Against Their Span Numbers

Span	Concrete
1 Span	15
2 Span	3
3 Span	64
4 Span	14
5 - 10 Spans	11
>10 Spans	0

The samples also had varying span lengths. Table 7.3 divides the bridges into six sets of structure lengths. Most of the bridges have lengths between 50 and 200 feet.

Table 7.3: Concrete Bridge Samples Classification by Length of the Structure

Length (Ft)	Concrete
0-30	4
31-50	9
51-80	19
81-120	37
120-200	28
201-350	10
TOTAL	107

The bridges were also divided by location, which determined that 97 of the 99 bridges were in non-commercial zones.

7.2 Objectives of the Reinforced Concrete Bridge Studies

The primary objectives of the reinforced concrete bridge study are as follows:

- Comparison of the rating factor and rating loads between LFR vs LRFR.
- Comparison of the rating factors and loads of MoDOT vs AASHHO legal vehicles.
- Comparison of the rating factor and loads of MoDOT vs AASHTO SUV vehicles.
- Provide recommendations to MoDOT.

7.3 Methodology

7.3.1 LRFR vs LFR Comparison

Currently, when using LFR, a bridge is posted if the rating factor is less than 1.0 and the rating load is less than the threshold value (30 tons in this example). The posting load is the rating load multiplied by the LFR factor of 0.86. This research describes the steps, when using the LRFR method, taken to determine the posting load and an LRFR factor, such as the factor currently used by MoDOT for LFR.

7.4 Results and Summary

7.4.1 Comparison between LFR and LRFR

The rating results obtained from analysis comparisons were plotted with LFR rating factors on the x-axis with the corresponding LRFR factors along the y-axis. As seen on the left side of Figure 7.1, if the plots fall above the 45-degree line, rating factors when using LRFR are greater than when using LFR. On the other hand, if the plots fall below the 45-degree line, bridges have higher rating factors when using LFR than when using LRFR.

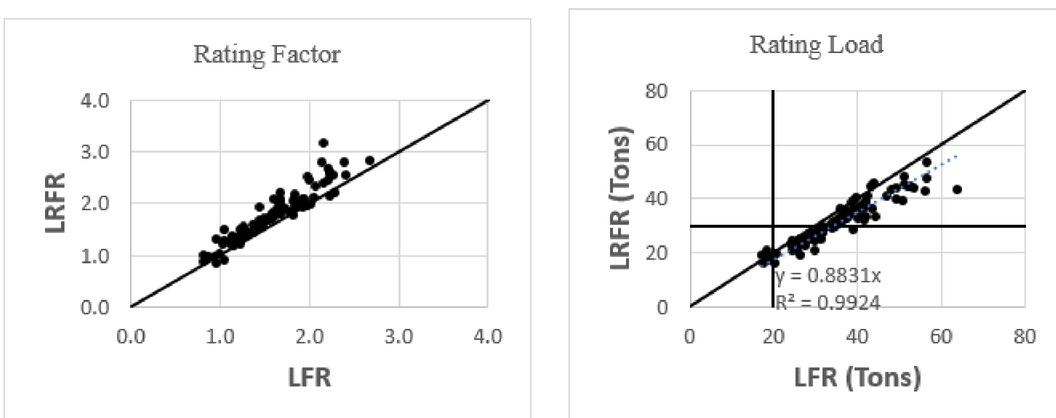


Figure 7.1: Sample LRFR vs LFR Rating Factor Plots (left) and Rating Load Plots (right)

Rating load and rating factor calculations are both accomplished with the addition of vertical and horizontal lines, as shown on the right side of Figure 7.4. The vertical line represents the BIRM threshold of the vehicle (there is no BIRM threshold for SU5) and the horizontal line represents the GWT of the vehicle for LRFR rating load. In the right side of Figure 7.3, plots to the right of the vertical line have rating loads greater than the MoDOT LFR threshold, whereas the plots above the horizontal line have rating loads greater than the vehicle's GWT in LRFR. Hence, whenever the plots are on the left of the vertical line, posting for LFR is required for that bridge, and LRFR, posting is required when the plots are below the horizontal line.

When comparing LFR and LRFR, the maximum GWT of the vehicles was used as a threshold to determine the posting requirement in LRFR based on the recommendations of the MCE (AASHTO, 2017). All these comparisons are done at the operating level for both LFR and LRFR. The equation on the graph is the best-fit curve, which is specifically used to determine the factor for the threshold load. It is obtained by removing the posting loads that have values of zero in either LFR or LRFR and using an iterative process to make the slope of the equation nearly equal to 1.

H20 Legal Truck Rating Data Comparison: Figure 7.2 shows the comparative plot between LFR and LRFR for rating factor and rating load, respectively. The LFR and LRFR rating factor graph shows scattered plots in and around the 45-degree line. The plots are mostly above the 45-degree line in the LRFR region, which means most bridges have higher rating factors in LRFR than in LFR. In the rating load graph, there are quite a few points below the horizontal line and to the left of the vertical line. Hence, these points/bridges require postings.

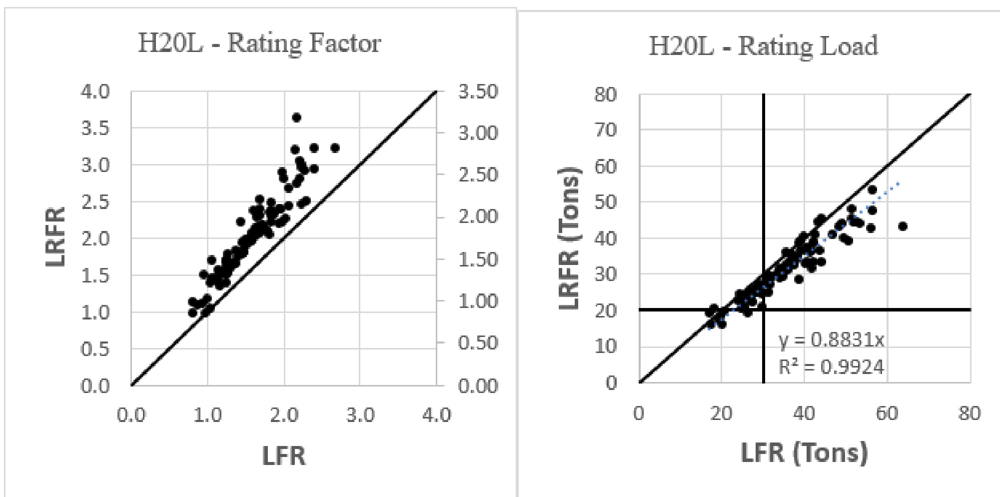


Figure 7.2: Rating Factor (left) and Rating Load (right) for H20L

Posting Requirement with Thresholds Applied: Table 7.4 outlines bridge postings using LRFR and LFR criteria, with two different thresholds: one with GWT and another with the threshold obtained from trial and error. During trial and error, a threshold weight was chosen that gives similar posting numbers but is higher than the GWT of the H20 vehicle. When GWT is used as the threshold applied on LRFR, a 30-ton LFR BIRM threshold load and a 20-ton LRFR threshold (equivalent to H20L GWT) is used along with factors of 0.86 for LFR and 1 for LRFR. We later introduced a 26-ton LRFR threshold, derived from iterative optimization, along with an LRFR factor of 0.97 from regression analysis (y = 0.1319x). Table 7.5 shows the number of bridges that needed posting with the different thresholds applied.

The graphs in Figure 7.3 are similar. The graph on the right consists of every point on the left plus the other points that are needed because when the threshold is higher more posting points are required.

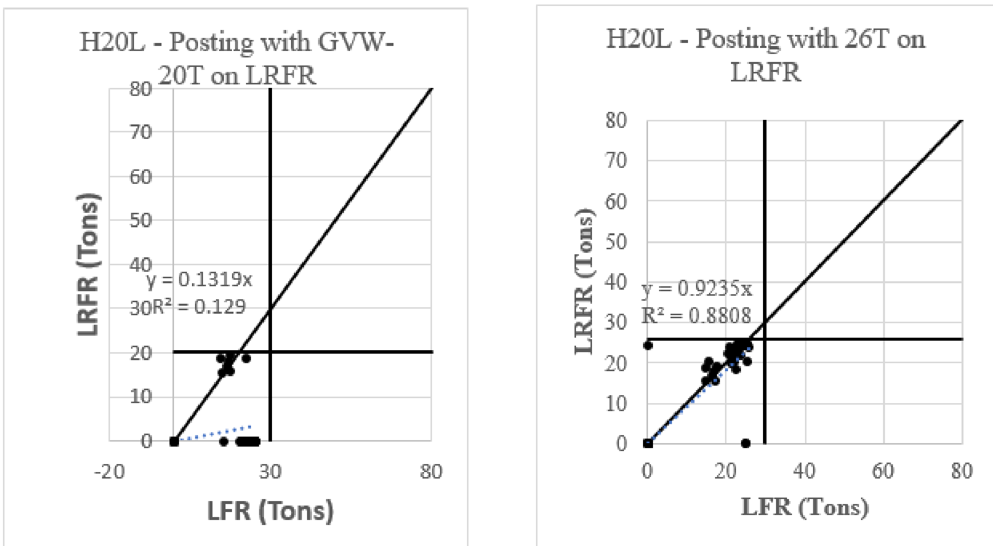


Figure 7.3: Posting Required for H20L Vehicle with Thresholds Applied

Table 7.4: Number of Bridges Needing Posting with Thresholds Applied on LRFR

	With Threshold of GVW-20T Applied on LRFR	**With Threshold of 26T Applied on LRFR**
LRFR	7	32
LFR	33	33
Both	7	31

Girder Controlling the Rating: Table 7.5 shows the number of bridges that are controlled by internal girder, external girder, and slab, respectively, in LFR and LRFR.

Table 7.5: Girder Controlling the Rating for H20L Vehicle

	LFR	LRFR
Interior Girder	52/99	50/99
Exterior Girder	11/99	14/99
Slab	36/99	35/99

Summary for H20L: Because there are few plots in the unsatisfactory rating (factor/ load) region for both the LRFR and the LFR, the threshold of LRFR was increased, from 26 tons to 31 tons, so that there are no points in that region as was seen in Figure 7.4 Hence, we propose a LRFR threshold for H20L vehicle as 31 tons with the LRFR factor being 0.97 as shown in the Table 7.6. With this new threshold for H20L, the number of bridges that needed posting for LRFR was 49, and the number for LFR was 33.

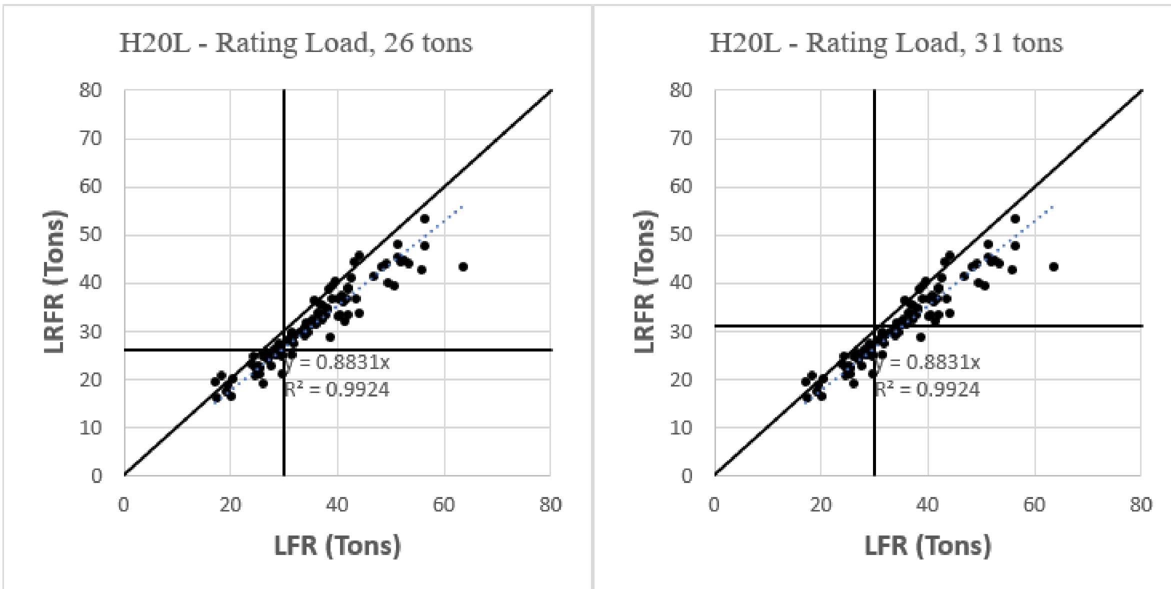


Figure 7.4: Rating Load Graph for 26 Tons and 31 Tons Applied to H20L

Table 7.6: LFR and LRFR Proposed Threshold and Factor for H20L

Threshold (Tons)		Factor	
LFR	LRFR (Proposed)	LFR	LRFR (Proposed)
30	31	0.86	0.97

MO3S2 Rating Data Comparison: In Figure 7.5 for rating factor, the plots are mostly below the 45-degree line in the LFR region, which means most bridges have higher rating factors in LFR than in LRFR. Similarly, in the rating load plot, there are multiple points below the horizontal line and to the left of the vertical line, indicating these plots/bridges require postings.

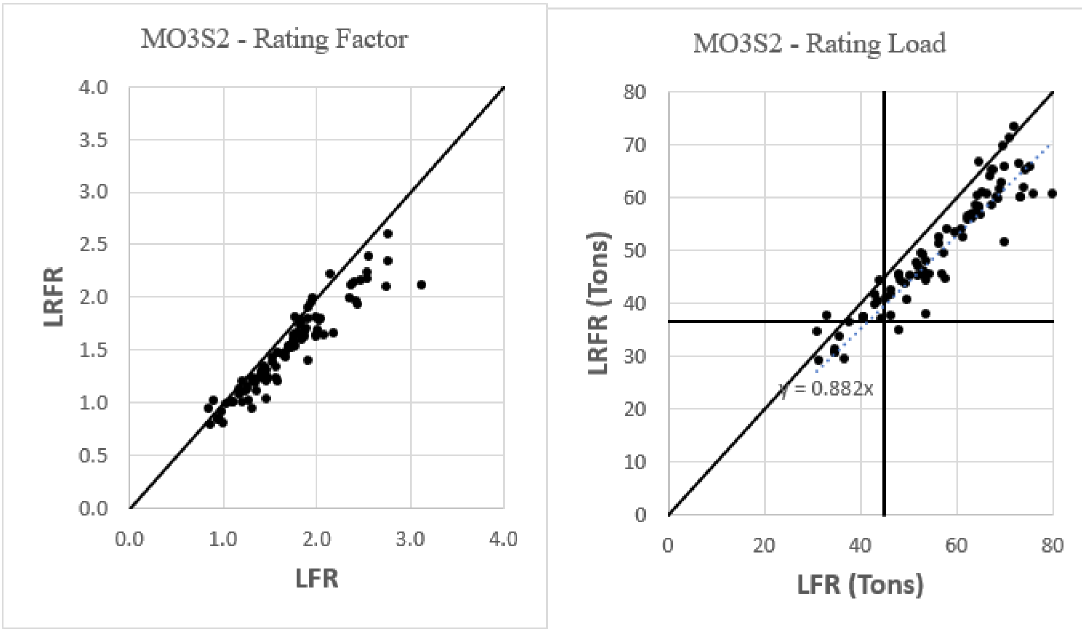


Figure 7.5: Rating Factor and Rating Load for MO3S2

Posting Requirement with Thresholds Applied: Table 7.7 shows that the number of bridges that require posting in LRFR, LFR, and with two different thresholds applied. A 45-ton LFR BIRM threshold load and a 36.64-ton LRFR threshold (equivalent to MO3S2 vehicle weight) were used along with factors of 0.86 for LFR and 1.0 for LRFR. Later, a 40-ton LRFR threshold derived from iterative optimization was introduced along with an LRFR factor of 0.93 from regression analysis (y = 0.7774x), as seen in Figure 7.6.

Table 7.7: Number of posting for MO3S2 With Thresholds Applied

	With Threshold of GWT-36.64T Applied on LRFR	With Threshold of 40T Applied on LRFR
LRFR	9	17
LFR	17	17
Both	8	14

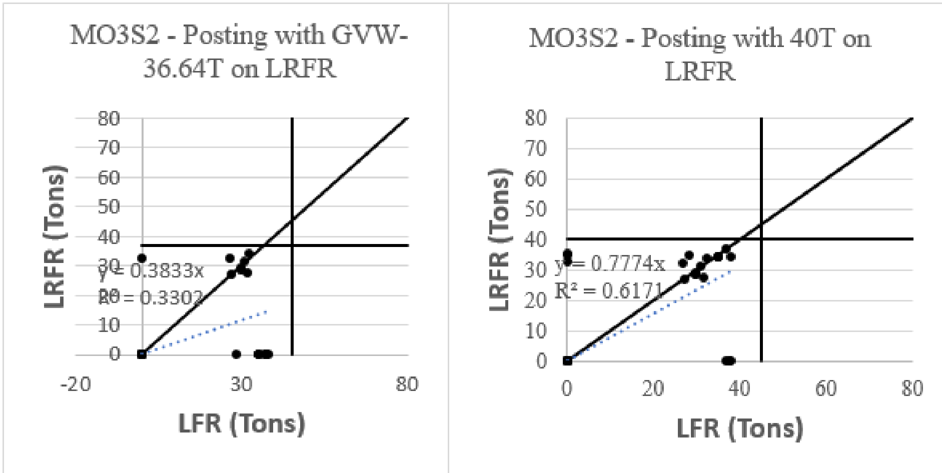


Figure 7.6: Posting Required for MO3S2 Vehicle With Thresholds Applied

Girder Controlling the Rating: Table 7.8 shows the number of bridges that are controlled by internal girder, external girder, and slab are 52, 11, and 36 respectively in LFR and that 51, 13, and 35 bridges are controlled by internal girder, external girder, and slab respectively in LRFR.

Table 7.8: MO3S2 Girder Controlling Rating

	LFR	LRFR
Interior Girder	52/99	51/99
Exterior Girder	11/99	13/99
Slab	36/99	35/99

Summary for M03S2: Results suggest an LRFR threshold of 40 tons with an LRFR factor of 0.93 that resonates with the LFR BIRM threshold of 45 tons and LFR factor of 0.86 as shown in Table 7.9. When a new LRFR threshold of 40 tons is applied to MO3S2, 17 bridges needed posting in both LFR and LRFR.

Table 7.9: LFR and LRFR Proposed Threshold and Factor for MO3S2

Threshold (Tons)		Factor	
LFR	LRFR (Proposed)	LFR	LRFR (Proposed)
45	40	0.86	0.93

CZSU Rating Data Comparison: Only two of the 99 reinforced concrete bridges that were investigated fall in commercial zones. Figure 7.7 shows that the two plot points are below the 45-degree line in the rating factor graph, which indicates that they have a larger rating load in LFR than in LRFR. The two points are also above the horizontal line and to the right of the vertical line in the rating load graph, so, these bridges do not require posting. With only two bridges, there is insufficient data to make any policy suggestions.

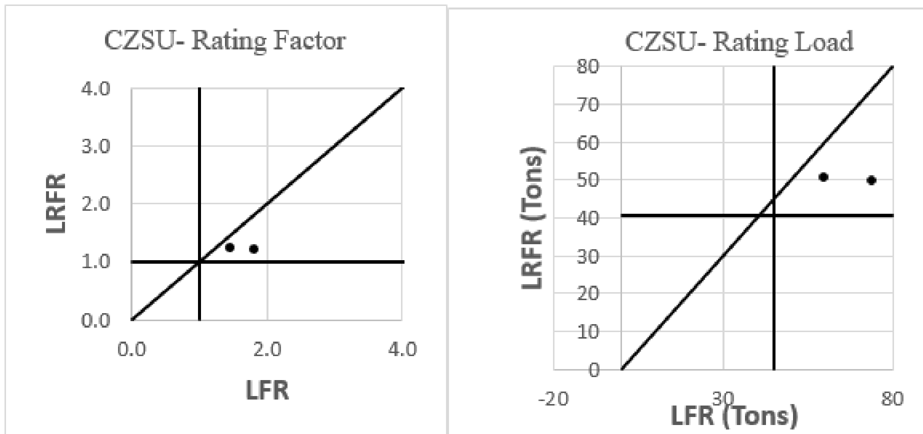


Figure 7.7: Rating Factor and Rating Load for CZSU

Posting Requirement with Thresholds Applied: As mentioned above, CZSU does not require posting with LRFR thresholds of 40.8 tons (equivalent to CZSU vehicle weight).

Girder Controlling the Rating: Table 7.10 shows the number of bridge ratings that are controlled by the interior girder, exterior girder, and slab.

Table 7.10: CZSU Girder Controlling Rating

	LFR	LRFR
Interior Girder	0/2	0/2
Exterior Girder	1/2	1/2
Slab	1/2	1/2

Summary for CZSU: Both the iterative value of 45 tons and CZSU's GWT of 40.8 tons produced similar results, so, the least of the two was selected as a low threshold value since it will result in fewer postings. Thus, an LRFR threshold of 40.8 tons with an LRFR factor of 1.0 (such as the LFR BIRM threshold of 45 tons and LFR factor of 0.86) was proposed for adoption.

Hence, when a new LRFR threshold of 40.8 tons is applied to CZSU, neither of the two bridges needed posting in LFR or LRFR as shown in Table 7.11.

Table 7.11: LFR and LRFR Proposed Threshold and Factor for CZSU

Threshold (Tons)		Factor	
LFR	LRFR (Proposed)	LFR	LRFR (Proposed)
45	40.8 (GWT)	0.86	1

CZRT Rating Data Comparison: The LFR and LRFR rating factor graphs show two plots below the 45-degree line, which means the two bridges have rating factors greater in LFR than in LRFR. Also, the rating load graph in Figure 7.8, shows no points below the horizontal line or to the left of the vertical line, so, neither of the two bridges need posting.

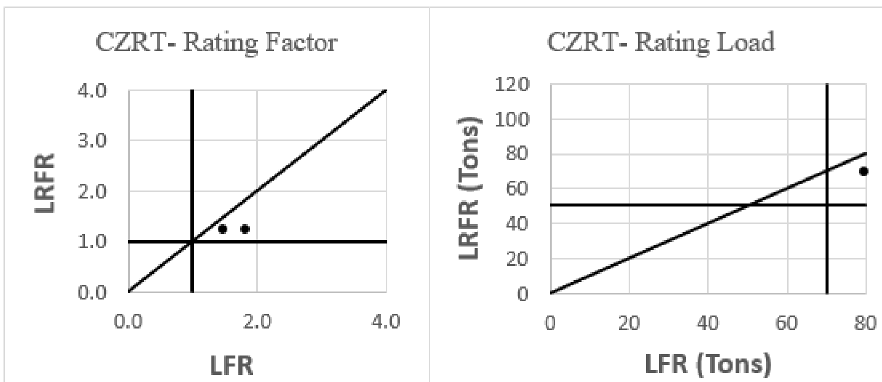


Figure 7.8: Rating Factor and Rating load for CZRT

Posting Requirement with Thresholds Applied: As shown in Figure 7.9, neither of the two bridges needed posting with LRFR thresholds of 51 tons (CZSU's GWT) and an iterative optimized threshold of 65 tons.

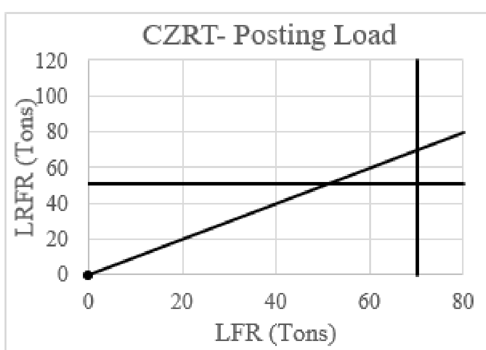


Figure 7.9: CZRT Posting Load with Thresholds

Girder Controlling the Rating: Table 7.12 shows 0, 1, 1 number of bridges are controlled by the interior girder, exterior girder, and slab respectively for both LRFR and LFR.

Table 7.12: CZRT Girder Controlling Rating

	LFR	LRFR
Interior Girder	0/2	0/2
Exterior Girder	1/2	1/2
Slab	1/2	1/2

Summary for CZRT: Both the iterative value of 65 tons and CZSU's GWT of 51 tons produced similar results, so, the least of the two was selected as a low threshold value since it will result in fewer postings. Thus, an LRFR threshold of 51 tons with an LRFR factor of 1 (such as the LFR BIRM threshold of 45 tons and LFR factor of 0.86 shown in Table 7.13) was proposed. Hence, when a new LRFR threshold of 51 tons is applied to CZRT, neither of the two bridges needed posting in LFR or LRFR.

Table 7.13: LFR and LRFR Proposed Threshold and Factor for CZRT

Threshold (Tons)		Factor	
LFR	LRFR (Proposed)	LFR	LRFR (Proposed)
70	51 (GVW)	0.86	1

SU5 Rating Data Comparison: In Figure 7.10 the graph for rating factor shows plots that are below the 45-degree line in the LFR region, which means most bridges have higher rating factors in LFR than in LRFR. Similarly, in the graph for rating load, there is a significant number of plots below the horizontal line and to the left of the vertical line, indicating that these plots require postings.

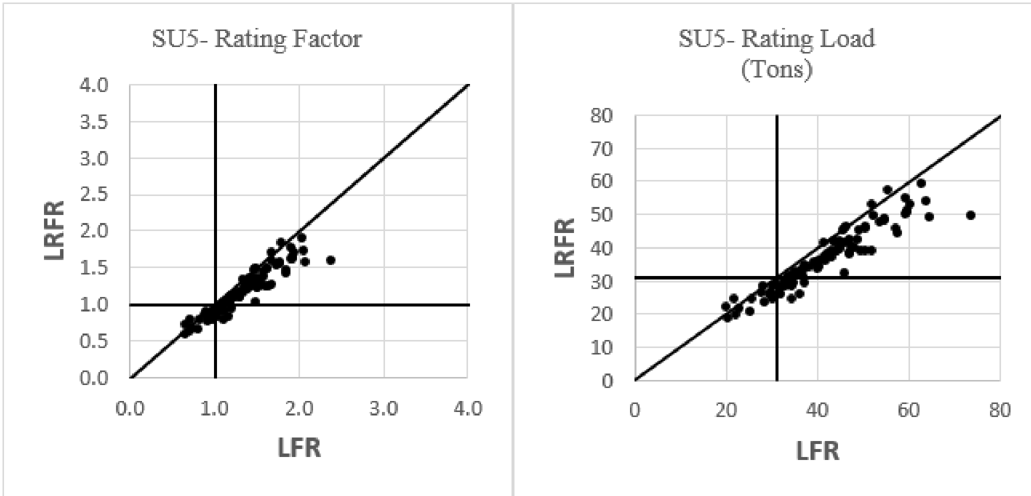


Figure 7.10: Rating Factor and Rating Load Graph for SU5

Posting Requirement with Thresholds Applied: Table 7.14 shows the number of bridges that require posting when LRFR is used, LFR is used, and both methods are used with different thresholds applied. First, GWT was used as the threshold, then a 31-ton LRFR threshold (equivalent to SU5 vehicle weight), while factors of 0.86 for LFR and 1 for LRFR were applied. We later introduced a 35-ton LRFR threshold derived from iterative optimization, along with an LRFR factor of 0.93 from regression analysis (y = 1.0025x). Figure 7.11 depicts posting loads with different thresholds applied during the research.

Table 7.14: Number of Bridges Requiring Posting for SU5 with Thresholds Applied

	With Threshold of GWT-31T Applied on LRFR	With Threshold of 35T Applied on LRFR
LRFR	33	46
LFR	17	17
Both	17	17

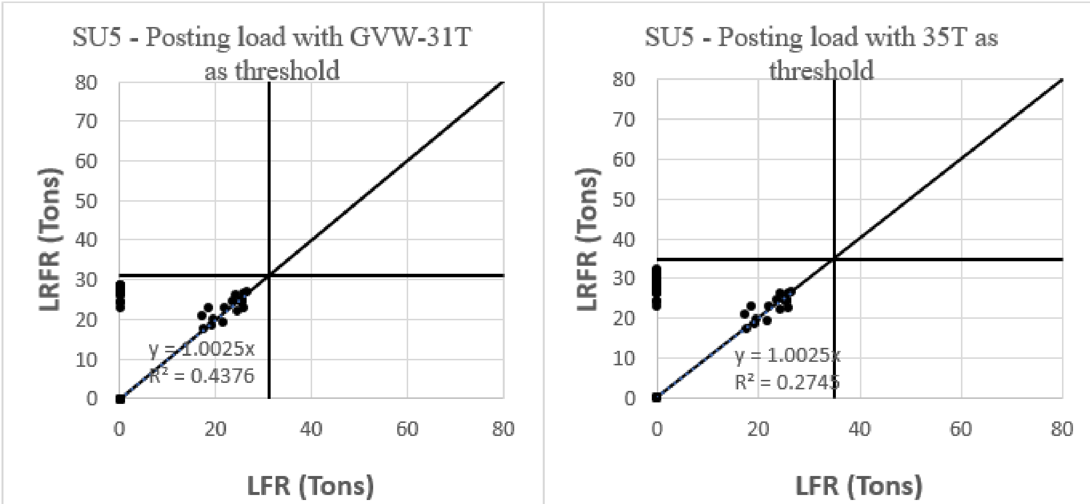


Figure 7.11: Posting Load for SU5 with 31 Tons and 35 Tons

Girder Controlling the Rating: Table 7.15 shows the bridges being compared in LFR and LRFR and whether the interior girder, exterior girder or slab controls the rating.

Table 7.15: SU5 Girder Controlling Rating

	LFR	LRFR
Interior Girder	52/99	50/99
Exterior Girder	11/99	14/99
Slab	36/99	35/99

Summary for SU5: A SU5 LRFR threshold of 31 tons with an LRFR factor of 0.93 is suggested. Table 7.15 shows that both 31 tons and 35 tons produced similar results, so the least of the two was selected as a low threshold value since it will result in fewer postings. When a new LRFR threshold of 35 tons is applied to SU5, the number of bridges needing posting in LFR and LRFR were 17 and 33 respectively.

Summary and Recommendation: Tables 7.16 and 7.17 show the average and standard deviation of the rating factors and rating loads, respectively, using LFR and LRFR. We also determined the ratio of the methods and calculated the average and standard deviation between the two. There are no significant differences in posting loads and interior/ exterior girder control in LRFR and LFR.

Table 7.16: Rating Factor Comparison between LFR and LRFR

	R. Factor LFR		R. Factor LRFR		LRFR / LFR Ratio	
Vehicle	Average	STD	Average	STD	Average	STD
H20L	1.77	0.48	1.57	0.41	1.12	0.10
MO3S2	1.68	0.48	1.49	0.40	1.13	0.10
CZSU	1.63	0.24	1.23	0.01	1.32	0.21
CZRT	1.85	0.40	1.42	0.07	1.29	0.22
SU5	1.33	0.35	1.18	0.30	1.12	0.10

Table 7.17: Rating Load Comparison Between LFR and LRFR

	R. Load LFR		R. Load LRFR		LFR / LRFR Ratio	
Vehicle	Average	STD	Average	STD	Average	STD
H20L	35.37	9.63	31.46	8.13	0.9	0.08
MO3S2	61.48	17.52	54.63	14.75	0.9	0.07
CZSU	66.48	9.94	50.33	0.43	0.77	0.12
CZRT	94.20	20.63	72.59	3.68	0.79	0.13
SU5	41.24	10.94	36.67	9.31	0.90	0.08

7.4.2 Comparison Between MoDOT and Special Hauling Vehicles (SHV) / SUVs

To assess the load-carrying capacity of MoDOT vehicles compared to single-unit vehicles (SUVs), a comprehensive analysis was conducted. The primary objective was to determine whether MoDOT vehicles are capable of accommodating SUVs. Additionally, any pertinent factors that might influence the ability of each type of single-unit vehicle to be accommodated by MoDOT vehicles were investigated.

For this research two single unit trucks currently used by MoDOT: H20L and commercial zone vehicle CZSU with GWTs of 20 tons and 40.8 tons, respectively, were used. According to BIRM, these two vehicles need posting if the rating is less than 30 tons and 45 tons, respectively. This is done to envelop the other single unit trucks operating within the state. Per NCHRP Report 700, SHVs have a lower load rating for certain bridges because they create higher force effects when compared to AASHTO Type 3, Type 3-S2, and Type 3-3 vehicles. So, these SHVs need to be included in rating analysis. The single-unit vehicles that were considered in this study include SU4, SU5, SU6, and SU7.

The findings from the above examination were then contrasted with those obtained from the comparison of MoDOT vehicles with AASHTO vehicles. The aim is to understand the load-carrying capabilities and potential limitations of MoDOT vehicles in relation to SUVs, as well as provide broader context of their performance compared to AASHTO vehicles.

The rating load data when using LRFR for 99 bridges were plotted with the x-axis representing MoDOT rating loads and y-axis representing the SHV and AASHTO rating loads. As seen in Figure 7.12, plots are above the 45-degree line indicating that SHVs vehicle rating loads are greater than MoDOT vehicle rating loads. The horizontal line represents GWT for SHVs, and the vertical line represents GWT for MoDOT vehicles.

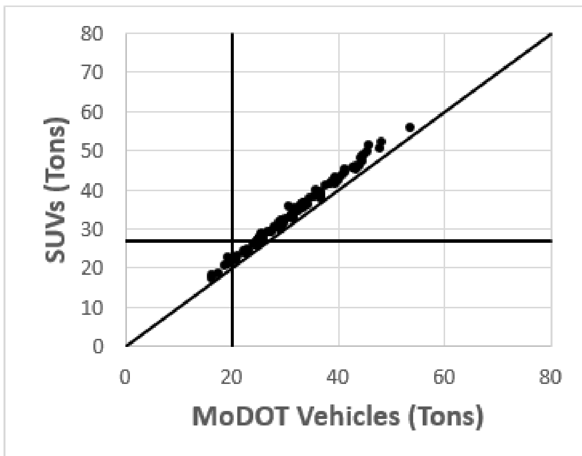


Figure 7.12: MoDOT Vehicles vs SHVs Comparison Graph

H20L vs SU4 Rating Load Data Comparison: The rating factors for SU4 vehicles were plotted on the x-axis and those for MoDOT's H20L vehicles on the y-axis for the graph in Figure 7.13. The results showed all the plots falling in the H20L region below the 45-degree line, meaning SU4 vehicles have lower rating factors compared to MoDOT's H20L vehicles. Similarly, in the rating load graph in Figure 7.13, all the points are in the SU4 region above the 45-degree line, meaning SU4 vehicles have higher rating loads compared to MoDOT's H20L vehicles.

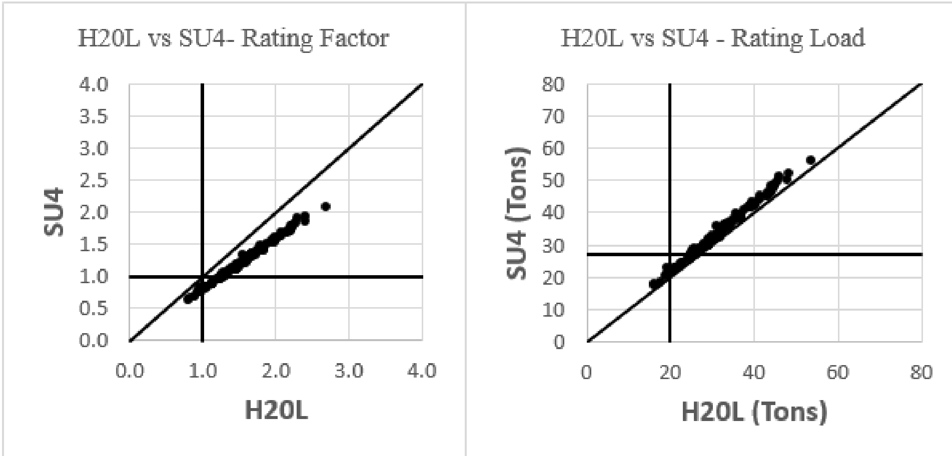


Figure 7.13: SU4 vs H20L Rating Factor and Rating Load

Posting Requirement: Table 7.18 shows 7 bridges require posting loads for H20L vehicles and 25 bridges require them for SU4 vehicles when applying a threshold of the H20L GWT of 20 tons. However, when the threshold increased to the SU4 GWT of 27 tons, 33 bridges needed posting for H20L vehicles, and 25 bridges needed posting for SU4 vehicles.

Table 7.18: H20L vs SU4 Posting Required When Threshold Applied on H20L

	With a Threshold of 20T Applied	With a Threshold of 27T Applied
H20L	7	33
SU4	25	25
Both	7	25

Girder Controlling the Rating: Table 7.19 shows the number of bridges controlled by internal girder, external girder, and slab, respectively, for H20L and SU4 vehicles.

Table 7.19: H20L vs SU4 Girder Controlling Rating

	H20L	SU4
Interior Girder	50/99	51/99
Exterior Girder	14/99	14/99
Slab	35/99	34/99

H20L vs SU5 Rating Load Data Comparison: When plotting the rating factors of SU5 vehicles on the x-axis and those of H20L vehicles on the y-axis the graph in Figure 7.14 shows all the plots falling below the 45-degree line, meaning SU5 vehicles have lower rating factors than H20L vehicles. Similarly, in the rating load graph, all the points are above the 45-degree line indicating that SU5 vehicles have higher rating loads than H20L vehicles.

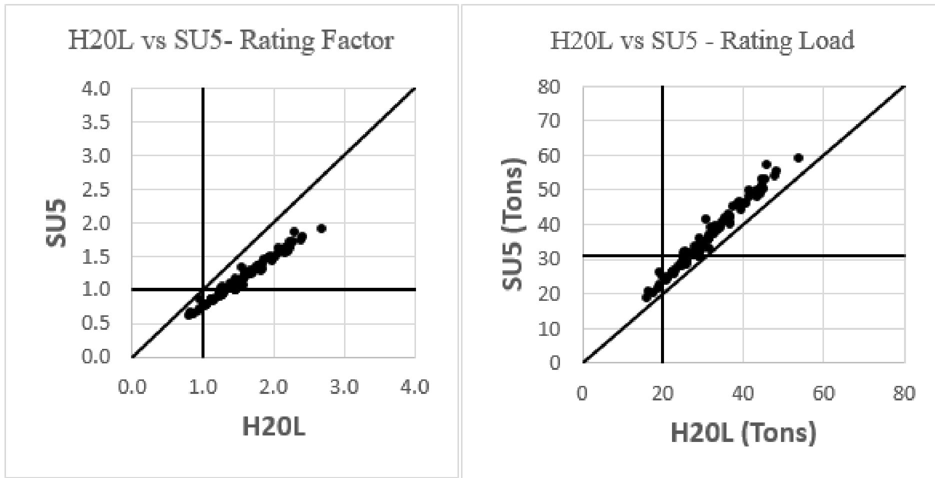


Figure 7.14: SU5 vs H20L Rating Factor and Rating Load

Posting Requirement with Thresholds Applied: Table 7.20 indicates that seven bridges for H20L vehicles and 33 bridges for SU5 vehicles needed posting with a threshold of 20 tons (GWT of H20L) applied to H20L vehicles. However, when a threshold of 31 tons (GWT of SU5) was applied to H20L vehicles, 49 bridges needed posting for H20L vehicles, and 33 bridges needed posting for SU5 vehicles.

Table 7.20: H20L vs SU5 Posting Required When Threshold Applied on H20L

	With the Threshold of GVW-20T Applied	With a Threshold of 31T Applied
H20L	7	49
SU5	33	33
Both	7	33

Girder Controlling the Rating: Table 7.21 shows the number of bridges controlled by internal girder, external girder, and slab, respectively, for H20L and SU5 vehicles.

Table 7.21: H20L vs SU5 Girder Controlling Rating

	H20L	SU5
Interior Girder	50/99	50/99
Exterior Girder	14/99	15/99
Slab	35/99	34/99

As SU6 and SU7 vehicles are regarded as the heavy trucks, they do not commonly operate in non-commercial zones. Hence, comparing them to H20L vehicles will result in high thresholds when encapsulating them and are therefore not compared. Figure 7.15 shows the rating load comparison between MoDOT H20L vehicles and SU6 and SU7 vehicles.

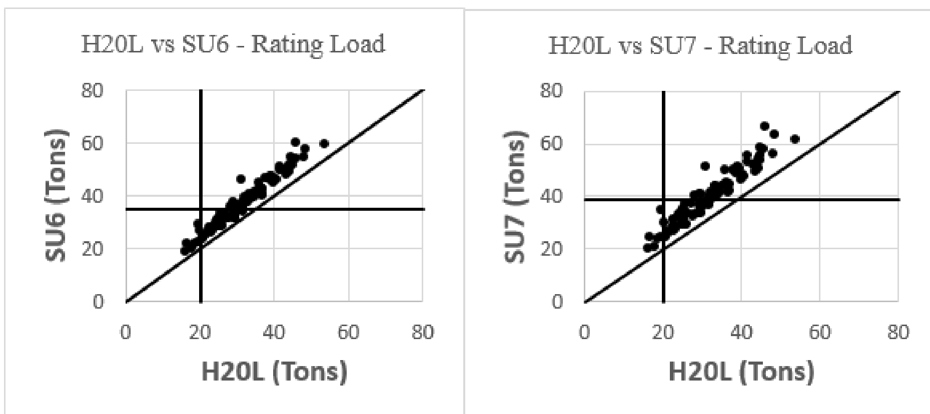


Figure 7.15: Rating Load of H20L vs SU6 and SU7

Summary of H20L with SUVs: Figures, 7.13 and 7.14 show that H20L encapsulates SU4 vehicles with a threshold of 27 tons and SU5 vehicles with a threshold of 31 tons. Hence, to encapsulate both SU4 and SU5, the H20L vehicles must have a threshold of 31 tons (the highest threshold between the two). Therefore, a threshold for H20L of 31 tons with a factor of 1 is suggested.

Table 7.22: Proposed Thresholds and Factors for H20L vs SUVs

Vehicle	LRFR (Tons)	Factor
SU4	27	1
SU5	31	1
Both	31	1

CZSU vs SU4 Rating Load Data Comparison: Only two reinforced concrete bridges in the sample fall in a commercial zone, so only two bridges were analyzed. Figure 7.16 shows two data points below the 45-degree line, implying that CZSU vehicles have higher load ratings compared to SU4 vehicles. The minimum of the ratio of SU4 to CZSU was used as the factor to shift the plots above the 45-degree line. CZSU has a maximum GWT of 40.8 tons, greater than the GWT of SU4 (27 tons), which is the threshold for CZSU to envelop SU4. This can also be summarized as SU4 is enveloped by CZSU vehicles with a factor of 0.92.

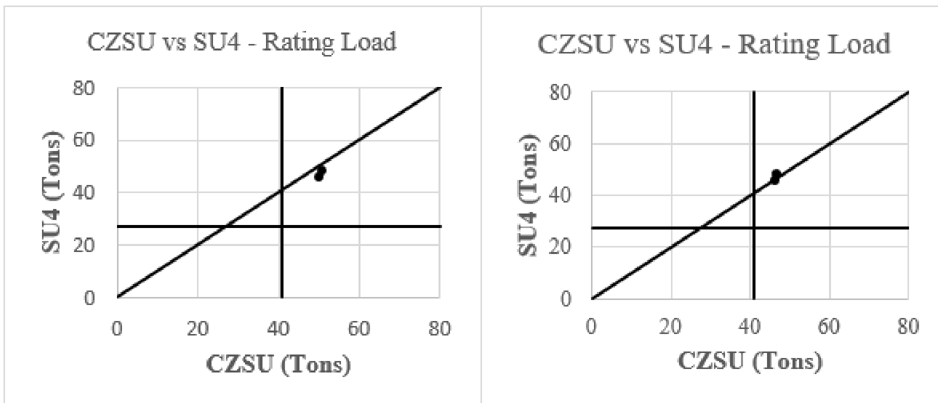


Figure 7.16: CZSU vs SU4 Rating Load Before and After Shifting Points

Posting Requirement with Thresholds Applied: Figure 7.17 shows that neither of the two bridges in commercial zone needed posting after application of 40.8 tons and 27 tons as thresholds on CZSU vehicles.

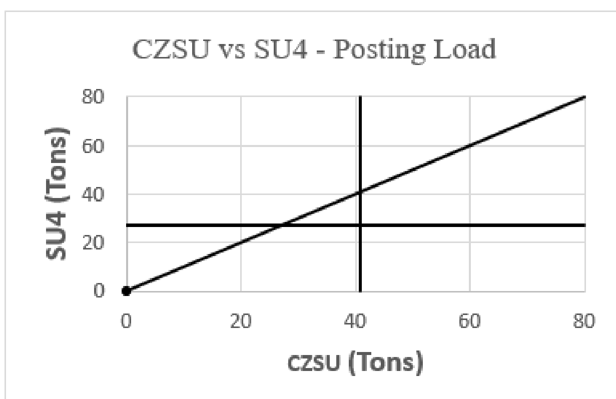


Figure 7.17: Posting Load CZSU vs SU4

Girder Controlling the Rating: Table 7.23 shows 0, 1, and 1 bridge are controlled by internal girder, external girder, and slab, respectively, for both CZSU and SU4 vehicles.

Table 7.23: CZSU vs SU4 Girder Controlling Rating

	CZSU	SU4
Int. Girder	0/2	0/2
Ext. Girder	1/2	1/2
Slab	1/2	1/2

CZSU vs SU5 Rating Load Data Comparison: Figure 7.18 shows two data points just above the 45-degree line on both the rating factor and rating load, resulting in a higher rating factor and rating load for SU5 compared to CZSU. CZSU has a GWT of 40.8 tons which is greater than the gross weight of SU5 (31 tons), and hence is the threshold to envelop SU5. It can also be summarized as CZSU vehicles envelop SU5 vehicles with a factor 1.

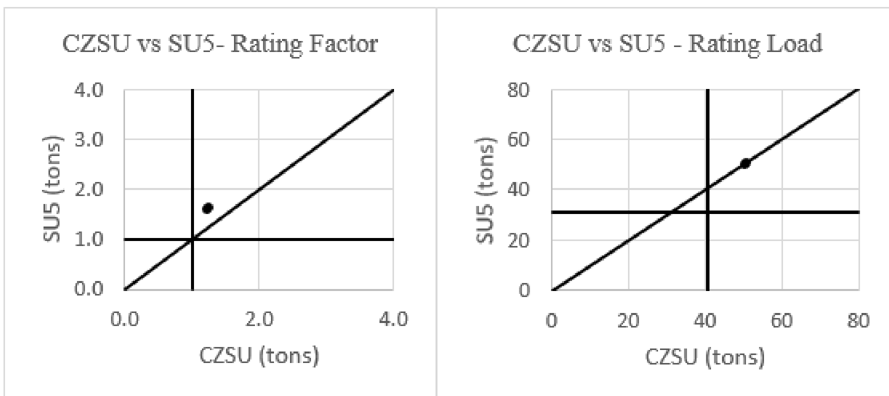


Figure 7.18: CZSU vs SU5 Rating Factor and Rating Load

Posting Requirement with Thresholds Applied: Figure 7.19 shows that neither of the two bridges in commercial areas needed posting after the application of 40.8 tons (GWT of CZSU) and 31 tons (GWT of SU5) as the thresholds on CZSU vehicles.

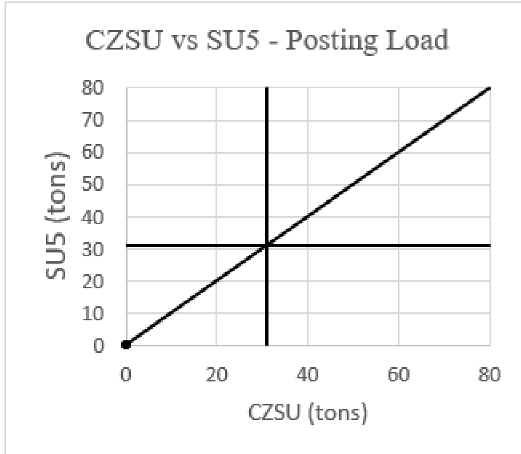


Figure 7.19: CZSU vs SU5 Posting Load

Girder Controlling the Rating: Table 7.24 shows 0, 1, and 1 bridges are controlled by internal girder, external girder, and slab, respectively, for both CZSU and SU5 vehicles.

Table 7.24: CZSU vs SU5 Girder Controlling Rating

	CZSU	SU5
Interior Girder	0/2	0/2
Exterior Girder	1/2	1/2
Slab	1/2	1/2

Since SU6 and SU7 are very heavy vehicles, comparing them with MoDOT single unit vehicle CZSU will have very high thresholds in order to encapsulate them and are therefore not compared with CZSU. Figure 7.20 shows the rating load comparison between MoDOT vehicles and SU6 and SU7.

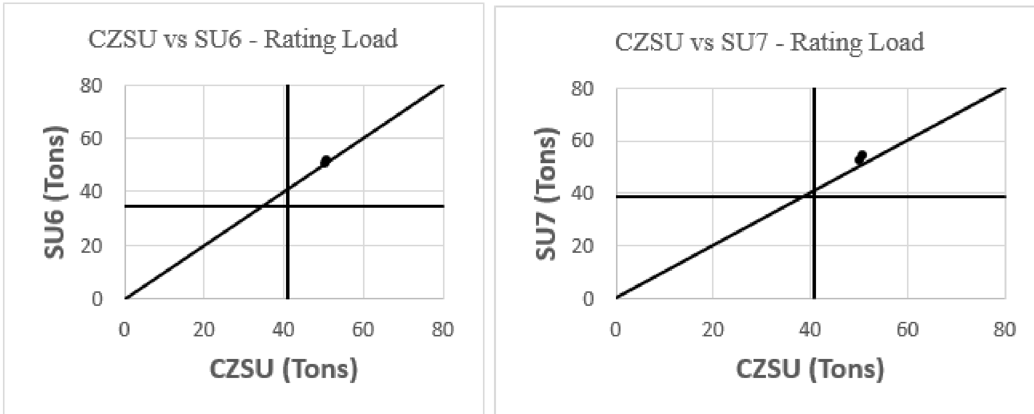


Figure 7.20: CZSU vs SU6 (left) Rating Load and CZSU vs SU7 (right) Rating Load

Summary of CZSU with SUVs: Figures 7.16 and 7.18 show that CZSU encapsulates SU4 with a threshold of 40.8 tons and a factor of 0.92, and it also encapsulates SU5 with a threshold of 40.8 tons and a factor of 1. A threshold of 40.8 tons with a factor of 0.92 is suggested for CZSU to encapsulate both SU4 and SU5, as shown in Table 7.25.

Table 7.25: Proposed Thresholds and Factors for CZSU vs SUVs

Vehicle	LRFR (Tons)	Factor
SU4	40.8 (GWT)	0.92
SU5	40.8 (GWT)	1
Both	40.8 (Proposed)	0.92

Summary and Recommendation: For each comparison, the ratios of rating load between MoDOT vehicles: H20L, and commercial zone vehicles CZSU and SHVs (SU4, SU5, SU6, SU7) were established. The rating load ratio of SUVs to the MoDOT vehicles is less than 1, meaning SHVs have more load effect than the MoDOT vehicles. Hence, the rating load of the MoDOT vehicles must be decreased by a multiplying factor when calculating postings to encapsulate the SHV ratings.

Because SU4 has a rating load ratio greater than 1, it has a load effect less than H20L across all the sample bridges (as seen in Figure 7.13 where all plots are above the 45-degree line). This would satisfy the condition one of the enveloping requirements. Therefore, to envelop SU4, the H20L vehicles must have posting thresholds equal to or greater than the SU4 maximum GWT of 27 tons. Similarly, SU5 has a load effect less than H20L, but greater in GWT (31 tons > 20 tons). Thus, H20L must have a threshold equal to or greater than 31 tons to envelop SU5. Lastly, SU6 and SU7 are considered heavy trucks and are not usually operated within non-commercial zones.

Overall, the final threshold for H20L vehicles to envelop SUVs would be 31 tons with a factor of 1, whereas, for CZSU to encapsulate the SUVs the threshold would be 40.8 tons with a factor of 0.92, as indicated in Table 7.26.

Table 7.26: Proposed Thresholds and Factors for H20L and CZSU to Envelop SUVs

Vehicle	LRFR (Tons)	Factor
H20L	31 Tons	1
CZSU	40.8 Tons (GVW)	0.92

Table 7.27: H20L and SHVs Rating Load Ratio, Mean, and Standard Deviation

Rating Load Ratio	Mean	Standard Deviation
SU4/H20L	0.92	0.02
SU5/H20L	0.86	0.03
SU6/H20L	0.84	0.05
SU7/H20L	0.79	0.06

Table 7.28: CZSU and SHVs Rating Load Ratio, Mean, and Standard Deviation

Rating Load Ratio	Mean	Standard Deviation
SU4/CZSU	0.94	0.02
SU5/CZSU	1.00	0.00
SU6/CZSU	0.98	0.01
SU7/CZSU	0.94	0.02

Tables 7.27 and 7.28 show that the rating load ratio of the MoDOT vehicles and SHVs is less than or equal to one. Hence, MoDOT vehicles H20L and CZSU envelop SHVs (SU4, SU5, SU6, and SU7).

7.4.3 MoDOT and AASHTO Legal Vehicles Comparison

This study explores measures for adapting AASHTO vehicle standards to Missouri's vehicles and envelop them. The vehicles from MoDOT under consideration for comparison are H20L, MO3S2, CZSU, and CZRT, while AASHTO vehicles used as benchmarks are Type 3 legal truck, Type 3S2 legal truck, and Type 3-3 legal truck.

H20L vs Type 3 Rating Load Data Comparison: Figure 7.21 shows the rating load plots of AASHTO Type 3 vehicles on the x-axis and the rating load plots of MoDOT H20L vehicles on the y-axis, with most of the plots falling above the 45-degree line. However, two points fall below the 45-degree line, so the factor of 0.993 was applied to bring all the points above the line. To get the factor, we calculated the ratio of AASTHO vehicles and MoDOT vehicles and used the least value obtained as the factor. Thus, H20L encapsulates Type-3 with a threshold of 25 tons and a factor of 0.993.

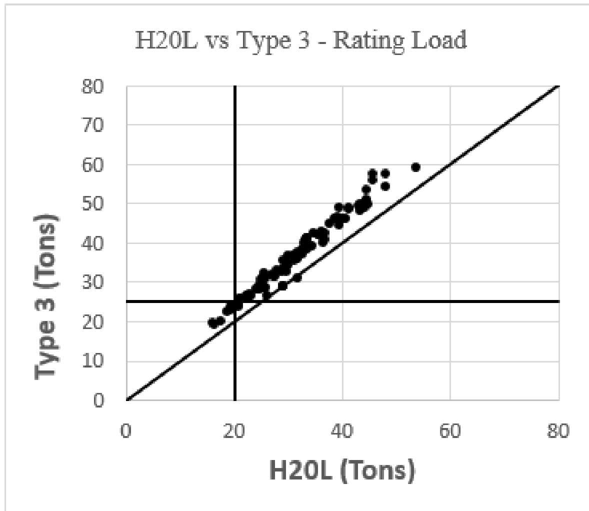


Figure 7.21: H20L vs Type 3 Rating load After Applying Factor

Posting Requirement with Thresholds Applied: Table 7.29 shows that AASHTO Type 3 and MoDOT H20L had seven bridges for H20L and nine bridges for Type 3 that needed posting after applying a threshold of 20 tons (GWT for H20L). When the GWT of Type 3 vehicles (25 tons) was used as the threshold for H20L vehicles, Table 7.29 showed 23 bridges for H20L vehicles and nine bridges for Type 3 vehicles that needed posting with the factor for H20L being 0.993.

Table 7.29: Number of Bridges for Posting H20L vs Type 3

	With Threshold as GVW-20T Applied on H20L	With Threshold as 25T Applied on H20L
H20L	7	23
Type 3	9	9
Both	7	9

Girder Controlling the Rating: Table 7.30 shows that 50, 14, and 35 bridges are controlled by an internal girder, external girder, and slab, respectively for H20L vehicles. Whereas 51, 14, and

34 bridges are controlled by internal girder, external girder, and slab, respectively, for Type 3 vehicles.

Table 7.30: H20L vs Type 3 Girder Controlling Rating

	H20L	Type 3
Int. Girder	50/99	51/99
Ext. Girder	14/99	14/99
Slab	35/99	34/99

Summary of H20L vs AASHTO Type 3: Figure 7.21shows that H20L encapsulates AASHTO Type 3 with a threshold of 25 tons and a factor of 0.993. Therefore, for H20L to encapsulate Type 3-3, a threshold of 25 tons and a factor of 0.993 (as seen in Table 7.31) is suggested.

Table 7.31: Proposed Threshold and Factor for CZSU vs SUVs

Vehicle	LRFR (Tons)	Factor
Type 3	25	0.993

MO3S2 vs Type 3S2 Rating Load Data Comparison: Figure 7.22 shows most plots falling below the 45-degree line when plotting rating loads for AASHTO Type 3S2 vehicles on the x-axis and those for MoDOT MO3S2 on the y-axis. Using the minimum value ratio of Type 3S2 and MO3S2 (0.944) as a factor shifted those points above the line.

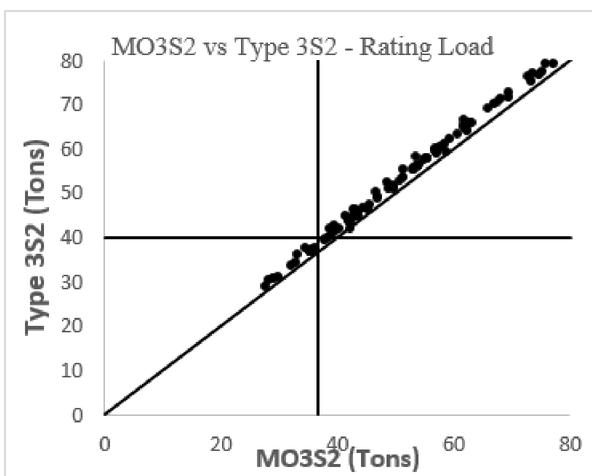


Figure 7.22: MO3S2 vs Type 3S2 Rating Load After Factor Applied

Posting Requirement with Thresholds Applied: Table 7.32 shows nine bridges for MO3S2 vehicles and seven bridges for Type 3S2 vehicles needed posting when the threshold applied was 36.64 tons (GWT of MO3S2). There were eight bridges for MO3S2 vehicles and seven bridges for Type 3S2 vehicles that needed posting with a factor of 0.944 for MO3S2. Therefore, MO3S2 envelops Type 3S2 with a threshold of 36.64 tons and a factor of 0.944.

Table 7.32: Number of Postings for MO3S2 vs Type 3S2 with Thresholds Applied

	With Threshold as GVW-36.64T Applied	With Threshold as 36T Applied
MO3S2	9	8
Type 3S2	7	7
Both	7	7

Girder Controlling the Rating: Table 7.33 shows the number of bridges controlled by internal girder, external girder, and slab, respectively, for MO3S2 and Type 3S2 vehicles.

Table 7.33: MO3S2 vs Type 3S2 Girder Controlling Rating

	MO3S2	Type 3S2
Interior Girder	51/99	51/99
Exterior Girder	13/99	14/99
Slab	35/99	34/99

M03S2 vs Type 3-3 Rating Load Data Comparison: When plotting rating loads for AASHTO Type 3-3 vehicles on the x-axis and MoDOT MO3S2 vehicles on the y-axis, Figure 7.23 shows all plots well above the 45-degree line, which signifies that MO3S2 vehicles have lower rating loads than Type 3-3. Therefore, MO3S2 envelops Type 3-3 with a threshold of 40 tons (GWT of AASHTO Type 3-3 vehicles) with a factor 1.

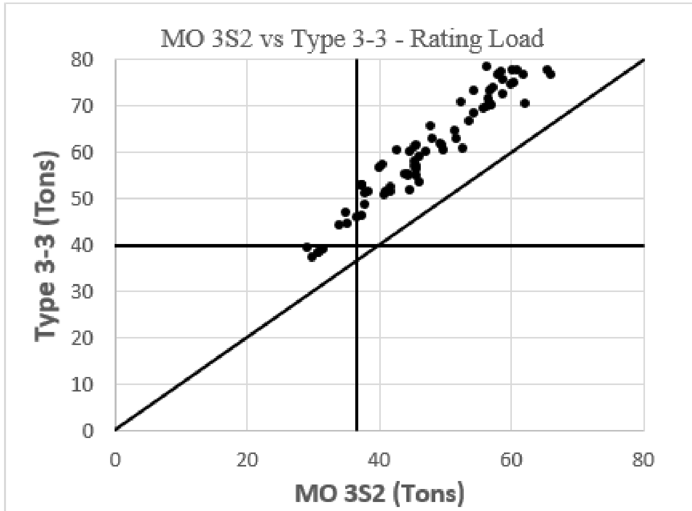


Figure 7.23: MO3S2 vs Type 3-3 Rating Loads

Posting Requirements with Thresholds Applied: Table 7.34 shows that nine bridges required posting for MO3S2 vehicles and five bridges required posting for Type 3-3 vehicles when applying a threshold of 36.64 tons (GWT of MO3S2). Whereas, when using a threshold of 40 tons (GWT of Type 3-3) there were 17 bridges that needed posting for MO3S2 and five for Type 3-3.

Table 7.34: Posting Numbers for MO3S2 vs Type 3-3 with Thresholds Applied on MO3S2

	With Threshold as GVW-36.64T Applied	With Threshold as 40T Applied
MO3S2	9	17
Type 3-3	5	5
Both	5	5

Girder Controlling the Rating: Table 7.35 shows that 51, 13, and 35 bridges were controlled by internal girder, external girder, and slab, respectively, for both vehicles.

Table 7.35: MO3S2 vs Type 3-3 Girder Controlling Rating

	MO3S2	Type 3-3
Interior Girder	51/99	51/99
Exterior Girder	13/99	13/99
Slab	35/99	35/99

Summary of MO3S2 with AASHTO vehicles: Figures 7.24 and 7.25 show that MO3S2 vehicles encapsulate AASHTO Type 3S2 vehicles with a threshold of 36.64 tons and a factor of 0.944 and that they encapsulate Type 3-3 with a threshold of 40 tons and a factor of 1. A threshold for MO3S2 to encapsulate AASHTO Type3S2 and Type 3-3 would be 40 tons with a factor of 1, as shown in Table 7.36.

Table 7.36: Proposed Thresholds and Factors for MO3S2 vs AASHTO

Vehicle	LRFR (Tons)	Factor
Type 3S2	36.64	0.944
Type 3-3	40 Tons (GVW)	1

CZSU vs Type 3 Rating Load Data Comparison: Only two reinforced concrete bridges in the sample fall in a commercial zone, so only two bridges were analyzed. Figure 7.24 shows two plots well above the 45-degree line, indicating that Type 3 vehicles have higher rating loads compared to CZSU. Thus, we can conclude that CZSU envelops Type 3 with a threshold of 40.8 tons (GWT of CZSU) with a factor of 1.

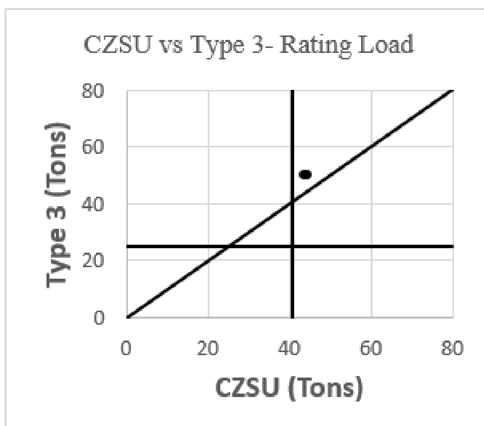


Figure 7.24: CZSU vs Type 3 Rating Load

Posting Requirement with Thresholds Applied: Figure 7.25 shows that neither of the two bridges needed posting with thresholds applied on CZSU. The thresholds used were 40.8 tons (GWT of CZSU vehicles) and 25 tons (GWT of Type 3 vehicles) on the CZSU vehicle.

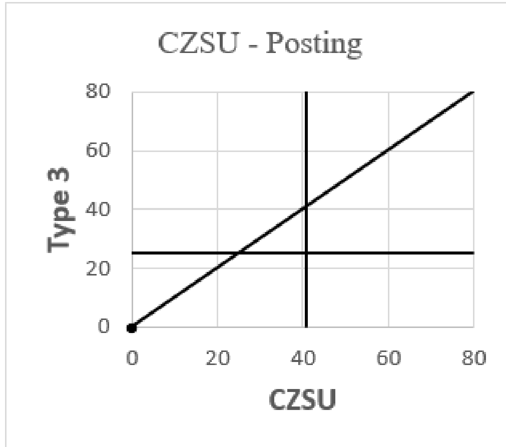


Figure 7.25: CZSU and Type 3 Posting Load

Girder Controlling the Rating: Table 7.37 shows that 0, 1, and 1 bridges are controlled by internal girder, external girder, and slab, respectively, for both CZSU and Type 3 vehicles.

Table 7.37: Type 3 vs CZSU Girder Controlling Rating

	CZSU	Type 3
Int. Girder	0/2	0/2
Ext. Girder	1/2	1/2
Slab	1/2	1/2

Summary of CZSU vs AASHTO Type 3: Figure 7.24 shows that CZSU encapsulates AASHTO Type 3 when using a threshold of 40.8 tons and a factor of 1. Thus, a threshold for CZSU to encapsulate Type 3-3 would be 40.8 tons with a factor of 1, as shown in Table 7.38.

Table 7.38: Proposed Thresholds and Factors for CZSU vs SUVs

Vehicle	LRFR (Tons)	Factor
Type 3	40.8 (GVW)	1

CZRT vs Type 3S2 Rating Load Data Comparison: Only two reinforced concrete bridges in the sample fall in a commercial zone, so only two bridges were analyzed. Figure 7.26 shows two plots above the 45-degree line, indicating that Type 3S2 vehicles have higher rating loads compared to CZRT vehicles. Hence, CZRT encapsulates Type 3S2 with a threshold of 51 tons (GWT of CZRT) with a factor of 1.

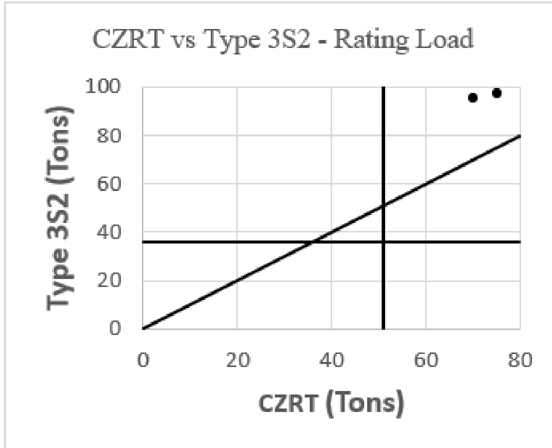


Figure 7.26: CZRT vs Type 3S2 Rating Load

Posting Requirement with Threshold Applied: Figure 7.27 shows that neither of the two bridges needed posting with the thresholds applied. Initially, the threshold applied was 51 tons (GWT of CZRT). Secondly, the threshold applied to CZRT was equal to GWT of Type 3S2 (36 tons).

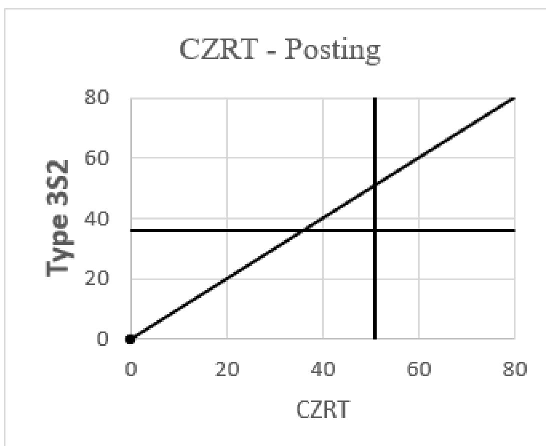


Figure 7.27: CZRT vs Type 3S2 Posting Load

Girder Controlling the Rating: Table 7.39 shows that 0, 1, and 1 bridges are controlled by interior girder, external girder, and slab, respectively, for both CZRT and Type 3S2 vehicles.

Table 7.39: CZRT vs Type 3S2 Girder Controlling Rating

	CZRT	Type 3S2
Int. Girder	0/2	0/2
Ext. Girder	1/2	1/2
Slab	1/2	1/2

CZRT vs Type 3-3 Rating Load Data Comparison: Only two reinforced concrete bridges in the sample fall in a commercial zone, so only two bridges were analyzed. Figure 7.28 shows two plots above the 45-degree line, meaning Type 3-3 vehicles have higher rating loads than CZRT vehicles. Therefore, CZRT encapsulates Type 3-3 with a threshold of 51 tons (GWT of CZRT) and a factor of 1.

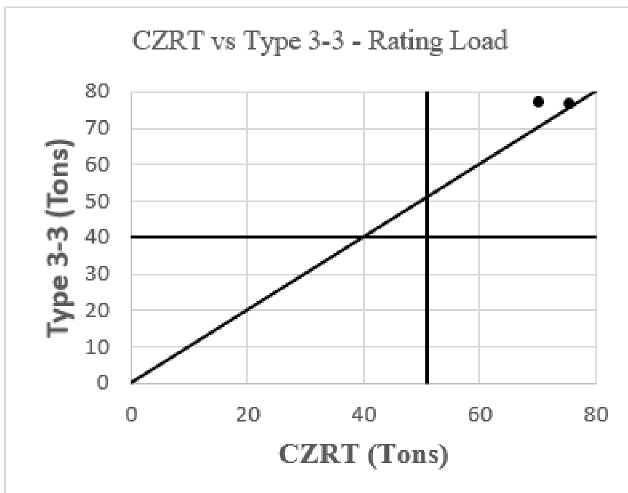


Figure 7.28: CZRT vs Type 3-3 Rating Load

Posting Requirement with Thresholds Applied: Figure 7.29 shows that neither of the two bridges needed posting when using thresholds of 51 tons (GWT of CZRT) or 40 tons (GWT of Type 3-3) for CZRT.

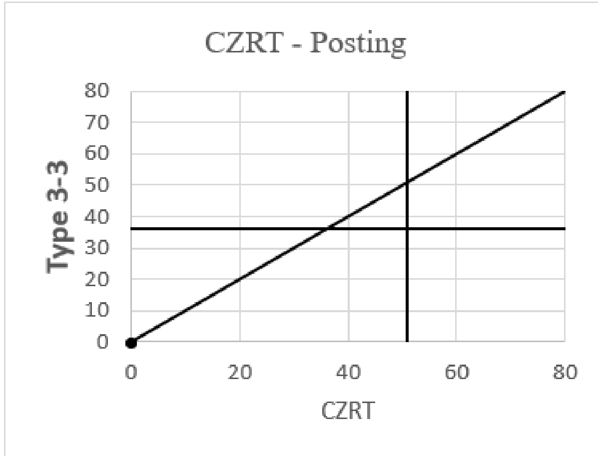


Figure 7.29: CZRT vs Type 3-3 Posting Load

Girder Controlling the Rating: Table 7.40 shows that 0, 1, and 1 bridges are controlled by internal girder, external girder, and slab, respectively, for both CZRT and Type 3S2 vehicles.

Table 7.40: CZRT vs Type 3-3 Girder Controlling Rating

	CZRT	Type 3-3
Interior Girder	0/2	0/2
Exterior Girder	1/2	1/2
Slab	1/2	1/2

Summary of CZRT with AASHTO Vehicles: Figures 7.26 and 7.28 show that CZRT encapsulates AASHTO Type 3S2 and Type 3-3 vehicles when using a threshold of 51 tons and a factor of 1. Therefore, a threshold for CZRT to encapsulate AASHTO Type 3S2 and Type 3-3 would be 51 tons with a factor of 1, as seen in Table 7.41.

Table 7.41: Proposed Thresholds and Factors for CZRT vs AASHTO Vehicles

Vehicle	LRFR (Tons)	Factor
Type 3S2	51 (GWT)	1
Type 3-3	51 (GWT)	1
Both	51 (GWT)	1

Summary for MoDOT vs AASHTO Vehicles: Table 7.42 indicates that MoDOT single unit vehicles H20 and MO3S2 will envelop AASTHO legal vehicles when H20L uses a threshold greater than GWT of the AASHTO Type 3 vehicle (25 tons) along with a factor of 0.993. The same holds true when MO3S2 uses a threshold greater than 36 tons (36.64 tons for Type 3S2 and 40 tons for Type 3-3) and a factor as 0.944.

Table 7.42: MoDOT Non-Commercial Vehicle vs AASHTO Legal Vehicles

AASHTO Legal Vehicle	H20L Threshold (Tons)	H20L Factor	MO3S2 Threshold (Tons)	MO3S2 Factor
Type 3	25	0.993	-	-
Type 3S2	-	-	36.64	0.944
Type 3-3	-	-	40	1

Table 7.43: MoDOT Commercial Vehicle vs AASHTO Legal Vehicle

AASHTO Legal Vehicle	CZSU Threshold (Tons)	CZSU Factor	CZRT Threshold (Tons)	CZRT Factor
Type 3	40.8	1	-	-
Type 3S2	-	-	51	1
Type 3-3	-	-	51	1

Table 7.43 indicates that MoDOT commercial zone vehicles CZSU and CZRT will envelop AASHTO legal vehicles when CZSU uses a threshold of 40.8 tons, which is greater than the GWT of the AASHTO Type 3 vehicle (25 tons) and when CZRT uses a threshold of 51 tons, which is greater than the GWT of Type 3S2 (36 tons) and the GWT of Type 3-3 (40 tons).

7.5. Recommendations

Table 7.22 shows that H20L vehicles need thresholds of 24 tons and 31 tons with a factor of 1 to encapsulate SUVs. Similarly, Table 7.31 shows that H20L envelops AASHTO Type 3 vehicles using a threshold of 25 tons and a factor of 0.993. In addition, the LRFR and LFR comparison shown in Table 7.6 determined that H20L uses a threshold of 31 tons with a 0.97 factor. Hence, an H20L threshold of 31 tons with a 0.97 factor is suggested to encapsulate vehicles operated within the state of Missouri.

Similarly, using figures from Table 7.36, the threshold (40 tons) and factor (1.0) were calculated for MO3S2 vehicles to encapsulate AASHTO vehicles. This corresponded with the threshold obtained from the LRFR and LFR comparison in Table 7.9. Thus, a threshold of 40 tons with a factor of 0.93 is suggested for MO3S2 vehicles.

For MoDOT CZSU trucks, the threshold was determined to be 40.8 tons and the factor to be 0.92 to envelop SUVs as shown in Table 7.25. Likewise, from Table 7.38, a threshold of 40.8 tons and a factor of 1 was obtained to encapsulate AASHTO vehicles, which is similar to the values obtained from the LRFR vs LFR comparison from Table 7.11. Thus, a threshold of 40.8 tons with a factor of 0.92 is suggested for CZSU vehicles.

Likewise, for MoDOT CZRT vehicles, Table 7.41shows that a threshold of 51 tons and a factor of 1.0 is needed to encapsulate AASHTO vehicles, which is identical to the figures obtained from the LRFR and LFR comparison shown on Table 7.13. Hence, a threshold of 51 tons with a factor of 1.0 is suggested for CZRT vehicles.

Table 7.44 summarizes all the suggested thresholds and factors needed to allow MoDOT vehicles to encapsulate all vehicles operated within the state.

Table 7.44: Proposed Threshold for the MoDOT Vehicles

Vehicle	Proposed Threshold (Tons)	Purposed Factor
H20L	31	0.97
MO3S2	40	0.93
CZSU	40.8	0.92
CZRT	51	1

Chapter 8: Culvert – Research Study

MoDOT provided models of 35 reinforced concrete culverts from the state to be analyzed with AASHTOWare v7.1 software for a load rating study. The culverts were categorized by the year built (Table 8.1), the number of cells in the culvert (Table 8.2) and the culvert span (Table 8.3).

Culvert Models by Year Built: Table 8.1 shows a summary of the culverts by the year they were built. Almost half were built between 1950 and 1970. In addition, it was noted that all of the culverts except three used ASD with either H10, H15 or H20 loading. The culverts using LFD were built in 1986, 1989 and 2006.

Table 8.1: Number of Concrete Culverts By Year Built

Year Built	Concrete
1920-1929	1
1930-1939	7
1940-1949	1
1950-1959	10
1960-1969	9
1970-1979	3
1980-1989	3
1990-1999	0
2000-2009	1
2010-2019	0
TOTAL	35

Culvert Models by Number of Boxes (Cells): The culverts used in this study had from one to three cells, and Table 8.2 summarizes how many structures there were from each type. About 70 percent of the culverts were double box (two-cell) culverts.

Table 8.2: Box Styles for Culverts (Cells)

Box type	No. of Culverts
Single Box (Cell)	1
Double Box (Cell)	27
Triple Box (Cell)	7
TOTAL	35

Sample of Culverts by the Total Length of the Structure: The culverts used in this study had varying lengths. Table 8.3 divides the culverts by span range.

Table 8.3: Concrete Culvert Lengths

Length (Ft)	No. of Culverts
20-30	22
31-40	8
51-80	5
TOTAL	35

Apart from above divisions, we also divided when dividing the culverts by location, it was noted that 33 out of 35 were from non-commercial zones.

8.1 Objectives

The primary objectives of the concrete culvert study are as follows:

- Comparison of the rating factor and rating loads between LFR and LRFR.
- Provide recommendations to MoDOT.

8.2. Methodology

Section 15.10.5.3 of the BIRM describes the rating process of culverts using LFR. The culverts have all been built using either ASD or LFD and ratings are described as conservative. BIRM further states that live load ratings in single cell culverts can be ignored, per AASHTO's MBE, when the fill depth exceeds eight feet and, for multicell culverts, exceeds the dimension between the stream face of the exterior walls. MoDOT has modifications based on AASHTO methods for LFD (using single and multi-lane analysis) to the live load distribution factors for load rating analysis under fill. The modifications are used for load posting and permitting decisions.

Live Load Distribution Factors (LLDF): MoDOT's advice is to rate the top slab of the culverts and apply single lane distribution factors. BrR version 7.1 was used for the analysis of rating factors, rating loads, and posting using both LFR and LRFR. For LFR, the distribution factors calculated by BrR 7.1 were obtained, while for LRFR, the distribution factors were calculated manually using AASHTO LRFD equation 4.6.2.10.3 for depth of fill less than two feet, and equations 3.6.1.2.6b-1,2,3 for depth of span greater than two feet. A sample calculation is shown below. The difference between the live load distribution factors calculated manually and those calculated automatically by BrR 7.1 is not significant, as seen in Table 8.4.

Table 8.4: LLDF Using Manual Method (column 5) and BrR 7.1 (columns 9 and 10)

Bridge ID	Bridge	Clear Span	Fill Depth	LRFR/ LLDF	Slab Width	Skew	Vitris LLDF	1-Lane	Multi-lane
355	P0738	11	1.83	0.107	35	15	0.2146	0.114	0.104
356	X0897	12	1.01	0.106	25.33	0	0.2119	0.121	0.109
357	N0157	12	1.27	0.106	12.33	65	0.2119	0.083	0.063
358	A1881	15	2.78	0.087	31.917	0	0.2041	0.101	0.103
359	R0080	12	3.29	0.082	25.667	0	0.1737	0.119	0.109
360	N0065	12	2.3	0.099	25.5	0	0.2119	0.12	0.109
361	A1436	10	2.29	0.102	21.667	45	0.2174	0.111	0.093
362	G0764	13	3.59	0.080	21.883	0	0.0825	0.111	0.087
363	X0103	9	3.59	0.081	19.25	30	0.1628	0.1	0.083
364	J0164	8	1.17	0.112	17.667	45	0.2232	0.132	0.094
365	A1492	13	3.11	0.083	41.875	27.25	0.1432	0.098	0.093
366	P0679	12	1.19	0.106	25.167	0	0.2119	0.1	0.083
367	S0626	10	0.83	0.109	21.167	0	0.2174	0.141	0.114
368	A3355	13	2.97	0.085	44.72	21	0.1924	0.099	0.094
369	T0676	10	0.83	0.109	21.67	20	0.2174	0.136	0.109
370	A2245	10	1.6	0.109	21.75	27	0.2174	0.116	0.105
371	P0879	12	1.39	0.106	25.167	35	0.2119	0.106	0.096
372	A4600	12	2.25	0.101	25.542	45	0.2119	0.096	0.087
373	A2160	11	3.23	0.083	23.5	30	0.1769	0.117	0.107
374	P0800	12	0.58	0.106	37.75	20	0.2119	0.107	0.1
375	S0936	12	1.89	0.106	25.333	20	0.227	0.105	0.105
376	P0059	8	1.27	0.112	17.83	40	0.152	0.143	0.099
377	G0766	10	2.21	0.104	32.083	40	0.2174	0.101	0.091
378	R0449	15	1.37	0.102	31.417	45	0.2041	0.081	0.083
379	A6403	13	1.94	0.105	27.667	20	0.2092	0.107	0.103
380	A2637	11	4	0.077	23.667	58.5	0.1538	0.116	0.101
381	A2473	10	1.5	0.109	21.667	58.5	0.2174	0.089	0.073
382	A4212	13	3.5	0.080	27.5	30	0.1649	0.101	0.097
383	A4615	11	1	0.107	23.75	10	0.2146	0.128	0.111
384	A2765	12	2	0.107	26	0	0.2119	0.119	0.109
385	A2469	10	1.99	0.109	21.25	30	0.2174	0.128	0.103
386	J0632	12	2.58	0.093	39	0	0.2119	0.11	0.103
387	P0407	10	2.19	0.104	21.33	0	0.2174	0.14	0.114
388	N0147	11	1.49	0.107	23.3	10	0.2146	0.13	0.11
389	T0466	8	2.12	0.109	25.5	45	0.2232	0.115	0.091

Culvert Live Load Distribution Factor Calculation

(Culvert with traffic parallels to the span - Culvert A1881)

Parameter:

- Depth of fill:

$H := 2.78\ ft$

- Inside diameter or clear span of the culvert

$D_i := 15\ ft$

- Clear Span

$S := D_i = 15\ ft$

- Factor for distribution of live load with depth of fill (AASHTO LRFD 8th 3.6.1.2.6)

$LLDF := 1.15$

- Wheel Spacing:

$s_w := 6\ ft$

- Tire patch width:

$w_t := 20\ in$

Case 1: Depth of fill < 2 ft

Equivalent distribution length perpendicular to span (in)

$E_{span} := 96\ in + 1.44\ \frac{S}{12} = 9.8\ ft$ (ASSHTO LRFD 4.6.2.10.3)

Case 2: Depth of fill >= 2 ft

The wheel/axle load interaction depth $H_{int\text{-}t}$: (Live load distribution transverse to culvert spans)

$H_{int\_t} := \frac{s_w - w_t - 0.06\ D_i}{LLDF} = 2.986\ ft$ (AASHTO LRFD 3.6.1.2.6b-1)

$w_{w1} := w_t + LLDF \cdot H + 0.06\ D_i = 5.764\ ft$ (AASHTO LRFD 3.6.1.2.6b-2)

$w_{w2} := w_t + s_w + LLDF \cdot H + 0.06\ D_i = 11.764\ ft$ (AASHTO LRFD 3.6.1.2.6b-3)

$$w_w := \begin{cases} 2 \cdot w_{w1} & \text{if } H \le H_{int\_t} \\ w_{w2} & \text{else} \end{cases} = 11.527\ ft$$

Culvert Live Load Distribution Factor for 12 in strip (Parallel to the span)

$$DF := \begin{cases} \frac{1 \cdot ft}{E_{span}} & \text{if } H < 2\ ft \\ \frac{1 \cdot ft}{w_w} & \text{else} \end{cases} = 0.087$$

Figure 8.1: Sample of Manual LLDF Calculations for Culverts Using the LRFR Methodology

The rating factor and rating loads for both LFR and LRFR analyses using BrR 7.1 for all the culverts were exported to the developed Excel file.

8.3 Results and Summary

8.3.1 Comparison of the Rating Factor and Rating Loads Between LFR vs LRFR

The culverts were analyzed using LFR and LRFR and the results were compared in the following graphs with LFR factors plotted on the x-axis and the corresponding LRFR factors along the y-axis. If the plots fell above 45-degree line, rating factors when using LRFR were larger than when using LFR and vice-versa. Based on the recommendation of MCE (AASHTO, 2017), the maximum GWT of the vehicles was used as a threshold to determine the posting requirement when using LRFR. The comparisons were done at operating level for both LFR and LRFR. Equations on the graphs were used during the analysis to represent the relationship of LRFR and LFR.

8.3.1.1 H20 Legal Truck Rating Data Comparison

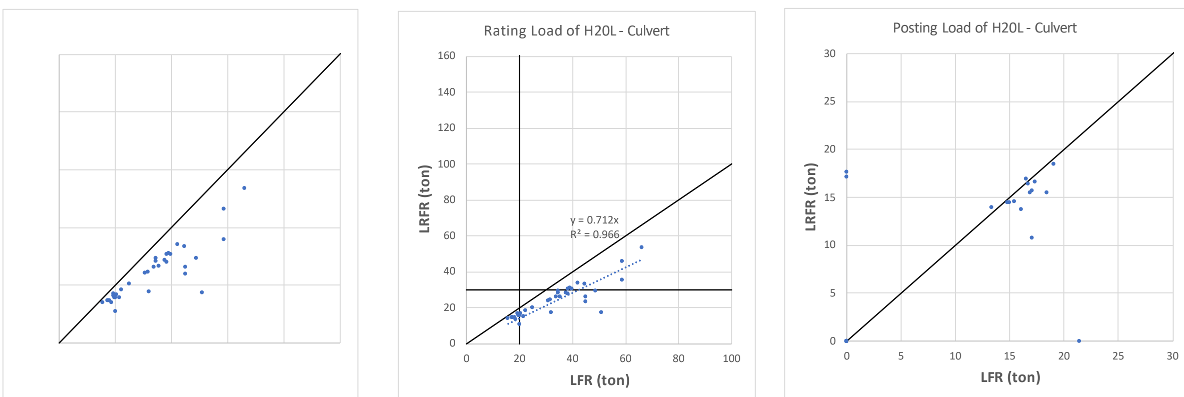


Figure 8.2: Rating Factor, Rating Load, and Posting Load Plots for H20L

Figure 8.2 compares the plots between LFR and LRFR for rating factor, rating load, and posting load for H20L vehicles.

8.3.1.2 MO3S2 Legal Truck Rating Data Comparison

Figure 8.3 compares LFR and LRFR for rating factor, rating load, and posting load for MO3S2. The plots are mostly below the 45-degree line in the LRFR region, implying that culverts have higher rating factors in LFR than in LRFR. In the rating load graph, there are quite a few points below the horizontal line and to the left of the vertical line. Hence, these points/culverts could require postings.

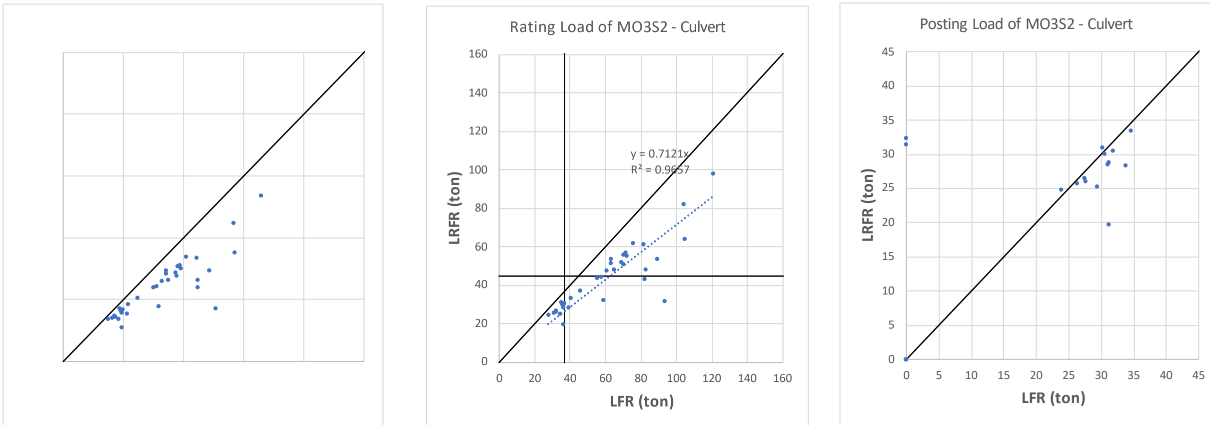


Figure 8.3: Rating Factor, Rating Load, and Posting Load Plots for MO3S2

8.3.1.3 CZSU Legal Truck Rating Data Comparison

Since only two culverts are located in commercial zones, only two culverts were analyzed. Figure 8.4 shows the comparative plot between LFR and LRFR for rating factor, rating load, and posting load for CZSU. The plots are all below the 45-degree line in the LFR region, which means most culverts have higher rating factors in LFR than in LRFR. Neither of the culverts required posting.

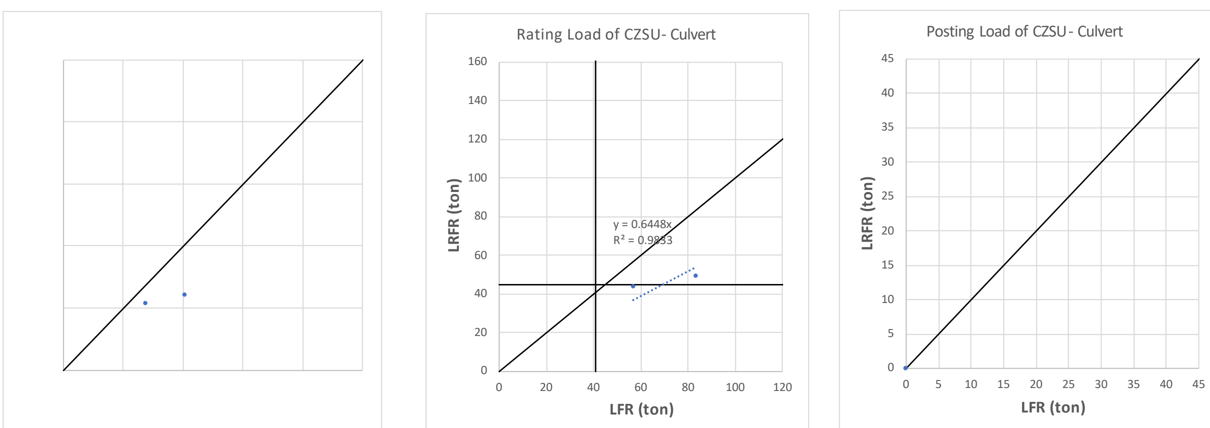


Figure 8.4: Rating Factor, Rating Load, and Posting Load Plots for CZSU

8.3.1.4 CZRT Legal Truck Rating Data Comparison

Figure 8.5 compares LFR and LRFR for rating factor, rating load, and posting load for CZRT. The plots are all below the 45-degree line, meaning these culverts have higher rating factors in LFR than in LRFR and do not require posting.

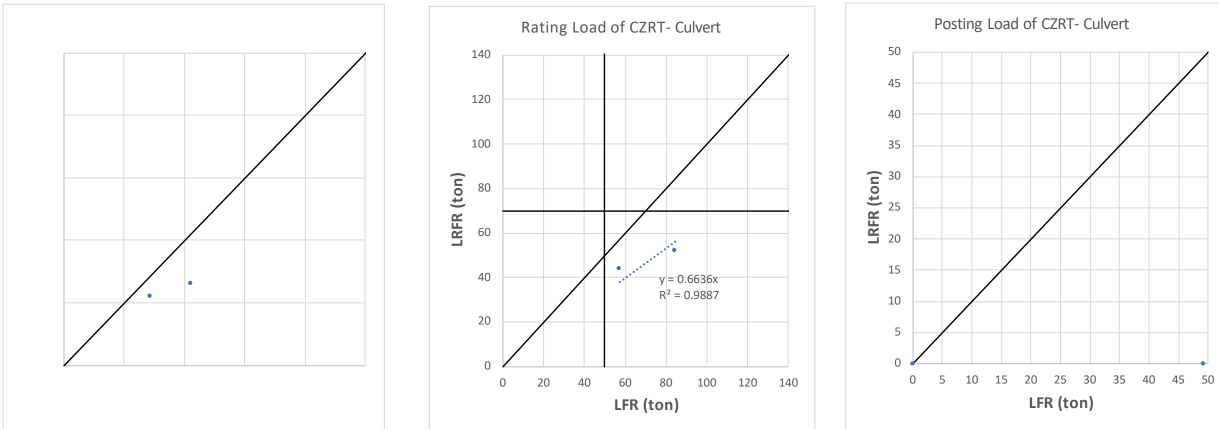


Figure 8.5: Rating Factor, Rating Load, and Posting Load Plots for CZR

8.3.1.5 SU5 Legal Truck Rating Data Comparison

Figure 8.6 examines rating factor and shows plots that are below the 45-degree line in the LFR region, indicating most structures have higher rating factors in LFR than in LRFR. Similarly, in the rating load graph, we can see a significant number of plots placed below the horizontal line and to the left of the vertical line, indicating culverts that might require postings.

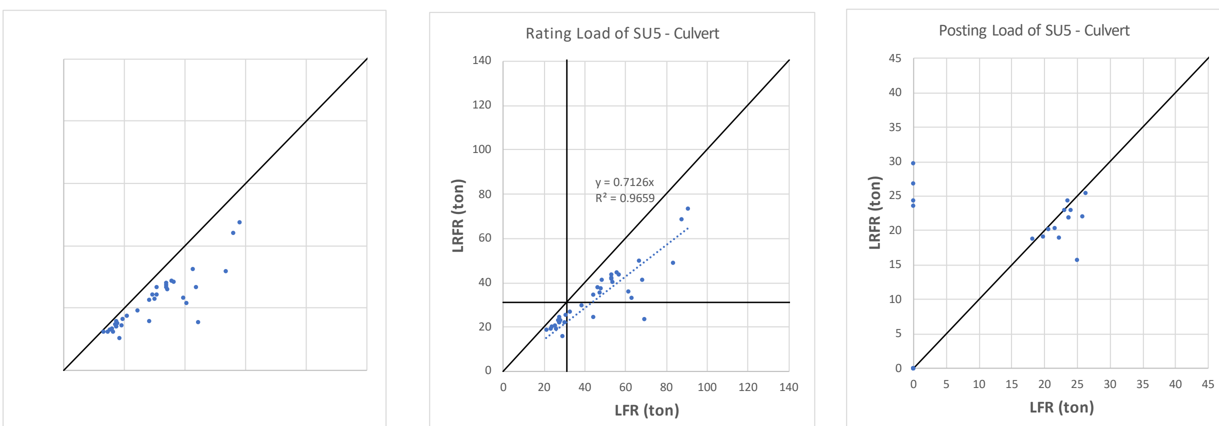


Figure 8.6: Rating Factor, Rating Load, and Posting Load Plots for H20L

8.4 Observations and Summary

The following overall observations were made from the culvert study.

1. The culverts were rated using the top slab with single lane distribution factors.
2. All the culverts have a fill less than six feet deep and manually calculated distribution factors were used for LRFR.
3. While some culverts required load posting when using LFR, none of them are currently restricted based on the document from MoDOT.
4. Comparing LFR and LRFR for H20L and M03S2 vehicles shows that LFR produces higher rating factors and rating loads than LRFR.

5. Comparisons of rating and load factors for CZSU and CZRT within commercial zones contain only two data points, which may not be sufficient to form conclusions. Despite this, results were similar to those produced with H20L and MO3S2 vehicles.
6. LRFR load rating results were more conservative than LFR. Rating loads when using LRFR are about 65%-70% compared to the rating loads obtained when using LFR. Rating loads when using LRFR might be smaller than when using LFR because the live load distribution factor could be more conservative when using LRFD.

Chapter 9: Conclusion

This comparative study evaluated several MoDOT bridge types, including culverts, at legal load level using LRFR. Traditionally, MoDOT has performed bridge load ratings with LFR. Now, with heavier vehicles traveling Missouri's highways, MoDOT is migrating to LRFR. With an eye toward aiding that move, this study set out to develop and recommend load posting policies using the LRFR method consistent with the current LFR policy. To accomplish this goal, MoDOT provided information on reinforced concrete, prestressed concrete and steel bridges, as well as concrete culverts from throughout the state. The structures were located in different commercial zones, had varying ages and construction features, and used different design methods. With such a varied database, MoDOT recognized the value in expanding the scope of this study to include the following objectives.

1. Review MoDOT's current load rating vehicle models and load posting thresholds and make recommendations on how these should be incorporated into LRFR.
2. Determine if the standard live load factors used for LRFR are still applicable to MoDOT's vehicle models and provide recommendations for any needed changes.
3. Provide recommendations for the use of the various system and condition factors in LRFR, including how they might influence a good inspection program.
4. Provide recommendations for the use of LRFR for super load and routine overweight permit loads.
5. Review MoDOT's current AASHTOWare load rating models for a variety of bridges and provide recommendations for the adjustments that will be needed to allow for LRFR.
6. Review MoDOT's current practice for determining single lane live load distribution factors on slab bridges and provide recommendations on a similar approach using LRFR.
7. Review how MoDOT currently uses LFR for culverts, and, if needed, make recommendations for changes for using LRFR.
8. Provide recommendations on how MoDOT's current use of a combination of single lane and multi-lane rating results along with truck traffic volume for determining load posting needs can be incorporated into LRFR.
9. Determine whether the current live load factors MoDOT uses for SHVs would be appropriate for use on CZV models.
10. Determine whether to include serviceability limit states on prestressed concrete bridge load ratings, which are currently optional for legal load ratings and for permit load ratings.
11. Investigate MBE requirements for load rating of structures with spans longer than 200 feet and provide ways to allow for reasonable load rating of these structures without a refined analysis.

12. Provide recommendations for the use of LRFR Service II load factors for steel bridges, which tend to result in significantly lower posting values compared to serviceability checks using LFR.

Several differences became apparent when studying LFR and LRFR to determine how MoDOT can best use the rating methods on bridges throughout the state. Among them, it was noted that (a) bridges analyzed with LFR govern in interior girders, while when using LRFR most bridges will govern in the exterior girders. (b) LRFR produces lower scores than LFR. (c) Using LRFR increased the number of posted bridges compared to using LFR. This suggests possible changes to the LRFR posting thresholds to better mesh with current MoDOT practices. Further conclusions for all the main structure types studied are summarized below.

Steel Bridges: Use of the current thresholds for CZSU and CZRT vehicles seems conservative and is likely to lead to more bridges being posted. The thresholds used with the bridge samples for CZSU (45 tons) and for CZRT (70 tons) within the commercial zones need to be adjusted to GWTs of 40.8 tons and 51 tons, respectively. The changes allow CZSU to envelop SU4, SU5, SU6, and SU7 vehicles, while also allowing CZRT to envelop Type 3-3 and Type 3S2.

The current live load model for LFR has a posting threshold of 30 tons for H20L vehicles that needs to be revised to 31 tons in LRFR. The posting load factors also need to be adjusted to work with LRFR. A factor of 0.94 can be used for H20L, 0.96 for MO3S2, 0.97 for CZRT and 0.91 for CZSU. The minimum factor of 0.91 can be used conservatively for posting purposes for all the bridges in the same way as the 0.86 factor is currently used in LFR by MoDOT.

Changing the Service II limit state factor from 1.3 to 1.0 showed a significant reduction in the number of bridges that required posting. This shift also improved most rating loads and rating factors by up to 30% of their initial values.

For bridges with spans longer than 200 feet, most MoDOT vehicles still envelop AASHTO vehicles, but some will require a factor. Within the sample of bridges used, H20L, H20L*0.75+ lane and H20L truck train envelops Type 3, Type 3*0.75+lane and Type 3 truck train, respectively when using LFR and LRFR. MO3S2, MO3S2*0.75+ lane and MO3S2 truck train require a scaling factor of 0.98 to envelop Type 3S2, Type 3*0.75+ lane and Type 3S2 truck train. CZRT and CZRT truck train can envelop Type 3-3 and Type 3-3 truck train, respectively without a scaling factor in both LFR and LRFR. CZRT*0.75+ lane requires a scaling factor of 0.93 to envelop Type 3-3*0.75+ lane in both rating methods.

Comparing rating results for bridges with spans longer than 200 feet showed that Type 3-3 vehicles have the highest rating loads, while H20 truck train has the lowest rating loads when using both LFR and LRFR. LFR has higher rating factors and rating loads than the LRFR. Generally, truck trains have the lowest rating loads and therefore govern by being the most conservative when using both LRFR and LFR.

The ratings for multilane loaded bridges are more conservative than for single lane loaded bridges when using both LRFR and LFR.

Prestressed Concrete Bridges: No significant difference in rating load or number of bridges requiring posting were identified when comparing the use of LRFR and LFR for prestressed concrete bridges. Prestressed girders are usually used in short span bridges. Unlike reinforced concrete slab bridges and steel bridges, most prestressed bridges are recent additions to MoDOT's inventory and have higher rating factors for all the vehicle types (about 3.5 for H20L, 2.5 for MO3S2 and SU5, and 2.04 for CZSU and CZRT).

MoDOT currently uses LFR with a posting factor of 0.86 to determine load postings for all vehicles across a wide variety of bridge types. For prestressed bridges and the seven vehicles to be enveloped, recommendations for H20L, MO3S2 and CZRT include thresholds ranging from 25-40 tons and factors ranging from 0.87 to 1.0 when using LRFR.

Six out of the 100 prestressed concrete bridges in the study's sample have load ratings controlled by Service III limit state and use the LRFR methodology. Serviceability rating loads are about 64% to 67% compared to strength limit state. However, all these bridges have remained in good condition during their service times of more than 10 years. It is recommended that the service limit state be excluded from LRFR rating load at legal load level.

Reinforced Concrete Bridges: For reinforced concrete bridges, an H20L threshold of 31 tons with a factor of 0.97 is suggested to encapsulate vehicles operated within the state. Other recommendations include a threshold of 40 tons with a factor of 0.93 for MO3S2 and a threshold of 40.8 tons with a factor of 0.92 for MoDOT commercial single unit truck CZSU along with a threshold of 51 tons with a factor of 1 for MoDOT commercial vehicle CZRT.

Culverts: This study analyzed 35 concrete culverts using BrR v7.1. Like bridges, the culverts had different ages, spans, designs, and construction features. They all used less than six feet of fill, but the material used differed. Nearly half of the culverts were built between 1950 and 1970. In addition, from the data provided, it was also noted that all but three of the culverts used ASD and were designed for H10, H15 or H20 loading. The three culverts that used LFD were built in 1986, 1989 and 2006.

Some of the culverts required load posting under LFR, while none of them are currently restricted based on the documents from MoDOT. LFR shows higher rating factors and rating loads compared to LRFR for H20L and M03S2. There were just two culverts located in commercial zones subject to CZSU and CZRT, making it difficult to form conclusions. However, results were similar to those produced with H20L and MO3S2 vehicles. The rating loads when using LRFR are about 65%-70% compared to rating loads obtained when using LFR. Rating loads when using LRFR might be smaller than when using LFR because the live load distribution factor could be more conservative when using LRFD.

References

1. Bridges, T.O.S.o., *Manual for Condition Evaluation of Bridges, 1994*. 2000: American Association of State Highway & Transportation Officials (AASHTO).
2. Bridges, T.O.S.o., *The manual for bridge evaluation*. 2018: AASHTO.
3. Bridges, S.o., *The Manual for Bridge Evaluation*. 2008: AASHTO.
4. LRFD, A., *Bridge design specifications*. 2007, American Association of State Highway and Transportation Officials.
5. Sivakumar, B. *Load rating and permit review using load and resistance factor philosophy*. in *1999 New Orleans Structures Congress*. 1999.
6. Sivakumar, B., *Load and resistance factor rating for more uniform safety in bridge load ratings and postings.* Transportation Research Record: Journal of the Transportation Research Board, 2005 (CD 11-S).
7. FHWA, F.H.A., *Bridge Inspector's Reference Manual:* 2005, United States. Federal Highway Administration.
8. Ghosn, M., B. Sivakumar, and F. Miao, *Development of State-Specific Load and Resistance Factor Rating Method.* Journal of Bridge Engineering, 2013. 18(5): p. 351-361.
9. Moses, F., *Calibration of load factors for LRFR bridge evaluation*. 2001.
10. Ghosn, M. and F. Moses, *Redundancy in highway bridge superstructures*. Vol. 406. 1998: Transportation Research Board.
11. Murdock, M., *Comparative load rating study under LRFR and LFR methodologies for Alabama highway bridges*. 2009.
12. Moses, F. and D. Verma, *NCHRP Report 301: Load Capacity Evaluation of Existing Bridges.* Transportation Research Board, Washington, DC, 1987.
13. Hearn, G., *State bridge load posting processes and practices*. 2014: Transportation Research Board Washington, DC.