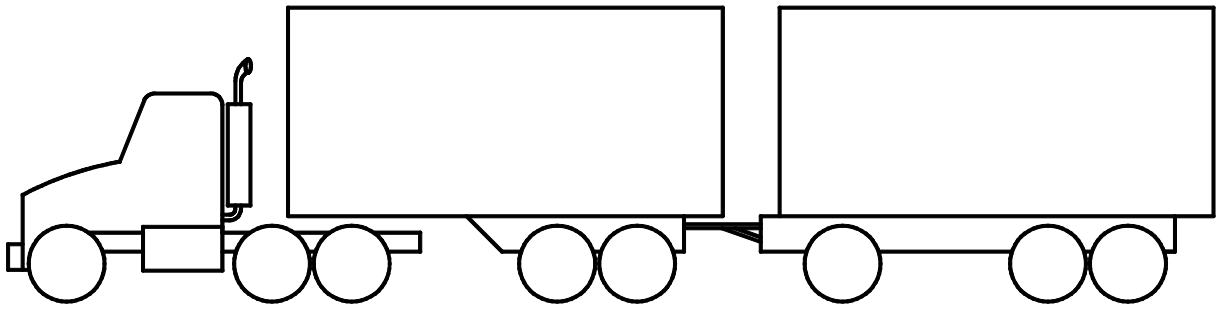
BRIDGE ANALYSIS GUIDE

2005 Edition

with

2009 Interim Update

Part 1



MDOT
Michigan Department of Transportation

MICHIGAN DEPARTMENT OF TRANSPORTATION
CONSTRUCTION AND TECHNOLOGY SUPPORT AREA

Engineering Manual Preamble

This manual provides guidance to administrative, engineering, and technical staff. Engineering practice requires that professionals use a combination of technical skills and judgment in decision making. Engineering judgment is necessary to allow decisions to account for unique site-specific conditions and considerations to provide high quality products, within budget, and to protect the public health, safety, and welfare. This manual provides the general operational guidelines; however, it is understood that adaptation, adjustments, and deviations are sometimes necessary. Innovation is a key foundational element to advance the state of engineering practice and develop more effective and efficient engineering solutions and materials. As such, it is essential that our engineering manuals provide a vehicle to promote, pilot, or implement technologies or practices that provide efficiencies and quality products, while maintaining the safety, health, and welfare of the public. It is expected when making significant or impactful deviations from the technical information from these guidance materials, that reasonable consultations with experts, technical committees, and/or policy setting bodies occur prior to actions within the timeframes allowed. It is also expected that these consultations will eliminate any potential conflicts of interest, perceived or otherwise. MDOT Leadership is committed to a culture of innovation to optimize engineering solutions.

The National Society of Professional Engineers Code of Ethics for Engineering is founded on six fundamental canons. Those canons are provided below.

Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform Services only in areas of their competence.
3. Issue public statement only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, reasonably, ethically and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

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Chapter 1

INTRODUCTION

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MICHIGAN DEPARTMENT OF TRANSPORTATION
BRIDGE ANALYSIS GUIDE

INTRODUCTION

Purpose of the Bridge Analysis Guide

The Michigan Bridge Analysis Guide (the Guide) has been prepared to assist engineers with and to promote uniformity in analyzing highway bridges for load-carrying capacity. The process of preparing a bridge load capacity analysis has many discrete steps, including gathering physical data for the specific bridge, selecting the appropriate truck type(s), choosing the correct live load distribution factor and performing the actual analysis. This guide is structured to inform and lead the user through all the required process steps, provide completed examples and list references for further information.

The requirements for load rating of highway bridges can be found in the American Association of State Highway and Transportation Officials (AASHTO) publication, Manual for Condition Evaluation of Bridges, Second Edition, 1994 with Interim Revisions through 2000. This Guide has been prepared using that manual as a primary source of information. The Load Factor (LF) method has been used throughout this Guide.

Purpose of Load Rating

Bridge load capacity analysis is required by federal regulation, the purpose of which is to assure the structure owner, and indirectly the highway user, that each bridge is safe for use by the motoring public. Through load capacity analysis, a bridge may be discovered to be incapable of safely carrying some legal loads. In that circumstance, it may be necessary to publicly “post” the bridge for the reduced safe load, or in the extreme case, to close the bridge. In addition, for those occasions when loads beyond the range of standard legal vehicles (or “permit” loads) need to use a specific structure, load capacity analysis can provide answers about which loads are safely acceptable.

Qualifications and Responsibilities

The individual with overall responsibilities for load rating bridges should be a licensed professional engineer and preferably shall have a minimum of 5 years of bridge design and inspection experience. The engineering skills and knowledge necessary to properly evaluate bridges may vary widely depending on the complexity of the bridge involved. The specialized skills and knowledge of other engineers may be needed to ensure proper evaluation.

Basic Definitions (see Chapter 12 for more definitions)

Inventory Rating. The Inventory Rating represents the normal live load capacity of a bridge using the current load distribution factors, calculated with the current Load Factor Methods, but reflects the existing member and material deterioration. The AASHTO HS loading configuration is the applied live load. The load rating is expressed in terms of HS-type loadings. This load rating is intended to represent the load that can be safely carried by the bridge on a frequently repeated and continuing basis.

Federal Operating Rating. The Operating Rating represents the maximum live load capacity of a bridge calculated as noted above for the Inventory Rating, but with a reduced load factor for Live Load. The AASHTO HS loading configuration is used as the applied load, however the load is reported to MDOT in terms of MS-type loading. (The metric equivalent of HS loading) This load rating is intended to represent loads that can be safely carried by the bridge on an infrequent basis. Allowing unlimited numbers of vehicles to use a bridge at the Operating Level may shorten the life of the bridge.

Michigan Operating Rating. Michigan law allows legal loads that are in excess of the gross weights for standard H and HS-type loads. For the Michigan Operating Rating, bridges are to be analyzed with operating load factors for the ability to carry all Michigan legal loads. The vehicle types to be investigated are the three AASHTO legal vehicles and all Michigan legal vehicles. Michigan legal vehicles include all legal single-unit trucks, two-unit trucks (tractors with a trailer) and three-unit trucks (a tractor with two trailers). The Michigan Operating Rating represents loads that can be safely carried by the bridge on an infrequent basis. This rating may sometimes be referred to as the *Legal Load Rating*.

Load Posting. When it is discovered that a bridge can not safely carry all Michigan legal loads at the operating level, the bridge is posted with a sign indicating the maximum weight of vehicles of all three types (one-unit, two-unit and three-unit) that can safely use the bridge. Agencies may choose to post bridges for less than the calculated capacity, or to post at the inventory rating level, in order to extend the life of the structure.

Overloads or Permit Loads. Occasionally, vehicles that are heavier than Michigan legal loads, or that have axle configurations or axle loads that are not allowed by Michigan law, may need to use the highways and may cross specific highway bridges. Those vehicles can be said to be “overloads” and are required to obtain a permit from the agency owning the highway and bridges in question. It is prudent to analyze the capacity of the specific bridges to be crossed for their ability to safely carry the overload. Overload analysis is ordinarily done at the Operating level. Permits are then issued or denied based on the bridge analysis.

Federal Regulations that Govern Load Rating

The requirement to analyze highway bridges for capacity stems from federal law and can be found in the National Bridge Inspection Standards (NBIS) October 1988, within the Code of Federal Regulations. Specifically, Title 23, Part 650, Subpart C, 650.303 (c) reads in part, "Each structure. . .shall be rated as to its safe load carrying capacity in accordance with Section 4 of the AASHTO Manual."

The requirements to maintain records related to bridge inspections and ratings can be found in the NBIS 650.311 (a), which reads in part, "Each State shall prepare and maintain an inventory of all bridge structures. . ." and ". . .certain structure inventory and appraisal data must be collected and retained within the various departments. . ."

When to Perform a Load Rating

In general, load ratings are performed on a bridge when one of five events has occurred: 1) the bridge is new and has not been previously rated, 2) the bridge has had a significant alteration that may affect the capacity of the bridge, 3) the bridge has incurred damage that affects the capacity, 4) a key component of the structure has deteriorated such that the previous load rating is no longer valid or 5) a request has been made to permit an overload vehicle to use the bridge.

New bridges must be load rated in order to comply with the Code of Federal Regulations requirements cited above. Rated capacities for new bridges are submitted to the MDOT and become the first recorded information retained about that topic.

In the second instance, if a bridge element has been repaired, rehabilitated, reconstructed or altered in a significant way, a load rating must be performed. This load rating could be triggered by such items as a deck overlay, the addition of a heavier railing, a new deck, a new superstructure, beam repairs, new beams, widening, significant substructure repair or any other rehabilitation that would affect the ability of the structure to carry load. The analyst must be aware of any changes in dead load that result from the work performed on the bridge.

The third case could be represented by an accident in which a vehicle struck a beam or substructure unit and significant damage occurred. The nature and extent of the damage would need to be included in modeling the structure for the new load rating.

In the fourth instance, a new load rating would be initiated after a field inspection indicated that a key element had deteriorated to a level not represented in the previous

load rating. This would include items such as beam flange or web section loss, deck deterioration, substructure unit section loss or being out of plumb.

In the final instance, a permit application may have been submitted for an overload vehicle to travel over a particular bridge or series of bridges along a proposed route. If a bridge has not been analyzed previously for this particular overload, that task must be completed before a answer to the permit application can be returned.

All load ratings should be performed based on the result of a recent inspection of the bridge and where possible the design and/or as-built plans for the structure must be reviewed.

Michigan's Heavy Trucks.

A key feature of Bridge Load Ratings in Michigan is the inclusion of all Michigan legal loads. Michigan law allows the use of trucks that far exceed the federal limit of 80,000 lb. Maximum total weights are not directly controlled by Michigan law; however, weights are indirectly controlled by a combination of maximum legal vehicle lengths, maximum legal axle loads and axle spacing. The combined effect of those items yields legal trucks that can weigh as much as 164,000 lb. Individual axle loads and tandem axle loads have a variety of legal limits based on spacing, but the overall maximums are limited to the federal limits for axle weights.

While it should be noted that a small percentage of commercial vehicles in Michigan operates at greater than the federal limit of 80,000 lb, the concentration of these heavy vehicles varies widely throughout the state. Some rural locations may rarely see a vehicle greater than 80,000 lb, while other areas, such as near an aggregate pit or manufacturing facility may experience frequent passage of heavy vehicles. As noted above, Operating Ratings are to be performed with the inclusion of all Michigan legal loads.

Chapter 2

MICHIGAN LEGAL LOADS

September 28, 2001

MICHIGAN LEGAL LOADS

Introduction

In an effort to provide an overall understanding of the Michigan Legal Loads, a summary of the evolution of legal loads nationwide is presented, followed by the background for legal loads in Michigan. The purpose is to give the document user the information needed to fully understand the loads to be used in rating bridges in Michigan.

Federal Regulations

Based on an American Association of State Highway Officials (AASHO) policy adopted in 1946, the first federal Truck Size and Weight (TS&W) limits were enacted in the Federal-Aid Highway Act of 1956. The federal involvement in setting interstate TS&W limits was motivated by the increased federal highway funding to the states in the years leading to the 1956 Act. The Act established the following limits:

- Single-axle weight limit of 18,000 lb;
- Tandem-axle weight limit of 32,000 lb;
- Gross Vehicle Weight (GVW) of 73,280 lb; and
- Maximum width limit of 96 inches.
- Alternate Military Loading of tandem axles spaced at 4' weighing 24,000 lbs each.

These limits were qualified by a “grandfather clause” that allowed continued operation of heavier trucks on the new interstate system consistent with state limits in effect prior to July 1, 1956.

In 1974, the limits were increased as follows, based on the Federal-Aid Highway Amendments:

- Single-axle weight limit of 20,000 lb;
- Tandem-axle weight limit of 34,000 lb; and
- Gross Vehicle Weight (GVW) of 80,000 lb.

Additional regulations followed in the Surface Transportation Assistance Act (STAA) of 1982 and the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. However, these regulations dealt primarily with size restrictions. The 1974 weight limits are still applicable today on the interstate system.

State Regulations

The extension of grandfather rights has allowed the states to continue operation of vehicles on state and interstate highways in excess of the limits mandated by federal regulations. These rights allowed individual states continued control of size and weight limits. The limits were influenced by three different grandfather rights provisions. The first, enacted in 1956, addressed axle weights, gross weights and permits. The second, adopted in 1975, applied to the bridge formula and axle spacings. The third, enacted in 1991, ratified state practices regarding Longer Combination Vehicles (LCV).

Currently throughout the nation, there are 40 different combinations of weight limits that apply both on and off the interstate system. (Ref 18) As a result, each state has a different weight limit "package" consisting of different mixes of these combinations.

Michigan Regulations

The three levels of Michigan Legal loads are called Normal, Designated and Special Designated, and are described in detail below. The current legal load limits in the State of Michigan are controlled either directly by axle load limits or indirectly by a combination of vehicle length limits, permissible axle spacing, permissible axle loads and number of axles allowed by law. In all loadings shown below, the axle loads are also limited by the width of the tire. The maximum load for any wheel is 700 pounds per inch of tire width.

Figure 2.1 illustrates common legal vehicles used on Michigan roads (truck numbers 1-25).
Front axle loads are shown as 15.4 kips since the trend in the trucking industry is moving to 11 inch tire widths. Truck numbers 26-28 shown on Figure 2.1 illustrate the AASHTO analysis vehicles.

Figure 2.2 illustrates the standard AASHTO design vehicles.

Normal Loading

Section 257.722.1 of the Michigan Vehicle Code (Act 300 of 1949) (Ref. 21) defines "Normal" loading as follows:

- If the axle spacing is 9 ft or more between axles, the maximum axle load shall not exceed 18,000 lb.

- If the axle spacing is less than 9 ft between 2 axles but more than (or equal to) 3 ft 6 in, the maximum axle load shall not exceed 13,000 lb. (The most common tandem axle spacing is 3 ft 6 in)

- If the axles are spaced less than 3 ft 6 in apart, the maximum axle load shall not exceed 9,000 lb per axle.

The above loading sets limitations on individual axles. There is no direct maximum for the total gross vehicle weight for normal loading. There is, however, an indirect limit caused by a combination of the maximum legal length of vehicles, maximum legal axle loads, axle spacing and total number of axles allowed. The Michigan Vehicle Code allows a maximum of 11 axles for legal vehicles.

According to the Michigan Vehicle Code, the length limits are briefly summarized as follows:

- Single Vehicle: 40 ft.

- Truck tractor and Semitrailer combinations: No overall length limit, but the semitrailer is not to exceed 50 ft.

- Truck and semitrailer or trailer combinations: 65 ft, with an exception for saw logs, pulpwood and tree length poles, where the maximum overall length shall not exceed 70 ft.

- Truck Tractor and two semitrailers, or truck tractor, semitrailer and trailer combinations: no overall length limit, if the length of each semitrailer or trailer does not exceed 28.5 ft, or the overall length of the trailers in combination does not exceed 58 ft, measured from the front of the first trailer to the rear of the second trailer.

- Tow bar and saddle-mount equipment: 75 ft.

“Normal” loading defines the lowest set of maximum loadings that applies to all Michigan roads. More permissive sets of legal loads are described below.

Designated Loading

Roadways owned by local authorities or by the state may be “designated” to allow heavier loads. This designation is a variation to the “normal” loading mentioned above and is as follows:

- If the gross vehicle weight is less than or equal to 73,280 lb, two tandem axle assemblies shall be allowed to carry 16,000 lb per axle so long as no other axle is within 9 ft of any axle of the assembly.

- If the gross vehicle weight is more than 73,280 lb, one tandem axle assembly shall be allowed to carry 16,000 lb per axle so long as no other axle is within 9 ft of any axle of the assembly, and if no other tandem axle assembly in the combination of axles exceeds a gross weight of 13,000 lb per axle.

As with normal loading, designated loading has no direct maximum of the total gross vehicle weight. The gross vehicle weight is indirectly controlled by the maximum legal length of the vehicle, axle spacing, legal axle weights and the maximum number of axles.

Special Designated Loading

In general, “special designated loading” applies to interstate highways. The state Department of Transportation for other routes, or a local authority with respect to highways under its jurisdiction may also adopt this loading. The “special designated loading” may be applied to vehicles with a gross vehicle weight less than 80,000 lb. The loading constraints are as follows:

- No axle can carry a load in excess of 20,000 lb.
- No tandem axle assembly can carry a load in excess of 34,000 lb (17,000 lb per axle of the assembly).
- The overall gross vehicle weight and the weight of any combination of consecutive axles are limited by the following formula, known as the Federal Bridge Formula B:

$$W=500[LN/(N-1)+12N+36]$$

Where: W = the maximum weight in pounds that can be carried by a consecutive combination of 2 or more axles.

L = spacing in feet between the outer axles of any consecutive combination of 2 or more axles.

N = number of axles be considered in the combination.

An exception is granted for a five axle vehicle with two consecutive sets of tandem axles. That vehicle configuration may carry a gross load of 34,000 lb for each tandem if the first and last axles of the consecutive sets of tandem axles are at least 36 ft apart.

However, when the gross vehicle weight of a 5-axle vehicle exceeds 80,000 lb, the above formula can not be utilized and gross vehicle loading is then controlled by “normal” loading and “designated” loading.

HISTORY OF DESIGN LIVE LOADS

Design live loads are used during the design of a new bridge, and reconstruction or rehabilitation designs. Design live loads are not legal loads. Generally speaking, design axle loads are more severe than legal axle loads and help to provide reasonable factors of safety for slab designs.

Figure 2.2 illustrates the current design vehicles (H-20 and HS-20) set forth by AASHTO in the Standard Specifications for Highway Bridges. The MDOT has gradually adopted HS-25 as the standard design live load, beginning with interstate and primary bridges and now extending to all trunkline bridges. HS-25 is 25% heavier than HS-20. Some local agencies have also adopted HS-25 live load as their standard.

Table 2.1 presents, as a historical reference, the history of Design Live Loads in the Michigan Bridge Specifications, according to the 1983 Michigan Bridge Analysis Guide. (Ref. 8)

TABLE 2.1 History of Design Live Loads in Michigan Bridge Specifications

Year	Loading (Floor System)	Long Span Girders, Trusses	Axle Loads
Law 1907*	10 T Traction Engine		
1907, 1909	12 T Steam Rd. Roller or 10 T	100 psf	(8 T)
1911	15 T Road Roller	100 psf	(10 T)
1914, 15, 16	18 T Road Roller	100 psf (80)**	(12 T) 10' (6 T)
1920, 22	18 T Truck or 10 T	100 psf (80)**	
1923	24 T Truck (Wayne Co.)	100 psf	(16 T) 12' (8 T)
1926	H15 Truck (H20, H12.5, H10)	Eq. Lane Load	
1936	H15 or H20	Truck Train***	(12 T) 14' (3T)
1946	H15, H20, H20-S16 (Adopted by Wayne Co., 1941)	Equivalent Lane Load	
1958	H15, H20 or H20-S16 + Alt. Mil. Load	Eq. Lane Load	
1972	H20 or HS20 + Alt. Mil. Load	Eq. Lane Load	(16 T) 14' (4 T)
1973	H25 or HS25 + Alt. Mil. Load	Eq. Lane Load	(20 T) 14' (5 T)

* The 10-ton Traction Engine is not a specification but was used as a legal design load in many localities when purchasing bridges as late as 1912 per L.C. Smith. He also states that “Modern Bridge Engineers are designing bridge floors for a 15-ton Road Rollers.”
** For spans between 100 ft and 200 ft, the 100 psf load is reduced by 1 psf for every 5 additional ft. Therefore, for a 200 ft span, 80 psf would be used. The 80 psf would also control for spans longer than 200 ft.

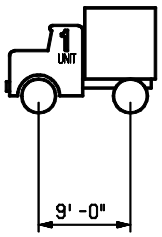
*** H15 Train is a series of H15 trucks separated by 30 ft. An H20 Train is an H15 Train with one H20 truck inserted.

Table 2.2 lists other specifications referred to in Michigan bridge designs, according to the 1983 Michigan Bridge Analysis Guide.

TABLE 2.2 Other Specifications Referred to in Michigan Bridge Designs

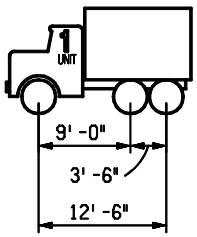
Year	Loading (Floor System)		Long Span Girders, Trusses	Axle Loads
	Niles MCRR		to 32' > 32'	
1890	8 T on axles 8' apart		100 psf (80)	(4T) 8' (4T)
1896	T. Cooper-Howell AARR		150 psf	
1909	T. Cooper's Br. Spec. Class			
	24 T City	A	100 psf	
	12 T Suburban	B	100 psf	
	12 T or 18 T St. Car	C		
	6 T Country	D	80	
	24 T Street Car	E1	Train	
	18 T Street Car	E2	Train	
1903 & 1911	Saginaw - Genessee and Johnson St. 40 T Street Car		100 psf	Two tandems spaced @ 20' c to c. Axles @ 6' spacing within tandems.
1911	Grand Rapids - Leonard St. 60 T Street Car		150 psf	Two axles spaced @ 22'.
1927	60 T Street Car (Monroe)			Two tandems spaced @ 30' c to c. Axles @ 7' spacing within tandems.

TRUCK NO. 1



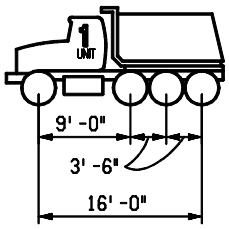
			Totals	Equivalent train load
NL (kips)	15.4	18	33.4	0.86 klf
DL (kips)	15.4	18	33.4	0.86 klf
SD (kips)	19	20	39	1.00 klf

TRUCK NO. 2



				Totals	Equivalent train load
NL (kips)	15.4	13	13	41.4	0.97 klf
DL (kips)	15.4	16	16	47.4	1.12 klf
SD (kips)	11.4	17	17	45.4	1.07 klf

TRUCK NO. 3



					Totals	Equivalent train load
NL (kips)	15.4	13	13	13	54.4	1.18 klf
DL (kips)	15.4	13	13	13	54.4	1.18 klf

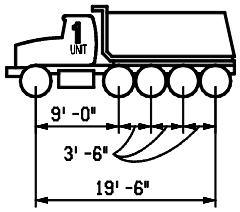
NL Denotes
Normal loading

DL Denotes
Designated loading

SD Denotes Special
Designated loading

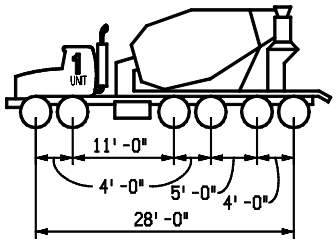
FIGURE 2.1
Michigan Legal Vehicles

TRUCK NO. 4



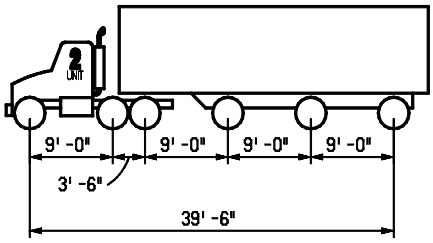
						Totals	Equivalent train load
NL (kips)	15.4	13	13	13	13	67.4	1.36 klf
DL (kips)	15.4	13	13	13	13	67.4	1.36 klf

TRUCK NO. 5



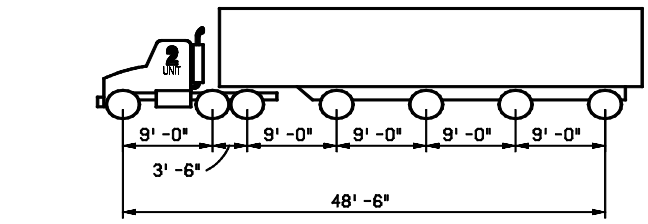
							Totals	Equivalent train load
NL (kips)	13	13	13	13	13	13	78	1.34 klf
DL (kips)	16	16	13	13	13	13	84	1.45 klf

TRUCK NO. 6



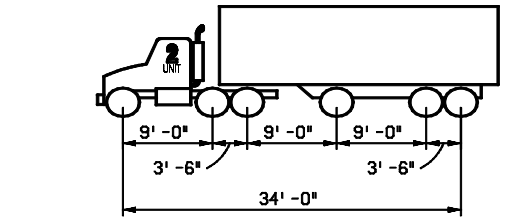
								Totals	Equivalent train load
NL (kips)	15.4	13	13	18	18	18		95.4	1.37 klf
DL (kips)	15.4	16	16	18	18	18		101.4	1.46 klf

FIGURE 2.1 (Continued)
Michigan Legal Vehicles



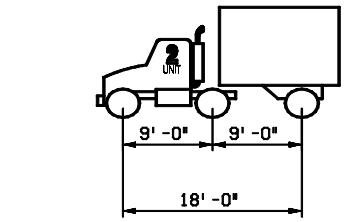
TRUCK NO. 7

								Totals	Equivalent train load
NL (kips)	15.4	13 13	18	18	18	18		113.4	1.44 klf
DL (kips)	15.4	16 16	18	18	18	18		119.4	1.52 klf



TRUCK NO. 8

							Totals	Equivalent train load
NL (kips)	15.4	13 13	18	13 13			85.4	1.33 klf
DL (kips)	15.4	16 16	18	13 13			91.4	1.43 klf

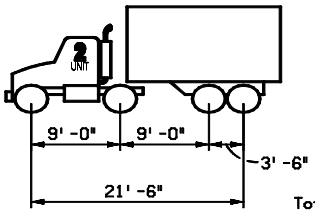


TRUCK NO. 9

				Totals	Equivalent train load
NL (kips)	15.4	18	18	51.4	1.07 klf
DL (kips)	15.4	18	18	51.4	1.07 klf
SD (kips)	10.5	19.5	19.5	49.5	1.03 klf

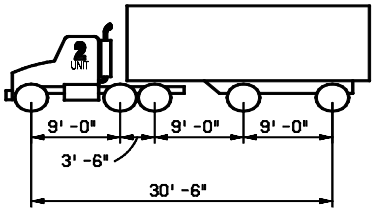
FIGURE 2.1 (Continued)
Michigan Legal Vehicles

TRUCK NO. 10



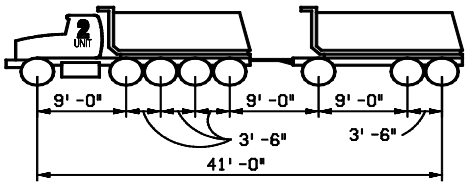
					Totals	Equivalent train load
NL (kips)	15.4	18	13 13		59.4	1.15 klf
DL (kips)	15.4	18	16 16		65.4	1.25 klf
SD (kips)	11	11.4	17 17		56.4	1.10 klf

TRUCK NO. 11



						Totals	Equivalent train load
NL (kips)	15.4	13 13	18	18		77.4	1.28 klf
DL (kips)	15.4	16 16	18	18		83.4	1.38 klf
SD (kips)	7.1	10.5 10.5	19.5	19.5		67.1	1.11 klf

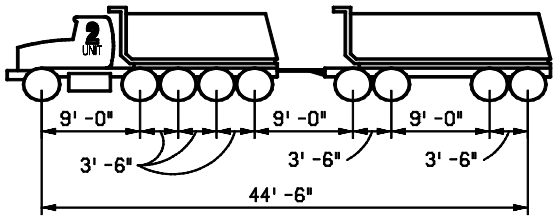
TRUCK NO. 12



						Totals	Equivalent train load
NL (kips)	15.4	13 13 13 13	18	13 13		111.4	1.57 klf
DL (kips)	15.4	13 13 13 13	18	16 16		117.4	1.65 klf

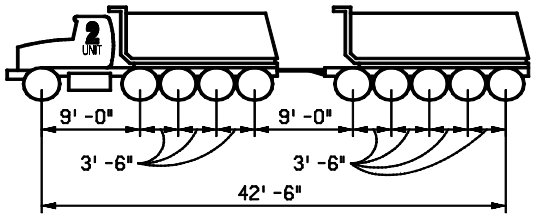
FIGURE 2.1 (Continued)
Michigan Legal Vehicles

TRUCK NO. 13



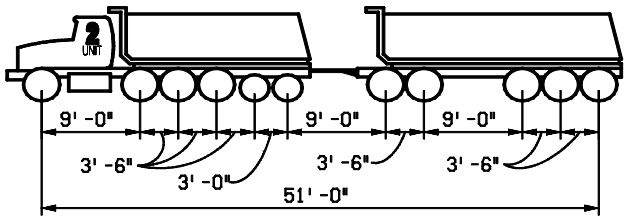
											Totals	Equivalent train load
NL (kips)	15.4	13	13	13	13	13	13	13	13		119.4	1.60 klf
DL (kips)	15.4	13	13	13	13	13	13	16	16		125.4	1.68 klf

TRUCK NO. 14



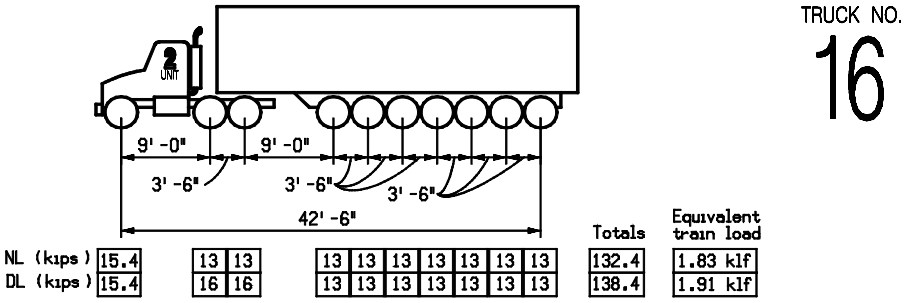
												Totals	Equivalent train load
NL (kips)	15.4	13	13	13	13	13	13	13	13	13		132.4	1.83 klf
DL (kips)	15.4	13	13	13	13	13	13	13	13	13		132.4	1.83 klf

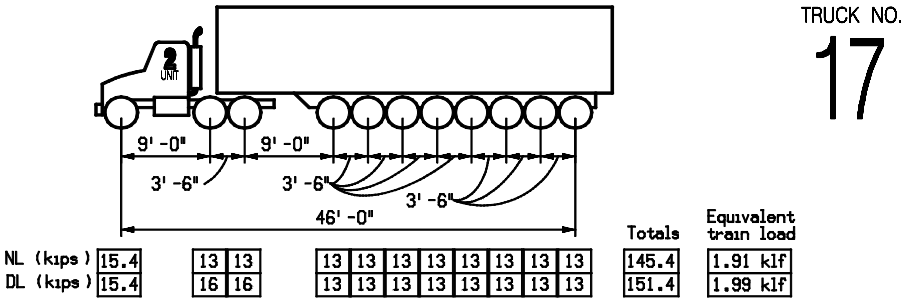
TRUCK NO. 15



													Totals	Equivalent train load
NL (kips)	15.4	13	13	13	9	9	13	13	13	13	13		137.4	1.70 klf
DL (kips)	15.4	13	13	13	9	9	16	16	13	13	13		143.4	1.77 klf

FIGURE 2.1 (Continued)
Michigan Legal Vehicles





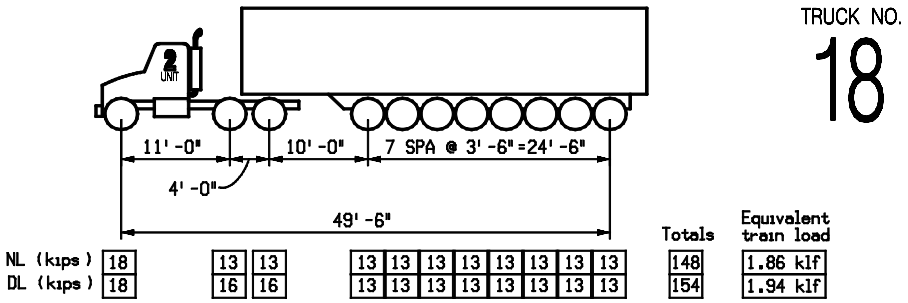
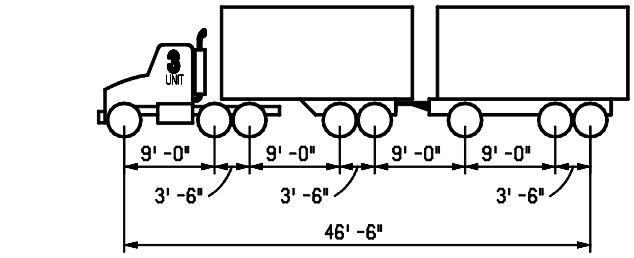
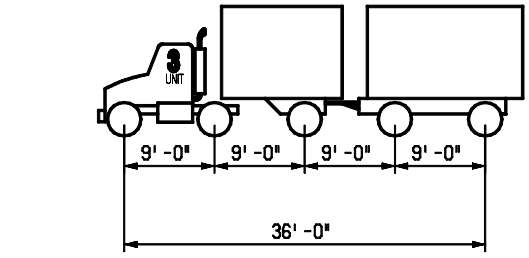


FIGURE 2.1 (Continued)
Michigan Legal Vehicles



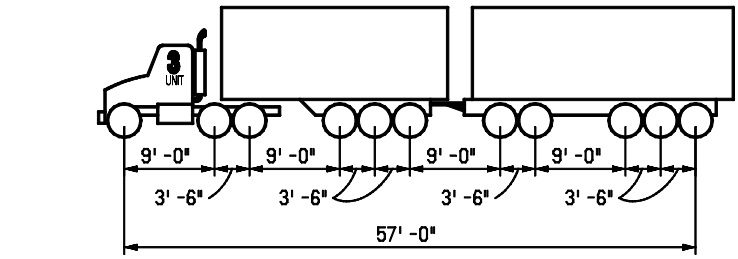
TRUCK NO. 19

									Totals	Equivalent train load
NL (kips)	15.4	13 13	13 13	18	13 13	111.4	1.46 klf
DL (kips)	15.4	16 16	13 13	18	13 13	117.4	1.53 klf



TRUCK NO. 20

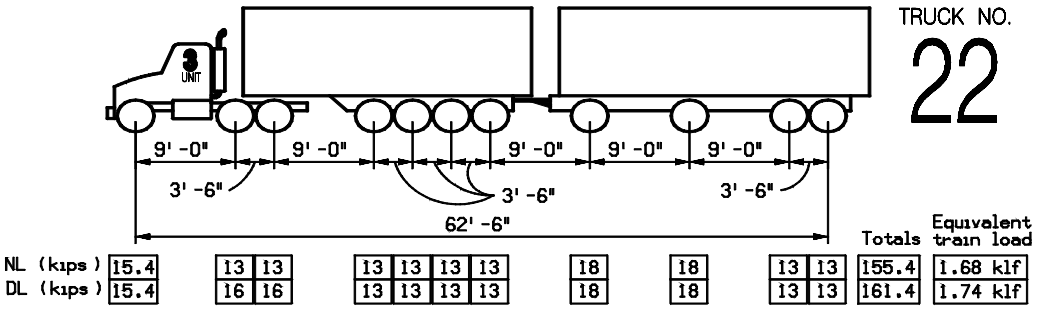
						Totals	Equivalent train load
NL (kips)	15.4	18	18	18	18	87.4	1.15 klf
DL (kips)	15.4	18	18	18	18	87.4	1.15 klf



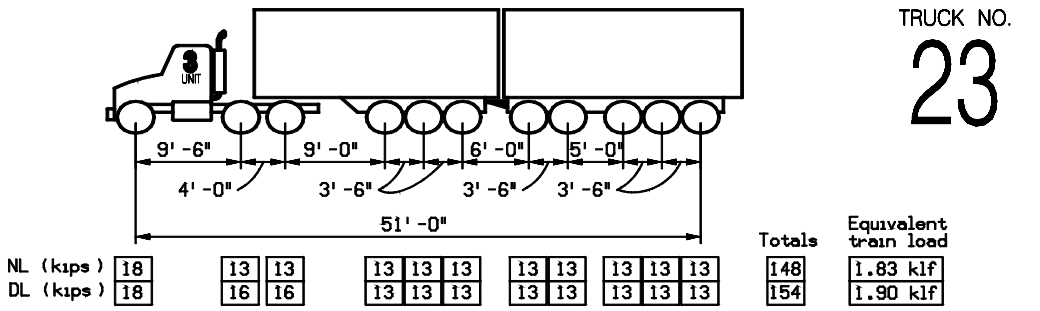
TRUCK NO. 21

							Totals	Equivalent train load
NL (kips)	15.4	13 13	13 13 13	13 13	13 13 13	145.4	1.67 klf
DL (kips)	15.4	16 16	13 13 13	13 13	13 13 13	151.4	1.74 klf

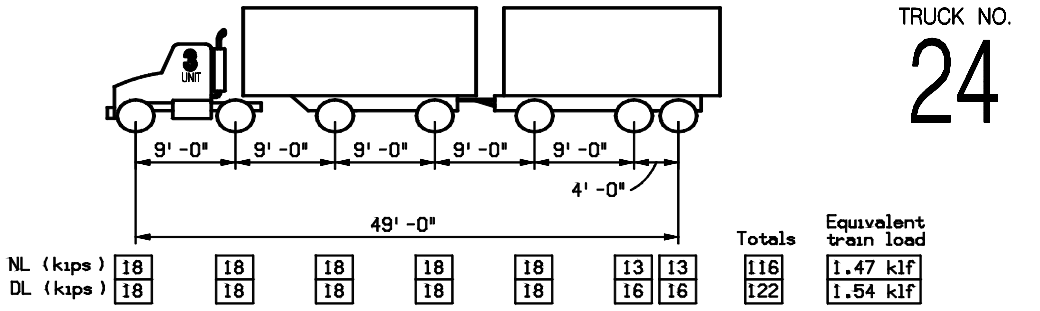
FIGURE 2.1 (Continued)
Michigan Legal Vehicles



										Totals	Equivalent train load
NL (kips)	15.4	13 13	13 13 13 13	18	18	13 13	155.4	1.68 klf
DL (kips)	15.4	16 16	13 13 13 13	18	18	13 13	161.4	1.74 klf

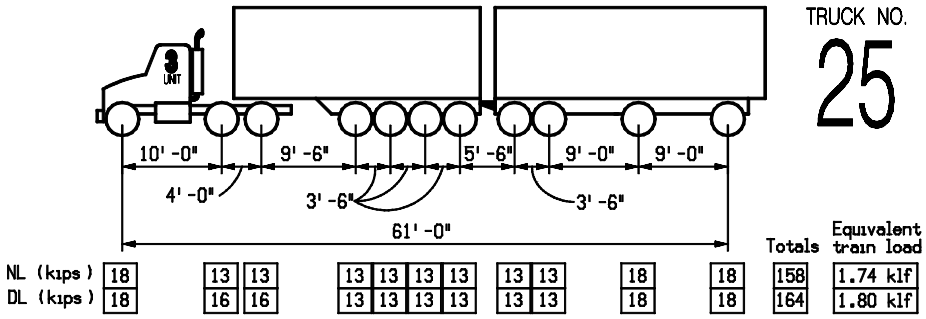


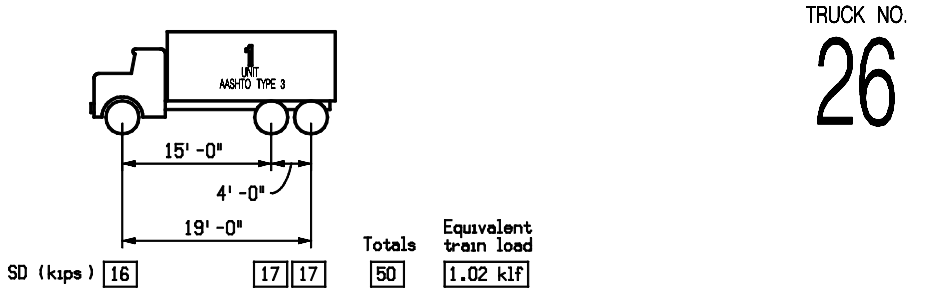
							Totals	Equivalent train load
NL (kips)	18	13 13	13 13 13	13 13	13 13 13	148	1.83 klf
DL (kips)	18	16 16	13 13 13	13 13	13 13 13	154	1.90 klf



								Totals	Equivalent train load
NL (kips)	18	18	18	18	18	13 13	116	1.47 klf
DL (kips)	18	18	18	18	18	16 16	122	1.54 klf

FIGURE 2.1 (Continued)
Michigan Legal Vehicles





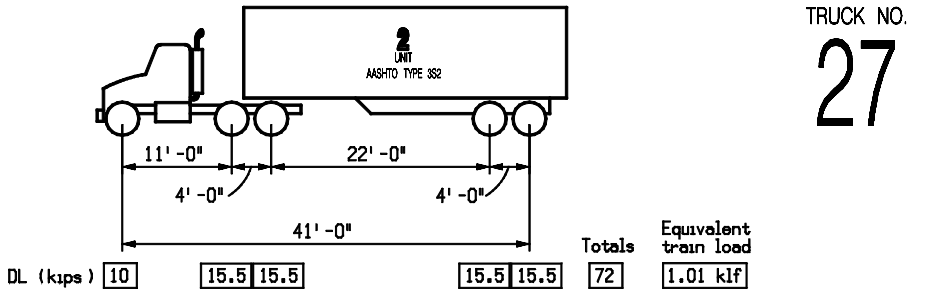
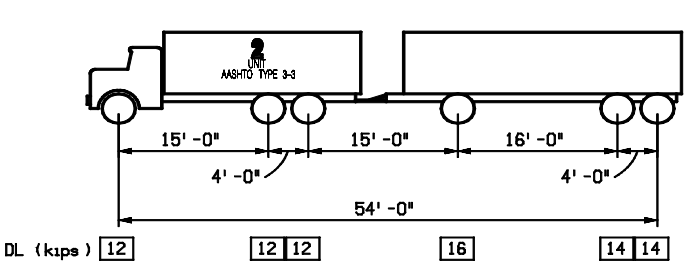


FIGURE 2.1 (Continued)
Michigan Legal Vehicles



TRUCK NO. 28

						Totals	Equivalent train load
DL (kips)	12	12	12	16	14	14	80	0.95 klf

NOTES:

NL Denotes Normal axle loading

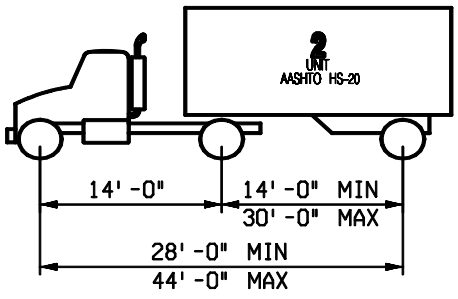
DL Denotes Designated axle loading

SD Denotes Special Designated axle loading

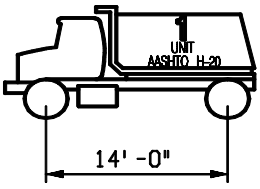
The maximum load of any tire is limited to 700 lbs per inch of tire width.

Normal, Designated and Special Designated loadings are defined in Chapter 2 of this guide.

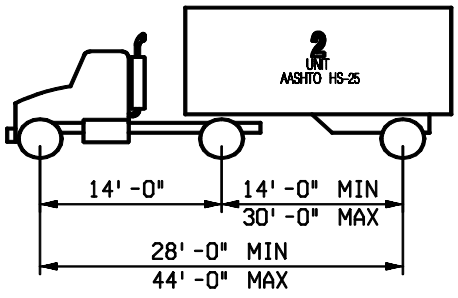
FIGURE 2.1 (Continued)
Michigan Legal Vehicles



				Totals	Equivalent train load
(kips)	8	32	32	72	*



				Totals	Equivalent train load
(kips)	8	32	40		*



HS-25 TRUCKS ARE NOT TO BE USED FOR ANY LOAD RATING CALCULATIONS

				Totals	Equivalent train load
(kips)	10	40	40	90	*

NOTE:

* See Figure 3.7.6B in the AASHTO Standard Specifications for Highway Bridges.

FIGURE 2.2
Design Live Loads

Chapter 3

LEGAL LOADS IN OTHER STATES/PROVINCES AND COUNTRIES

January 3, 2002

LEGAL LOADS IN OTHER STATES AND PROVINCES

Introduction

The purpose of this chapter is to provide the engineer with the legal loads in neighboring states so that border bridges can be properly rated for both states involved. This chapter also include a brief summary of the influence of North America Free Trade Agreement (NAFTA) requirements on bridges. The information presented in this chapter was gathered from a number of sources, including interviews with personnel from the Engineering Departments of the various Departments of Transportation and the Federal Highway Administration (FHWA); Department of Transportation Internet websites and technical journal articles.

Bridge Load Ratings and Legal Vehicles in Nearby States and Provinces

Each state or province has weight and dimensional limitations for all vehicles traveling on its roads. If these limitations are exceeded, a permit must be obtained from the governing transportation agency.

The following paragraphs present a summary of the general procedures that the states or provinces nearby to Michigan use in the calculation of load ratings for their bridges. The summary includes information regarding vehicles used for the ratings and analysis methods to be used. Also included is a discussion of general size and weight limitations the jurisdiction may have.

Neighboring States/Provinces with Michigan Border Bridges

For those bridges which lie on the border of Michigan and another state, the bridge rating analyst is directed to rate the structures with Michigan legal loads, but to do so in concert with the owning agency from the neighboring state.

Wisconsin

The Wisconsin Department of Transportation (WisDOT) uses the AASHTO HS20-44 vehicle as well as a 190,000 lb Standard Permit Vehicle for its load ratings. The configuration of the Standard Permit Vehicle is shown in Figure 3.1. WisDOT uses the Load Factor Method for the calculation of load ratings and its own in-house software to do the ratings calculations.

The maximum legal weight of any vehicle in Wisconsin with at least 5 axles is 80,000 lb. In general, individual axle weight limitations are as follows: 13,000 lb

for a steering axle and 20,000 lb for any single axle. The limitations for trucks with 4, 3 and 2 axles are 76,000 lb, 60,000 lb, and 40,000 lb, respectively. All of these limitations are further modified depending on the spacing of the axles.

The maximum height and width are 13 ft 6 in and 8 ft 6 in, respectively. Lengths are limited to 40 ft and 65 ft for single vehicles and combination vehicles, respectively (including loads).

Ontario

The Ontario Ministry of Transportation (MTO) has a standard set of "controlled vehicle loads" called "Ontario Highway Bridge Evaluation Loads (OHBEL)." These loads are designated Level 1, Level 2 and Level 3 and include truck and lane loadings for each level. The vehicle configurations are shown in Figure 3.1. MTO uses the Load Factor Method for the calculation of load ratings.

The maximum legal weight of any vehicle in Ontario is 63,500 kilograms (140,000 lb).

In general, the maximum height and width are 4.15 meters (13 ft 6 in) and 2.6 meters (8 ft 6 in), respectively. The maximum lengths for single vehicles and combination vehicles (including loads) are 12.5 meters (41 ft) and 23 meters (75 ft 5 in), respectively.

Neighboring States without Michigan Border Bridges

The following information is supplied so that owning agencies along Michigan's borders can have basic knowledge about the legal weights and practices in other nearby jurisdictions.

Illinois

The Illinois Department of Transportation (IDOT) uses the AASHTO HS20-44 vehicle to calculate its load ratings. IDOT's load ratings are performed in accordance with the Load Factor Method.

The maximum legal weight of any vehicle in Illinois is 80,000 lb. Permit vehicles may exceed this weight but are limited to IDOT's "Practical Maximum Weights." These are 120,000 lb for 6-axle vehicles, 100,000 lb for 5-axle vehicles, 76,000 lb for 4-axle vehicles, 68,000 lb for 3-axle vehicles, and 48,000 lb for 2-axle vehicles.

The general maximum height and width limitations are 13 ft 6 in and 8 ft 6 in, respectively, although IDOT has a set of legal dimensions for various configurations of trucks.

Indiana

The Indiana Department of Transportation (INDOT) uses the AASHTO H20-44 and HS20-44 vehicles to establish load ratings for their bridges. All INDOT load ratings are calculated using the Load Factor Method of analysis. INDOT's Superload Permit Section uses AASHTO Bridge Analysis and Rating System (BARS) software to calculate its load ratings.

The maximum legal weight of any vehicle in Indiana is 80,000 lb. Individual axle weights are limited to those specified by FHWA Bridge Formula B.

The maximum height and width are 13 ft 6 in and 8 ft 6 in, respectively. The limitations for length are 40 ft for a single vehicle and 60 ft for a combination vehicle (the semitrailer length is limited to 53 ft). Any vehicles exceeding these restrictions must obtain a permit prior to moving on Indiana highways.

If the vehicle exceeds any of the following limits, a "superload" permit is required: 16 ft in width, 15 ft in height, 110 ft in length and 108,000 lb in weight.

Ohio

The Ohio Department of Transportation (ODOT) has a standard set of design vehicles called "Ohio Legal Loads" that are used to rate all bridges in its inventory. These vehicles include the AASHTO HS20-44 design vehicle, and special vehicles with designations 2F1, 3F1, 4F1 and 5C1. The vehicle configurations are shown in Figure 3.1.

ODOT uses the Load Factor Method to calculate load ratings. ODOT's preferred software to perform bridge load rating analyses is AASHTO BARS. ODOT has made a personal computer version of this software available free of cost on its website. ODOT also accepts software such as BRASS, Merlin-Dash, STAAD, GT STRUDL, SAP 90 and SAP 2000.

Legal weight limits in Ohio are 80,000 lb for the gross vehicle weight, and individual axle weights are restricted based on the FHWA Federal Bridge Formula B. Vehicles exceeding 80,000 lb must apply for a "Routine Issue Permit" before traveling on Ohio

highways. ODOT considers any vehicle with a total gross vehicle weight equal to or more than 120,000 lb to be a "Superload."

The legal size limitations are 13 ft 6 in, 8 ft 6 in, and 53 ft for height, width and length, respectively.

Ramifications of the North American Free Trade Agreement (NAFTA)

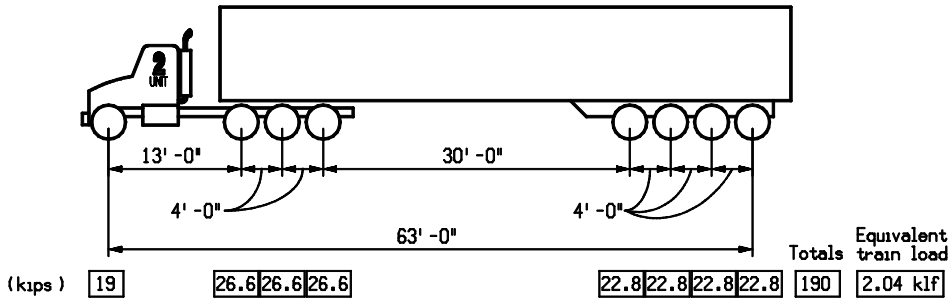
The table below shows current general truck size and weight limitations in the United States, Canada and Mexico.

Country	Overall Length	Trailer Length	Height	Gross Vehicle Weight (lb)	Single Axle (lb)	Tandem Axle (lb)	Tridem Axle (lb)
United States			13'-6"	80,000	20,000	34,000	
Canada	75'-5"	53'-0"		140,000		37,479	46,297
Mexico				146,600		42,990	49,604

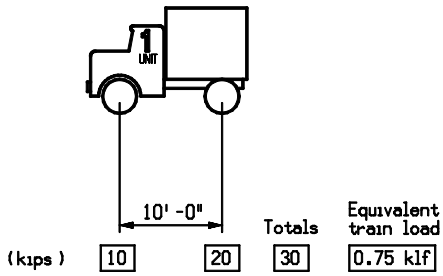
International harmonization committees have been established under the auspices of the U.S. Department of Transportation to attempt to establish uniform limits, but because harmonization is not required under NAFTA, this effort has been unsuccessful thus far.

To date, the influence of NAFTA on the design or load rating of bridges has been virtually non-existent. Some states and provinces have raised the lower thresholds of weight and size limitations for overweight and oversize vehicles requiring permits, but these increases have resulted more from lobbying efforts by the U.S. and Canadian trucking industries rather than from influences due to NAFTA. However, if the harmonization committees establish uniform truck size limits in the future, it is a certainty that AASHTO will update their design loads and load rating criteria for bridges in the United States.

WISCONSIN STANDARD PERMIT VEHICLE



OHIO LEGAL LOADS-2F1



OHIO LEGAL LOADS-3F1

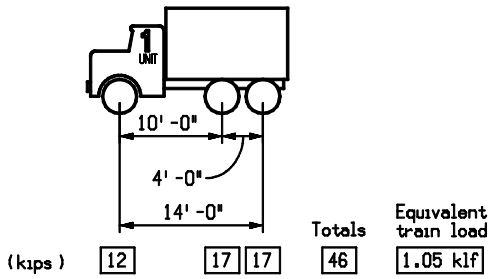
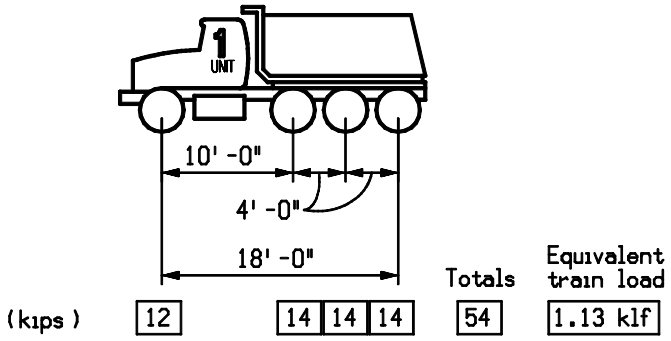
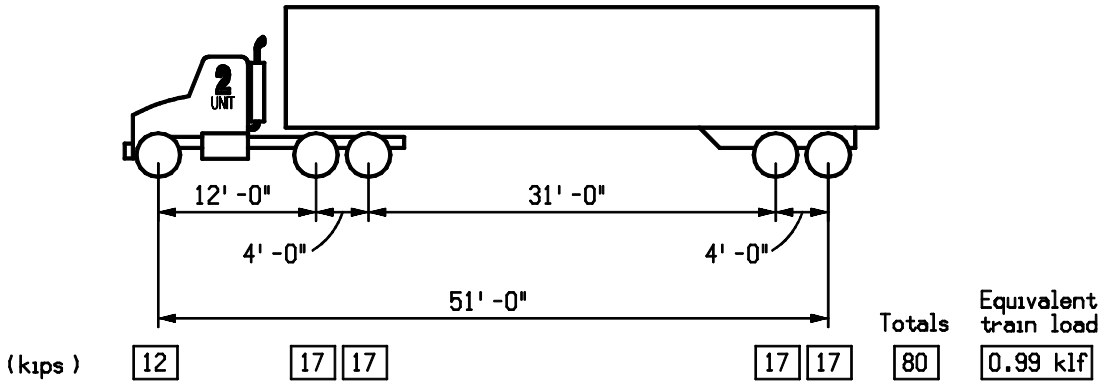


FIGURE 3.1
Legal Vehicles in Other States and Countries

OHIO LEGAL LOADS–4F1



OHIO LEGAL LOADS–5C1



ONTARIO EVALUATION LOADS–LEVEL 1

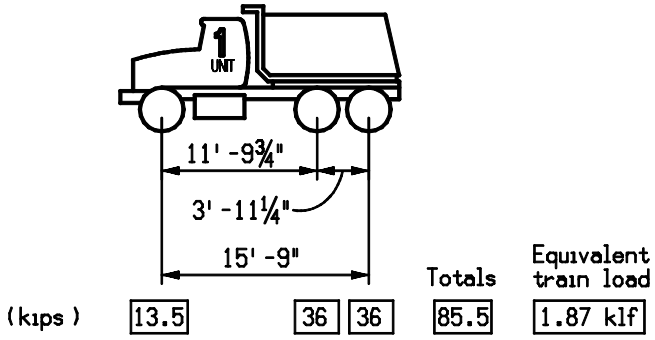
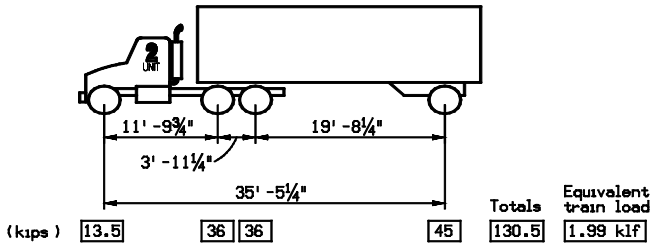


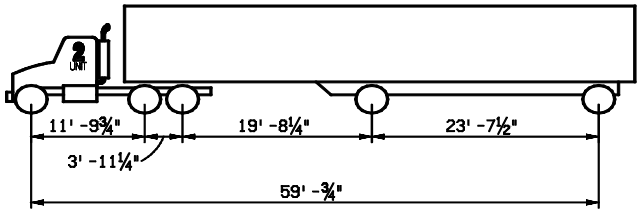
FIGURE 3.1 (Continued)
Legal Vehicles in Other States and Countries

ONTARIO EVALUATION LOADS–LEVEL 2



					Totals	Equivalent train load
(kips)	13.5	36 36	45		130.5	1.99 klf

ONTARIO EVALUATION LOADS–LEVEL 3



						Totals	Equivalent train load
(kips)	13.5	36 36	45	36		166.5	1.87 klf

FIGURE 3.1 (Continued)
Legal Vehicles in Other States and Countries

Chapter 4

GENERAL ANALYSIS PROCEDURES

April 3, 2009

GENERAL ANALYSIS PROCEDURES

Purpose of Load Rating

The safe load carrying capacity of a bridge is determined through the load rating process. The bridge owner and, indirectly, the bridge user must be assured that each structure is being used in a safe and sustainable manner. Through load rating, it may be discovered that a bridge is incapable of safely carrying some legal loads. In that circumstance, it is necessary to publicly "post" the bridge for the reduced safe load or, in the extreme case, to close the bridge. In addition, for those occasions when loads beyond the range of standard legal vehicles (or "permit" loads) need to use a specific structure, load rating can provide answers about which loads are safely acceptable.

The requirement to perform load ratings on highway bridges stems from federal law and can be found in the *National Bridge Inspection Standards*, October 1988, within the Code of Federal Regulations. Specifically, Title 23, Part 650, Subpart C, 650.303 (c) reads:

> "Each structure required to be inspected under the Standards shall be rated as to its safe load carrying capacity in accordance with Section 4 of the AASHTO Manual. If it is determined under this rating procedure that the maximum legal load under state law exceeds the load permitted under the Operating Rating, the bridge must be posted in conformity with the AASHTO Manual or in accordance with State law."

In this context "AASHTO Manual" refers to Reference 1 (see Chapter 11).

Process Outline for Load Rating

The process of preparing a bridge load rating has many components. Perhaps the most significant items include gathering physical data for the specific bridge, selection of the appropriate truck type(s), choosing the correct live load distribution factor and performing the actual analysis.

Information Gathering

Basic information may be available from a variety of sources. Specific details regarding span length, beam spacing, beam size, material properties and other miscellaneous items is ordinarily available in the original design plans and/or as-constructed plans. If these sources are unavailable, an inspection of the bridge by a qualified inspector to measure pertinent details may be sufficient for an approximate rating. If a more exact rating is required, load tests may be necessary to determine the safe load capacity. Historical information regarding material properties is included in Chapter 10.

The existence, extent and thickness of any overlay on a bridge deck is of great significance when performing load rating calculations. Deck overlays are very common, and they can have a profound effect on that capacity of a structure which remains

available for carrying live load. It is the responsibility of the bridge analyst to be aware of the details of any overlay which may exist on a structure to be load rated.

The condition of all structural components and extent of deterioration must be considered in the calculation of a load rating. This information may be available in a recent thorough field inspection. Inspections are to be performed as described in Section 3 of the AASHTO Manual for Condition Evaluation of Bridges. The effective area of members used in a capacity analysis must be the original gross area minus the area that can no longer carry load due to deterioration or corrosion.

Analysis Truck Selection

As can be seen in Chapter 2, there is a great variety of legal vehicles that use the roads and bridges in Michigan. Michigan law elaborates loads that fall in three categories: “Normal,” “Designated” and “Special Designated.” It is of primary importance to know whether a particular road or road system has been selected as “Designated” and/or “Special Designated.” Bridges within a system that has no designation can be analyzed for “Normal” loads. A more conservative assumption would be to include all Michigan legal load categories in the analysis.

Tables showing maximum moments and shears caused by all three categories of loads are included in Chapter 10. Also, see Chapter 5 for an expanded discussion of vehicle selection.

LL Distribution factor

When using the Load Factor (LF) method, live load distribution factors vary greatly depending on beam spacing, bridge deck type and beam or girder type. Although this Guide focuses primarily on LF, there may be circumstances when the Load and Resistance Factor Design (LRFD) method will prove useful to the analyst. For more information about live load distribution factors, see Chapter 6.

Calculations

The final element in completing an analysis is performing and documenting the analysis calculations. For several examples of actual calculations, see Chapter 9.

Summary of AASHTO Manuals

Manual for Condition Evaluation of Bridges (Ref 1)

This manual is a very useful and thorough resource. The information contained in this MDOT Bridge Analysis Guide is based in large measure on information available in the AASHTO Manual. A summary of the chapters contained in the AASHTO manual is as follows:

• Chapter 1 - Introduction	This chapter gives a basic introduction into load rating.
• Chapter 2 - Bridge File (Records)	This chapter summarizes the types of records that should be kept for each bridge by the bridge owner.
• Chapter 3 - Inspection	Types of inspections are listed as well as frequency of, planning of and equipment for inspection operations.
• Chapter 4 - Material Testing	Testing of material may be necessary to determine material strength. This chapter describes various methods of testing.
• Chapter 5 - Nondestructive Load Testing	This chapter briefly explains that load testing is an option in lieu theoretical analysis calculations.
• Chapter 6 - Load Rating	The guiding principles of load rating calculations are contained in this chapter of the AASHTO manual.
• Chapter 7 - Additional Considerations	Other items such as sign posting, vehicle permits and historic bridges are discussed in this section.

Standard Specifications for Highway Bridges, Sixteenth Edition (Ref 2)

This AASHTO manual has been used to guide the direction of bridge design in the United States for decades. The purpose of the Standard Specifications is to "standardize" the way bridges are designed in the United States. Both Allowable Stress Design and Load Factor Design are covered in the Standard Specifications.

Load and Resistance Factor Bridge Design Specifications (Ref 3)

This newer manual was first published in 1994 and may someday supercede the Standard Specifications. The LRFD Specifications have been adopted by some states as the new "standard" for bridge design. Michigan has not yet adopted LRFD methods. However, much useful information is contained in this manual.

Summary of MDOT Manuals

Standard Specifications for Construction (Ref 9)

Past editions of the Michigan Department of Transportation Standard Specifications for Construction may be very helpful. These specifications may provide information useful in determining the original material properties of concrete, structural steel and steel reinforcement.

Bridge Design Manual and Bridge Design Guides (Refs. 11 and 12)

When existing plans of the subject bridge are unavailable, old editions of the MDOT Bridge Design Manual and Bridge Design Guides may provide useful information regarding the design techniques/criteria common to the year of the bridge.

Specifications for Design of Highway Bridges, 1958 Edition (Ref 30)

A complete description of bridge design practice at MDOT in 1958.

Road and Bridge Standard Plans

Similar to the Bridge Design Manual and Bridge Design Guides, older editions of Standard Plans may also provide helpful information. Old bridge railings are shown in detail in previous editions of the Standard Plans.

Structure Inventory and Appraisal Coding Guide (Ref 10)

This Guide is intended to aid local agencies in completing and submitting the Structure Inventory and Appraisal forms for all bridges in their jurisdiction.

Theoretical Analysis Methods for Load Rating

The three primary analysis methods for load rating bridges include: 1) the Allowable Stress (AS) method, 2) the Load Factor (LF) method and 3) the Load and Resistance Factor (LRF) method. All three will be briefly described. This Guide focuses primarily on the Load Factor Method. An additional method for studying live load distribution, finite element analysis, will be discussed in Chapter 6, Live Load Distribution.

It should be noted that Federal Regulations require that LF methods be used for Federal Inventory and Operating ratings. Michigan Operating and Permit ratings may be performed using any of the above methods.

ASD, sometimes referred to as Working Stress Design is oldest of the three methods introduced above. This was the design philosophy used in the earliest Standard Specification for Highway Bridges, issued by AASHO in 1931. In this method, service (or unfactored) loads are applied to the structure and used to determine stresses. The relationship between stress and strain is always taken as linear. The calculated stresses are then compared to an allowable stress. The allowable stresses are determined by applying a factor of safety to the yield stress or ultimate stress of the material. In ASD, live load is treated with the same importance as dead load.

LFD began to be implemented by AASHTO in the early 1970's. In the LFD methodology, various factors are applied to the loads to increase them based on the predictability of each load type. Load factors for live loads are higher than for dead loads because dead loads can be calculated fairly accurate, whereas, live loads are more unpredictable. In addition, reduction factors are applied to the strength of each structural member. These reduction factors lower the strength of the member based on the probabilities of achieving the planned for material properties and dimensional accuracy of the member, among other potential variables. LFD is also based on the knowledge that members continue to gain capacity beyond the linear stress versus strain stage. Member capacities are calculated with the member at full yield strength. LFD is viewed as a more rational and accurate method than ASD. Both ASD and LFD methods are contained in the current AASHTO Standard Specifications for Highway Bridges; however, LFD is more widely used.

LRFD as the most recent method for design and analysis of highway structures, began to be implemented in the 1990's. This method is an extension of the LFD theory. LRFD is more refined in terms of the use of probability and statistical data for both loads and member capacities. New live load configurations were developed and equations were rewritten to include current research. The AASHTO LRFD Bridge Design Specification is anticipated to someday replace the Standard Specifications that contains the ASD and LFD methods.

Material Sampling for Strength Determination In conjunction with theoretical analysis, field samples may be taken and tests conducted to determine the actual “as-built” strength of the structural components. For structural steel strength measurement, MDOT’s practice has been to take three samples from three different beams, usually from the bottom flange near an end support. Tensile testing should be done in accordance with ASTM A-370. Deck concrete may be cored and tested for compressive strength in accordance with ASTM C-39. A minimum of three cores should be tested.

If the results of these tests indicate that greater than anticipated strength is present, that greater strength can be used for analysis and rating of the bridge. However, if lower than anticipated strength is found, that result can not be ignored, and must be used in the rating process.

Actual steel and concrete strength results may be utilized with any approved analytical technique.

Load Testing Method of Load Rating

Load testing of bridges for load rating purposes is also a useful method in certain circumstances. Some bridges can not be satisfactorily analyzed due to a lack of design plans or because of deterioration that is difficult to quantify. In other cases, unusual structure types may not lend themselves to definitive analysis techniques.

A potential advantage of load testing is that some bridges have been shown to have a higher capacity using this method than that derived by normal calculations. An obvious disadvantage is that load testing is generally significantly more expensive than performing normal calculations. However, the cost of load testing may be acceptable to a bridge owner if faced with the possibility of a more expensive bridge replacement or major bridge rehabilitation.

To be useful in establishing (or proving) maximum safe live load capacity, “proof” load testing should be performed. The test load magnitude should be such that it will cause at least the Operating level of live load effects of the live load that would be allowed to use the bridge. For details regarding load testing procedures and methods of determining proof load test values see the Manual for Bridge Rating through Load Testing (Ref 31) Careful planning of loads needed, load application, instrumentation and personnel requirements should be carried out, prior to testing. A condition survey of the structure and an analysis to identify critical components should be completed as part of the planning. The bridge should be closed to traffic during proof load testing.

MDOT has sponsored load testing of various bridges throughout the state and has reports available. If load testing is appropriate for a given bridge, it may be helpful to obtain this information from MDOT. See Chapter 11 for specific references related to MDOT sponsored load testing.

Judgment Load Ratings

Generally, Judgment Ratings are performed with few or no calculations to support such ratings. An example of a judgment rating can be found in the text of Chapter 7 of the AASHTO Manual for Condition Evaluation of Bridges:

> “A concrete bridge need not be posted for restricted loading when it has been carrying normal traffic for an appreciable length of time and shows no distress. This general rule may apply to bridges for which details of the reinforcement are not known. However, until such time as the bridge is either strengthened or replaced, it should be inspected at frequent intervals for signs of distress. In lieu of frequent inspections, a bridge may be load tested to determine its capacity.”

In all cases that a Judgment Rating is performed, it should be after a thorough visual observation of the bridge and with a clear knowledge of the traffic loading using the bridge. However, if signs of distress are observed, normal load rating procedures should be considered.

Judgment Ratings should be accompanied by written documentation that supports the conclusions of the Engineer. These documents should include copies of at least the following items: the inspection report, a detailed technical description of member condition (and damage if any exists), a technical description of the traffic that does or may use the bridge, any calculations made to rate the bridge and a listing of assumptions used as a basis for those calculations. Whenever possible, photographs should be included in the Judgment Rating documentation for further support.

Substructure Considerations

Section 6.1.2 of the AASHTO Manual for Condition Evaluation of Bridges gives guidance regarding substructure ratings. In essence, that section allows the engineer to use his/her judgment in the rating of substructures. If the substructure show no signs of instability or deterioration, then the substructures may be considered to be adequate for the existing traffic. However, if the substructure does show signs of deterioration and/or distress, the engineer should perform a conservative judgement rating.

Deck Considerations

In general, stresses in the deck do not control the load rating except in special cases, as noted in Section 6.7.2.1 of the AASHTO Manual for Condition Evaluation of Bridges. This is easier to understand if one compares the maximum axle load of an HS20 design truck, which is 32 kips, to the maximum normal legal axle load of 18 kips. In addition, bending in two directions, or plate action, is a known behavior of deck slabs that may have been excluded in the original design but does have a significant effect on the capacity of the slab.

However, some bridge deck slabs originally designed for H-15 loading may be over stressed by the tandem axles of Michigan Designated or Special Designated legal vehicles. AASHTO section 3.24.3.1 (ref 2) is based on a spread of the effect of individual wheel loads. Based on a study of the AASHTO method, for bridges with normal beam spacing, the moment effect of the wheels of tandem axles spaced at 3'-6" will overlap, and hence are additive.

It is appropriate to examine the Michigan Operating capacity of bridge decks designed for H-15 loading, which are exposed to Designated or Special Designated Michigan legal vehicles. See Chapter 9 for an example of an H-15 slab analysis. In general, examinations for Inventory Rating and for Federal Operating rating need not be conducted.

Simple Spans Versus Continuous Spans

The majority of bridges throughout Michigan is made up of simple spans. Simple spans have supports that allow the beam ends to rotate freely. Continuous spans have beam members extending over several supports. Continuous bridges have become more popular since deck joints can be eliminated thereby reducing future maintenance problems. All other details remaining constant, continuous beams can carry more load than simply supported beams. Simple span bridges are the general focus of this Bridge

Analysis Guide.

Overview of Computer Software

Available Software

Commercial software is available to aid in load rating calculations. Some of these software packages are available from AASHTO and some are available from private companies. Since computers and software change so rapidly, this Bridge Analysis Guide will not supply great detail with regard to software. Perhaps the best advice is to study the specific details prior to purchasing any software to be confident that the product that is chosen is capable of performing the functions that are desired. Most software manufacturers advertise their products in trade magazines. Each software manufacturer specifies the minimum system requirements that your computer must have to properly run their software. Most manufacturers now require Microsoft Windows 95 or higher, a CD-ROM drive, a mouse or other pointing device, a Pentium processor and a specified amount of hard drive space.

Listed below are some software packages that are currently available:

- *Virtis* is available from AASHTO, and was specifically created to aid in the load rating of highway bridges.

- *STAAD* is a program developed by Research Engineers International. STAAD is an acronym for Structural Analysis And Design and is a general analysis program that can be used for design as well as ratings.

- *SAP2000*, developed by Computers & Structures, Inc.; is another general analysis program that can be used for designing or load rating bridges.

- *DESCUS* is a software package that designs, analyzes and rates curved or straight steel bridge girders. Opti-Mate, Inc. is the company that produces DESCUS.

- *BRASS* is an acronym for Bridge Rating and Analysis of Structural Systems and is available from the Wyoming Department of Transportation.

Spreadsheets

With a few basic equations, an engineer can create a spreadsheet to aid in load rating calculations. Spreadsheets offer an inexpensive method to make use of the computer. An advantage that a spreadsheet has over using commercially available software is that it can be specifically tailored to individual needs and that the formulas, or code, can be easily checked, verified and modified. Spreadsheet concepts and operating details should always be verified by someone other than the originator.

Overview of Hand Calculation Methods

Superposition

The principle of superposition is often used in mechanics of materials and structural analysis. For example, in strength-of-materials studies, the total stress at a point in a material resulting from various applied forces can be obtained by summing the stresses due to each force considered individually. In determining the reactions of a simple beam subjected to a number of loads, the total reaction can be obtained by summing the reactions due to each load considered individually. The principle of superposition can be stated as follows:

> Principle of Superposition: The total effect at some point in a structure due to a number of loads applied simultaneously is equal to the sum of the effects for the loads applied individually.

For the principle of superposition to be valid there must be a linear relationship among forces, stresses and deflections. There are two conditions for which superposition is *not* valid:

1. When the structural material does not behave according to Hooke's law; that is, when the stress is not proportional to the strain.
2. When the deflections of the structure are so large that computations cannot be based on the original geometry of the structure (Ref 15).

Unless otherwise stated, the principle of superposition is assumed to be valid in this Bridge Analysis Guide.

Beam Diagrams and Formulas

Many publications contain common beam loadings that can be used to analyze a variety of bridge superstructure loading scenarios. An example of two of the most common beam diagrams taken from the American Institute for Steel Construction (Ref 5) are shown below in Figure 4.1.

With the principle of superposition in mind, these beam diagrams can be added together in a variety of ways to reproduce dead and live loads for simple spans. An example of superposition can be shown in Figure 4.2.

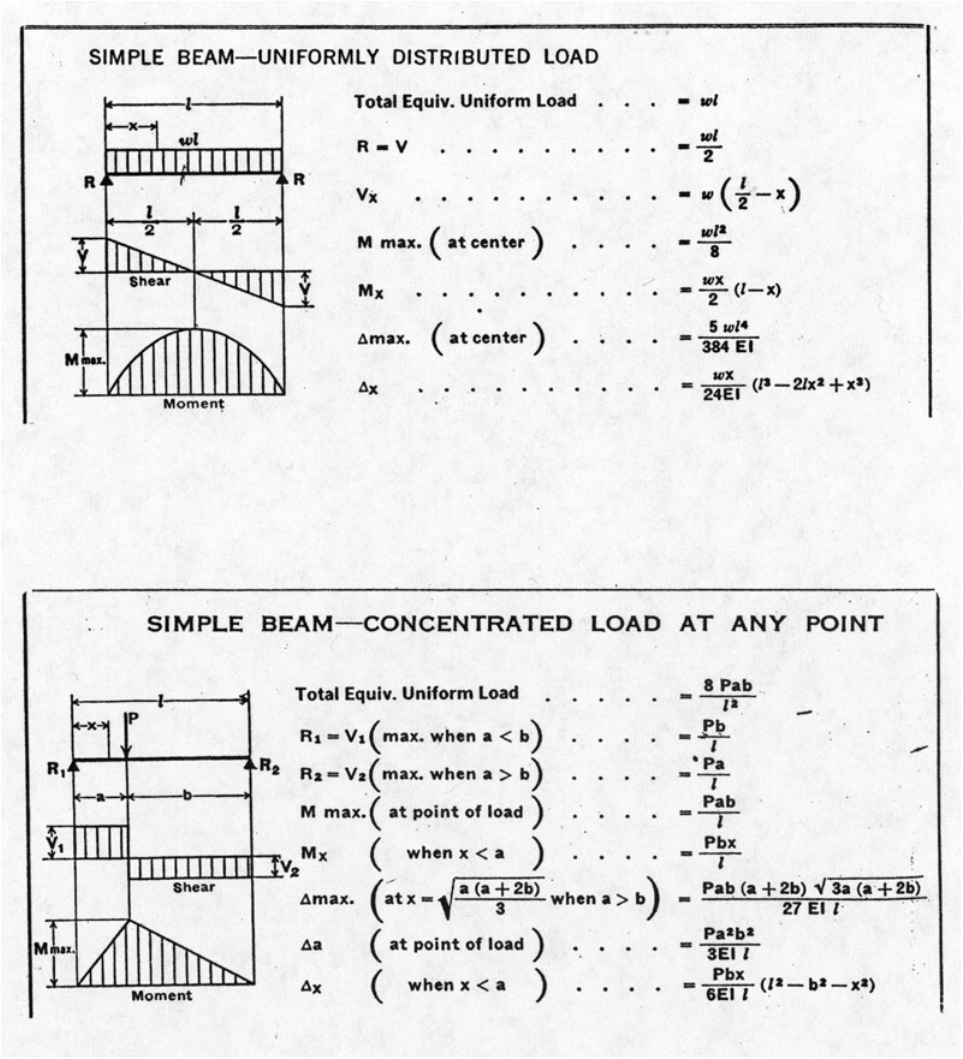


FIGURE 4.1
Common Beam Diagrams

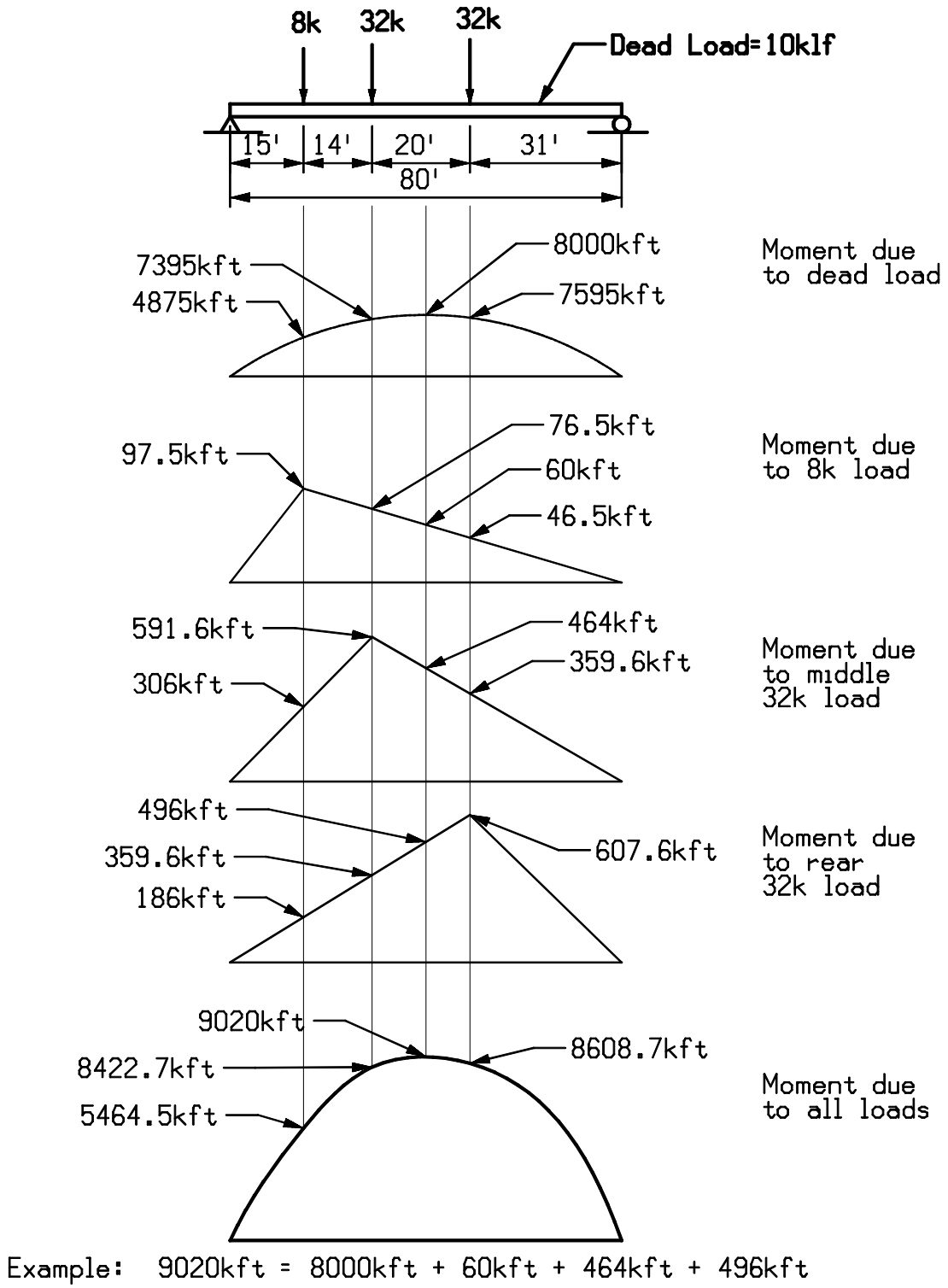


FIGURE 4.2
Example of Superposition

Various beam diagrams also exist for fixed end moments and continuous spans. Using the same methodology as depicted in Figure 4.2 with superposition in mind, beam diagrams can also be used for continuous superstructures. For continuous spans, the engineer should be aware of the degree of fixity at each support and whether a beam diagram is appropriate. If it is determined that the degree of fixity at each support is such that it cannot be modeled using the standard beam formulas, then a more detailed analysis is needed. The Moment Distribution Method and differential equations are among other hand calculation methods available to the engineer, all of which are beyond the scope of this manual.

Influence Lines

Influence lines are another method used to calculate bending moments and shears. Influence lines can be defined as a function whose value at a point represents the value of some structural quantity due to a unit force placed at the point (Ref 15). Consider a three span continuous model. An influence line for determining the negative moment at the left interior support would appear similar to that shown below in Figure 4.3.

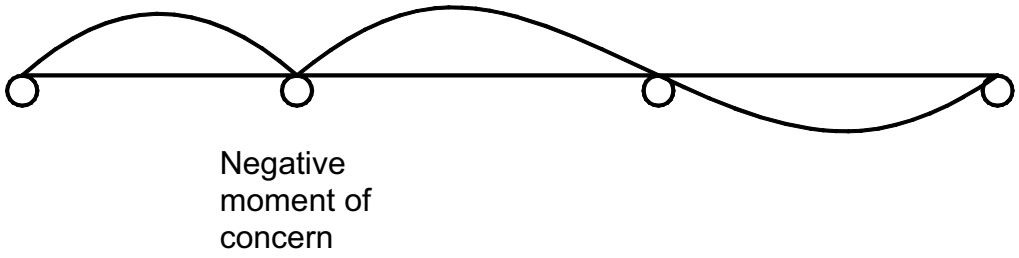


FIGURE 4.3
Example of Influence Line

Influence lines require careful forethought in order to understand which points are of significance and how to have the greatest effect on those points. One useful design aid is a publication called *Moments, Shears and Reactions for Continuous Highway Bridges*. This publication is produced by the American Institute of Steel Construction (AISC) and is quite useful for continuous structures. This publication gives influence coefficients that are derived from influence lines. Again, superposition can be used with influence lines. Though this publication was originally published in 1959, it is still available for purchase and can be obtained by contacting AISC or going to the website www.aisc.org.

Critical Locations on Beams

For simple spans, worst case moments will occur at or near midspan and worst case shears will occur at the supports. Evaluations of capacity versus applied midspan moments and end shears are the most important examinations for load rating of simply supported bridges. However, for bridges with continuous spans or with pin and hangers, critical sections are not as obvious and require careful analysis.

On simply supported structures two other circumstances may require an investigation of capacity at a location other than the two most important locations noted in the above paragraph. If a structural section change, such as a cover plate end or flange transition, occurs on a beam or girder, it may be necessary to examine the capacity of the reduced section versus the applied moment at that change location. Also, if significant deterioration has occurred at a location other than at midspan (for moment) or beam end (for shear) it may be necessary to evaluate the capacity of the member at that compromised location. Maximum moment and/or shear at these locations or any other location on a simple beam can be calculated using the AISC diagrams mentioned above. In addition, many currently available computer programs will generate the required information for any location on a beam.

Since the advent of high speed computers, the process of evaluating all appropriate live load configurations and placements has become much simpler. To determine the maximum bending moments and shears, each applicable vehicle must be “rolled” across the bridge. During this process, maximum values for bending moment and shear are recorded along a given span for each vehicle and for each placement. These tabulations of moments and shears for each vehicle are called “envelopes.” An example of moment and shear envelopes is shown in Figure 4.4. Once created, the envelopes for each vehicle can be compared to determine which vehicle produces the most severe loading effects for each span length. These maximums can be compiled into a chart for all applicable span lengths. A complete set of maximum charts is contained in Chapter 10 of this Guide.

Documentation of Load Rating

Reasons for Documentation

Documentation is important in load rating just as it is in most engineering calculations. Calculations create a written record of the basis for the load rating of a given bridge. It is recommended that a copy of all load rating calculations, along with any structure inspection information that formed a basis for the rating, should be maintained in a file for each bridge. This allows individuals in the future to refer to a previous load rating and see the assumptions that were used in that work. This information may also be helpful for future ratings.

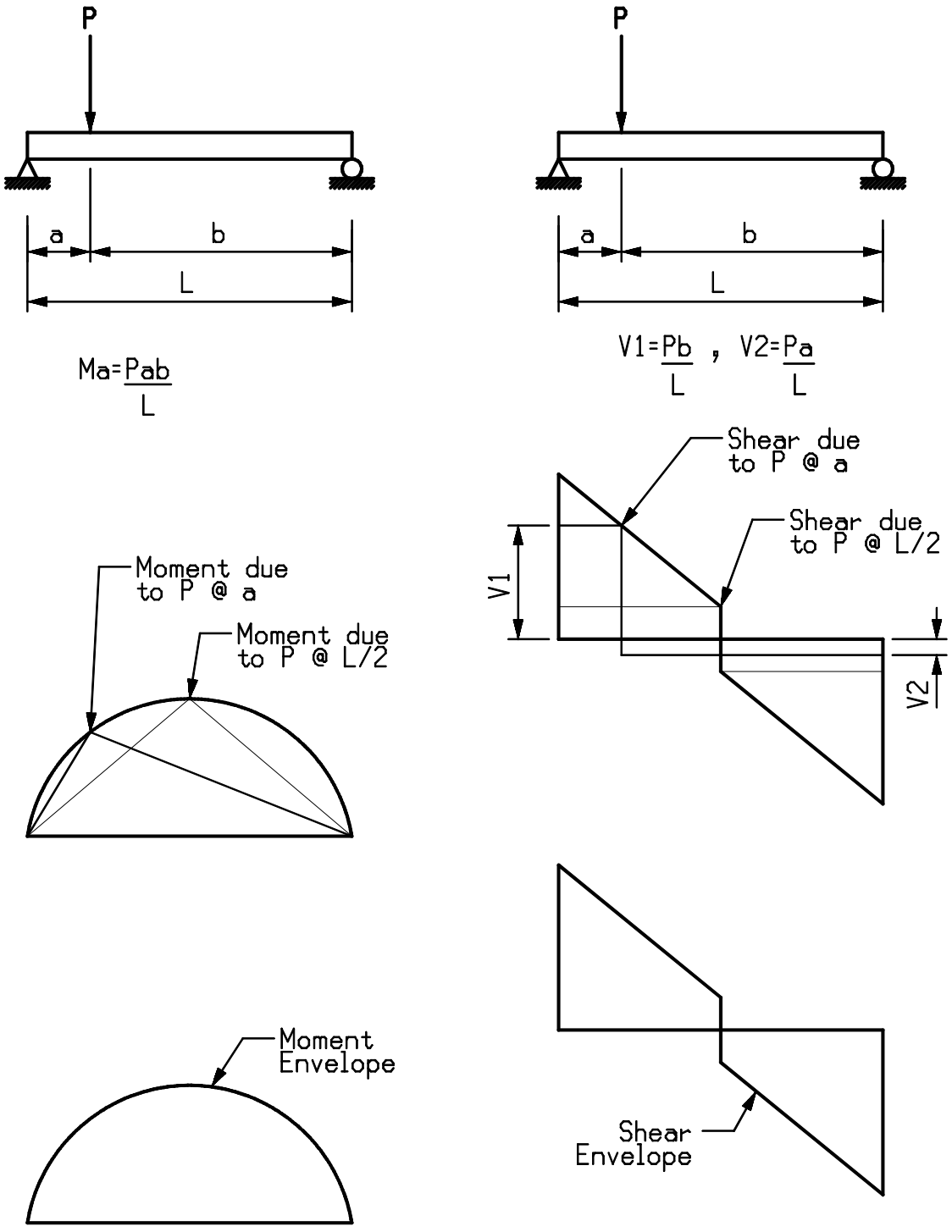


FIGURE 4.4
Example of Moment and Shear Envelopes

Documenting Hand Calculations

Hand calculations should be performed by a competent engineer familiar with bridge design. It is important that hand calculations be neat and orderly and accompanied by references to books, manuals, inspection information, test data or anything that was used to aid in the calculations. Assumptions should be noted to provide clarity. Hand calculations should be checked and ultimately sealed by a Professional Engineer licensed in the state of Michigan. A sample hand calculation is shown in Figure 4.5. When reviewing Figure 4.5, please note that the right edge of the paper is reserved for references to manuals and codes. Also note how results are clearly identified, equations are fully written out and units of measure are clearly labeled.

A summary of results should be prepared at the conclusion of all rating calculations. The summary should contain at a minimum: the inventory and operating capacities of the structure, the controlling member, and a description of any posting that may be required.

Documenting Software

Software can be used to significantly aid in the load rating of bridges. Software is especially useful for continuous or complex bridges. It should be noted that the engineer should be familiar with the capabilities and limitations of the software. When documenting software, the following information should be identified as a minimum: Name of software, version, manufacturer's name and address.

A printout of the final input and output should be included in the file. Important results should be highlighted on the output for easy review. A diskette with the electronic input and output files should be included in the files. Significant limitations that affect the results should be documented.

It is important that the input and output be checked to verify that the software is running correctly. The input should be checked to verify that all parameters are entered correctly. The output should be checked for "reasonableness." The reasonableness check requires a certain level of experience. Also, rough hand calculations can be performed to approximate output values. Software should not be used blindly.

Documenting Assumptions

Any assumptions that are made during load rating should be clearly identified as being such. When possible, assumptions should be accompanied by a brief statement that substantiates the assumption.

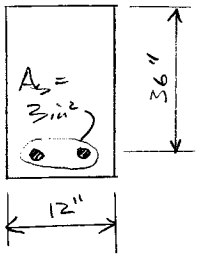
URS

Job MAIN ST. BRIDGE OVER BIG RIVER Project No. _____ Page ____ of ____
Description LOAD RATING Computed by JOHN DOE Sheet ____ of ____
Checked by JANE DOE Date 1/23/01 Date 2/12/01

Reference

BEAM ANALYSIS

SHEAR CAPACITY



$\phi V_n = \phi(V_c + V_s)$ — AASHTO 8.16.6.1.1

No shear reinf' $\Rightarrow V_s = 0$

$\phi V_n = \phi V_c = \phi\, 2\sqrt{f'_c}\, b d$ — AASHTO 8.16.6.2.1

$= 0.85(2)\sqrt{3000}(12")(36")$

$\boxed{\phi V_n = 40224.7 \text{ lbs}}$

MOMENT CAPACITY

$a = \frac{A_s f_y}{0.85 f'_c b} = \frac{3 in^2 (60 ksi)}{0.85(3 ksi)(12")} = 5.9"$ — AASHTO 8.16.3.2.1

check $\epsilon_s > \epsilon_y$, $\epsilon_y = \frac{f_y}{E_s} = \frac{60 ksi}{29000 ksi} = 0.00207$

$c = \frac{a}{\beta_1} = \frac{5.9}{0.85} = 6.9"$ — AASHTO 8.16.2.7

$\epsilon_s = \left(\frac{d-c}{c}\right)\epsilon_u = \left(\frac{36-6.9}{6.9}\right).003 = 0.0127$ — NILSON p80

$\epsilon_s = 0.0127 > \epsilon_y = .00207$ ✓

$\phi M_n = \phi A_s f_y (d - a/2)$ — AASHTO 8.16.3.2.1

$= (0.9)(3 in^2)(60 ksi)(36 - 5.9/2)\ 1/12"$

$\boxed{\phi M_n = 446.2 \text{ k-ft}}$

FIGURE 4.5
Hand Calculation Example

LOAD FACTOR RATING AND LOAD AND RESISTANCE FACTOR RATING

Load Rating Methods

There are three methods for performing load ratings. These methods are Allowable Stress Rating (ASR), Load Factor Rating (LFR) and Load and Resistance Factor Rating (LRFR). ASR is considered to be an obsolete code. While certain existing ratings are acceptable to remain in ASR, this method is only used for new Federal Ratings of policy exceptions such as timber and masonry bridges. LFR is being phased out as the preferred Federal Rating method. LRFR is the preferred Federal Rating method, and will be required on all bridges designed by Load and Resistance Factor Design (LRFD) after October 1st, 2010. Please refer to the Federal Highway Administration (FHWA) Bridge Technology website for further details on this policy (http://www.fhwa.dot.gov/bridge/nbis/103006.cfm)[1]. NBI Item 70, Bridge Posting, and the Michigan Operating Rating may be computed by LRFR, LFR or ASR. It is preferred that LFR is used for structures designed by Allowable Stress Design (ASD) or Load Factor Design (LFD) and LRFR is used for structures designed by LRFD. ASR may be used for timber and masonry.

Design Live Loads

Design live loads are used during the design of a new bridge, and reconstruction or rehabilitation designs. Design live loads are not legal loads. Generally speaking, design axle loads are more severe than legal axle loads and help to provide reasonable factors of safety for slab designs.

The American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges[3] specifies the HS-20 Live Load as the design live load for bridges designed under Allowable Stress Design (ASD) and Load Factor Design (LFD). Please refer to these specifications for details of this design load. HS-20 is used in Load Rating when calculating the Federal Inventory and Operating Rating for bridges analyzed by Allowable Stress Rating (ASR) or Load Factor Rating (LFR). In 1978, the HS-20 load in Michigan was increased by 25% and named HS-25. HS-25 was used for certain routes in Michigan to account for the stress caused by the heaviest legal loads. HS-25 is a design loading only, and is not used in Load Rating.

The HL-93 Live Load is the design live load for bridges designed under Load and Resistance Factor Design (LRFD). Please refer to the latest edition of the AASHTO LRFD Bridge Design Specifications[4] for details of this design load. HL-93 is used in Load Rating when calculating the Federal Inventory and Operating Rating for bridges analyzed by Load and Resistance Factor Rating (LRFR). In 2008, the HL-93 loading configuration was modified slightly, increased by 20% and renamed HL-93-mod. HL-93-mod is used for certain routes in Michigan to account for the stress caused by the heaviest legal and permit loads. HL-93-mod is a design loading only, and is not used in Load Rating.

State Regulations on Legal Loads

The extension of grandfather rights has allowed the states to continue operation of vehicles on state and interstate highways in excess of the limits mandated by federal regulations. These rights allowed individual states continued control of size and weight limits. As a result, each state has a different weight limit "package" consisting of different mixes of these combinations.

Michigan Regulations on Legal Loads

The three levels of Michigan Legal loads are called Normal, Designated and Special Designated, and are described in detail in Chapter 2 of the BAG. **It is the responsibility of the engineer to determine whether Normal, Designated or Special Designated loadings are appropriate for the specific agency/roadway under consideration**. As a majority of roadways in Michigan are Designated, only that loading is listed in this interim update in order to simplify the information contained and to avoid confusion. **Designated loading is not the most conservative loading and the assumption to use Designated loading should not be made on the presence of the loading in the Condensed Guide.**

Figure 2.1 in the Bridge Analysis Guide illustrates common legal vehicles used on Michigan roads (truck numbers 1-28). All of the legal vehicles are used to determine the Michigan Operating Rating and Load Posting Values.

Legal Loads in Other States and Provinces

The engineer should take into account the legal loads in neighboring states and provinces for border bridges. Chapter 3 of the BAG includes information of bordering states and a brief summary of the influence of North America Free Trade Agreement (NAFTA) requirements on bridges.

Load Factor Rating (LFR)

There are four categories of bridge rating for **Load Factor Rating (LFR)**. These four categories use three different groups of live loads.

<u>Federal Inventory Rating</u>

1. HS20 truck or lane load
2. In general, the truck load controls for shorter span lengths and lane load controls for longer lengths
3. For continuous structures, lane loadings may be continuous or discontinuous
4. As many lanes may be loaded as is required to produce the maximum desired effect
5. This rating is performed at the Inventory level

Federal Operating Rating

1. HS20 truck or lane load
2. In general, the truck load controls for shorter span lengths and lane load controls for longer lengths
3. For continuous structures, lane loadings may be continuous or discontinuous
4. As many lanes may be loaded as is required to produce the maximum desired effect
5. This rating is performed at the Operating level

Michigan Operating Rating (Legal or Posting Load Rating)

1. The controlling legal vehicle of the 28 different legal loads. Different vehicles may control different load effects (such as shear or moment). The truck that is recorded should be the truck that produces the lowest load factor for all limit states.
2. As many lanes may be loaded as is required to produce the maximum desired effect
3. Only one standard truck per lane is allowed on a span for spans <200-ft
4. A train of trucks must be applied for spans >200-ft (Chapter 5 of the BAG). A research project is currently in progress to find the appropriate loading configurations for spans between 200-ft and 400-ft and to develop site-specific analysis criteria for spans greater than 400-ft (10-3-2008).
5. The analyst must determine if Normal, Designated, or Special Designated loading applies
6. See Chapter 2 of the BAG for illustrations of the Legal Load vehicle configurations
7. See Chapter 10 of the BAG for tables for all maximum moments and shears for the Legal Load configurations, for simple span lengths between 5-ft and 300-ft
8. If any of the rating factors are below 1, then the lowest tonnage of all vehicles below 1 is the load limit for that Truck Type (1, 2 or 3 Unit)
9. If all vehicles in a particular category (1-unit, 2-unit, 3-unit) can be safely carried by a bridge, the Posting Load will be the largest legal load in that category
10. This rating is performed at the Operating Level

Permit Load Rating (see Chapter 8)

1. This capacity rating is used when a request has been made to transport a load that is not included in the Michigan legal loads
2. The exact load shall be analyzed and that one vehicle placed so as to produce the maximum effect
3. See Chapter 8 of the BAG for a chart illustrating the more common permit type vehicle configurations
4. See Chapter 10 of the BAG for tables for all maximum moments and shears for the more common permit type vehicle configurations, for simple span lengths between 5-ft and 300-ft
5. This rating is performed considering loading of only one lane for Load Factor and Allowable Stress Ratings
6. This rating is performed at the Operating Level

Load and Resistance Factor Rating (LRFR)

Similar to LFR, there are four categories of bridge rating for **Load and Resistance Factor Rating (LRFR)**. These four categories use three different groups of live loads.

Federal Inventory Rating (also called Design Load Rating at Inventory Level)

1. HL-93 loading
2. This load rating is sometimes referred to as a "screening" level for other states, however, **some Michigan Legal Loads exceed this design loading and therefore the Legal Load Rating should always be calculated**.
3. As many lanes may be loaded as is required to produce the maximum desired effect
4. This rating is performed at the Inventory level

Federal Operating Rating (also called Design Load Rating at Operating Level)

1. HL-93 loading
2. As many lanes may be loaded as is required to produce the maximum desired effect
3. This rating is performed at the Operating level

Michigan Operating Rating (Legal or Posting Load Rating)

1. The controlling legal vehicle of the 28 different legal loads. Different vehicles may control different load effects (such as shear or moment). The truck that is recorded should be the truck that produces the lowest load factor for all limit states.
2. The Live Load Factor, γ_L, to be used for the Strength I and II Limit States varies based on the Average Daily Truck Traffic (ADTT) of the structure and the weight of the truck being analyzed. See MDOT Research Report R-1511[5] for more information on the variable load factor. Tables 4a-1 through 4a-3 summarize the Live Load Factors for the Strength I and II Limit States. The Load Factor may be interpolated for a specific ADTT.
3. The Live Load Factor to be used for the Service II Limit State varies based on the weight of the truck being analyzed. Trucks with a Gross Vehicle Weight (GVW) less than 100-kip use a Load Factor of 1.3. Trucks with a GVW greater than or equal to 100-kip use a Load Factor of 1.0 for Service II.
4. As many lanes may be loaded as is required to produce the maximum desired effect.
5. The loading configuration of Legal Loads varies for moments and shear at interior supports as well as for span lengths greater than 200-ft. Table 4a-7 summarizes the loading configurations required to analyze Legal Loads. Spans greater than 400-ft require site-specific analysis. A research project is currently in progress to find the appropriate loading configurations for spans between 200-ft and 400-ft and to develop site-specific analysis criteria for spans greater than 400-ft (10-3-2008).
6. The analyst must determine if Normal, Designated, or Special Designated loading applies.
7. If posting is required, the lightest Posting Loads for each category (1 unit, 2

unit, and 3 unit) must be calculated
8. If all vehicles in a particular category (1-unit, 2-unit, 3-unit) can be safely carried by a bridge, the Posting Load will be the largest legal load in that category

Permit Load Rating

1. This capacity rating is used when a request has been made to transport a load that is not included in the Michigan legal loads
2. There are two levels of Permits identified in LRFR. See Table 6A.4.5.4.2a-1 of the AASHTO Manual for Bridge Evaluation[6] (MBE) for more information. Routine Permits are annual or unlimited permits that are allowed to mix with traffic. Special or Limited Crossings are limited to less than 100 crossings and may or may not be escorted to prevent other vehicles on the structure.
3. Routine Permits should use Strength Limit State Live Load factors, γ_L, as identified in MDOT Research Report R-1511 and as given in Tables 4a-4 through 4a-6, based upon ADTT and GVW. The load factor may be interpolated for a specific ADTT. These permits are based on as many lanes loaded as would produce the maximum effect.
4. Special or Limited Crossing Permits may use the Strength Limit State Live Load factors given in Table 6A.4.5.4.2a-1 of the MBE. These permits are based on single lane loading.
5. The Live Load Factor to be used for the Service II Limit State varies based on the weight of the truck being analyzed. Trucks with a Gross Vehicle Weight (GVW) less than 100-kip use a Load Factor of 1.3. Trucks with a GVW greater than or equal to 100-kip use a Load Factor of 1.0 for Service II Limit State.
6. See Chapter 8 of the BAG for a chart illustrating the more common permit type vehicle configurations
7. See Chapter 10 of the BAG for tables for all maximum moments and shears for the more common permit type vehicle configurations, for simple span lengths between 5-ft and 300-ft
8. The loading configuration of Legal Loads varies for moments and shear at interior supports as well as for span lengths greater than 200-ft. Table A-9 summarizes the loading configurations required to analyze Permit Loads. Spans greater than 400-ft require site-specific analysis. A research project is currently in progress to find the appropriate loading configurations for spans between 200-ft and 400-ft and to develop site-specific analysis criteria for spans greater than 400-ft (10-3-2008).

Michigan Legal Vehicle Load Factors for Strength Limit States, 5000 ADTT						
	Normal Loading		Designated Loading		Special Designated Loading	
Truck	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}
1	33.4	1.80	33.4	1.80	39.0	1.80
2	41.4	1.80	47.4	1.80	45.4	1.80
3	54.4	1.80	54.4	1.80	54.4	1.80
4	67.4	1.80	67.4	1.80	67.4	1.80
5	78.0	1.80	84.0	1.75	84.0	1.75
6	95.4	1.61	101.4	1.54	101.4	1.54
7	113.4	1.44	119.4	1.39	119.4	1.39
8	85.4	1.73	91.4	1.65	91.4	1.65
9	51.4	1.80	51.4	1.80	49.5	1.80
10	59.4	1.80	65.4	1.80	56.4	1.80
11	77.4	1.80	83.4	1.76	67.1	1.80
12	111.4	1.45	117.4	1.41	117.4	1.41
13	119.4	1.39	125.4	1.35	125.4	1.35
14	132.4	1.31	132.4	1.31	132.4	1.31
15	137.4	1.28	143.3	1.25	143.3	1.25
16	132.4	1.31	138.4	1.28	138.4	1.28
17	145.4	1.24	151.4	1.21	151.4	1.21
18	148.0	1.23	154.0	1.20	154.0	1.20
19	111.4	1.45	117.4	1.41	117.4	1.41
20	87.4	1.71	87.4	1.71	87.4	1.71
21	145.4	1.24	151.4	1.21	151.4	1.21
22	155.4	1.20	161.4	1.17	161.4	1.17
23	148.0	1.23	154.0	1.20	154.0	1.20
24	116.0	1.42	122.0	1.37	122.0	1.37
25	158.0	1.18	164.0	1.16	164.0	1.16
26	50.0	1.80	50.0	1.80	50.0	1.80
27	72.0	1.80	72.0	1.80	72.0	1.80
28	80.0	1.80	80.0	1.80	80.0	1.80

Table 4a-1

Michigan Legal Vehicle Load Factors for Strength Limit States, 1000 ADTT						
	Normal Loading		Designated Loading		Special Designated Loading	
Truck	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}
1	33.4	1.65	33.4	1.65	39.0	1.65
2	41.4	1.65	47.4	1.65	45.4	1.65
3	54.4	1.65	54.4	1.65	54.4	1.65
4	67.4	1.65	67.4	1.65	67.4	1.65
5	78.0	1.65	84.0	1.65	84.0	1.65
6	95.4	1.57	101.4	1.51	101.4	1.51
7	113.4	1.40	119.4	1.36	119.4	1.36
8	85.4	1.65	91.4	1.61	91.4	1.61
9	51.4	1.65	51.4	1.65	49.5	1.65
10	59.4	1.65	65.4	1.65	56.4	1.65
11	77.4	1.65	83.4	1.65	67.1	1.65
12	111.4	1.42	117.4	1.37	117.4	1.37
13	119.4	1.36	125.4	1.32	125.4	1.32
14	132.4	1.28	132.4	1.28	132.4	1.28
15	137.4	1.25	143.3	1.22	143.3	1.22
16	132.4	1.28	138.4	1.25	138.4	1.25
17	145.4	1.21	151.4	1.19	151.4	1.19
18	148.0	1.20	154.0	1.18	154.0	1.18
19	111.4	1.42	117.4	1.37	117.4	1.37
20	87.4	1.65	87.4	1.65	87.4	1.65
21	145.4	1.21	151.4	1.19	151.4	1.19
22	155.4	1.17	161.4	1.15	161.4	1.15
23	148.0	1.20	154.0	1.18	154.0	1.18
24	116.0	1.38	122.0	1.34	122.0	1.34
25	158.0	1.16	164.0	1.14	164.0	1.14
26	50.0	1.65	50.0	1.65	50.0	1.65
27	72.0	1.65	72.0	1.65	72.0	1.65
28	80.0	1.65	80.0	1.65	80.0	1.65

Table 4a-2

Michigan Legal Vehicle Load Factors for Strength Limit States, 100 ADTT						
	Normal Loading		Designated Loading		Special Designated Loading	
Truck	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}
1	33.4	1.40	33.4	1.40	39.0	1.40
2	41.4	1.40	47.4	1.40	45.4	1.40
3	54.4	1.40	54.4	1.40	54.4	1.40
4	67.4	1.40	67.4	1.40	67.4	1.40
5	78.0	1.40	84.0	1.40	84.0	1.40
6	95.4	1.40	101.4	1.40	101.4	1.40
7	113.4	1.35	119.4	1.31	119.4	1.31
8	85.4	1.40	91.4	1.40	91.4	1.40
9	51.4	1.40	51.4	1.40	49.5	1.40
10	59.4	1.40	65.4	1.40	56.4	1.40
11	77.4	1.40	83.4	1.40	67.1	1.40
12	111.4	1.36	117.4	1.32	117.4	1.32
13	119.4	1.31	125.4	1.27	125.4	1.27
14	132.4	1.23	132.4	1.23	132.4	1.23
15	137.4	1.21	143.3	1.18	143.3	1.18
16	132.4	1.23	138.4	1.20	138.4	1.20
17	145.4	1.17	151.4	1.14	151.4	1.14
18	148.0	1.16	154.0	1.13	154.0	1.13
19	111.4	1.36	117.4	1.32	117.4	1.32
20	87.4	1.40	87.4	1.40	87.4	1.40
21	145.4	1.17	151.4	1.14	151.4	1.14
22	155.4	1.13	161.4	1.11	161.4	1.11
23	148.0	1.16	154.0	1.13	154.0	1.13
24	116.0	1.33	122.0	1.29	122.0	1.29
25	158.0	1.12	164.0	1.10	164.0	1.10
26	50.0	1.40	50.0	1.40	50.0	1.40
27	72.0	1.40	72.0	1.40	72.0	1.40
28	80.0	1.40	80.0	1.40	80.0	1.40

Table 4a-3

Overload Class Vehicle Load Factors for Strength Limit States, Annual Permits, 5000 ADTT						
	Class A		Class B		Class C	
Truck	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}
1	120.0	1.39	120.0	1.39	120.0	1.39
2	120.0	1.39	120.0	1.39	120.0	1.39
3	120.0	1.39	118.0	1.40	114.0	1.43
4	120.0	1.39	108.0	1.48	98.0	1.58
5	120.0	1.39	104.0	1.52	88.0	1.70
6	126.0	1.35	108.0	1.48	90.0	1.67
7	138.0	1.28	114.0	1.43	93.0	1.64
8	149.6	1.22	127.6	1.34	105.6	1.50
9	158.4	1.18	129.6	1.33	105.6	1.50
10	177.0	1.12	146.4	1.24	122.0	1.37
11	180.0	1.11	159.0	1.18	138.0	1.28
12	190.6	1.10	160.2	1.18	134.4	1.30
13	195.0	1.10	168.8	1.14	147.4	1.23
14	211.2	1.10	179.2	1.11	153.6	1.20
15	238.0	1.10	204.0	1.10	170.0	1.14
16	244.4	1.10	203.6	1.10	173.0	1.13
17	272.6	1.10	232.4	1.10	182.8	1.10
18	283.4	1.10	241.6	1.10	200.0	1.10
19	277.2	1.10	234.4	1.10	200.8	1.10
20	264.0	1.10	225.8	1.10	191.4	1.10

Table 4a-4

Overload Class Vehicle Load Factors for Strength Limit States, Annual Permits, 1000 ADTT						
	Class A		Class B		Class C	
Truck	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}
1	120.0	1.36	120.0	1.36	120.0	1.36
2	120.0	1.36	120.0	1.36	120.0	1.36
3	120.0	1.36	118.0	1.37	114.0	1.40
4	120.0	1.36	108.0	1.45	98.0	1.54
5	120.0	1.36	104.0	1.48	88.0	1.65
6	126.0	1.32	108.0	1.45	90.0	1.63
7	138.0	1.25	114.0	1.40	93.0	1.59
8	149.6	1.19	127.6	1.31	105.6	1.47
9	158.4	1.16	129.6	1.30	105.6	1.47
10	177.0	1.10	146.4	1.21	122.0	1.34
11	180.0	1.10	159.0	1.16	138.0	1.25
12	190.6	1.10	160.2	1.15	134.4	1.27
13	195.0	1.10	168.8	1.12	147.4	1.20
14	211.2	1.10	179.2	1.10	153.6	1.18
15	238.0	1.10	204.0	1.10	170.0	1.12
16	244.4	1.10	203.6	1.10	173.0	1.11
17	272.6	1.10	232.4	1.10	182.8	1.10
18	283.4	1.10	241.6	1.10	200.0	1.10
19	277.2	1.10	234.4	1.10	200.8	1.10
20	264.0	1.10	225.8	1.10	191.4	1.10

Table 4a-5

Overload Class Vehicle Load Factors for Strength Limit States, Annual Permits, 100 ADTT						
	Class A		Class B		Class C	
Truck	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}	GVW (kips)	Load Factor, γ_{LL}
1	120.0	1.30	120.0	1.30	120.0	1.30
2	120.0	1.30	120.0	1.30	120.0	1.30
3	120.0	1.30	118.0	1.32	114.0	1.34
4	120.0	1.30	108.0	1.39	98.0	1.40
5	120.0	1.30	104.0	1.40	88.0	1.40
6	126.0	1.27	108.0	1.39	90.0	1.40
7	138.0	1.20	114.0	1.34	93.0	1.40
8	149.6	1.15	127.6	1.26	105.6	1.40
9	158.4	1.12	129.6	1.25	105.6	1.40
10	177.0	1.10	146.4	1.16	122.0	1.29
11	180.0	1.10	159.0	1.12	138.0	1.20
12	190.6	1.10	160.2	1.11	134.4	1.22
13	195.0	1.10	168.8	1.10	147.4	1.16
14	211.2	1.10	179.2	1.10	153.6	1.14
15	238.0	1.10	204.0	1.10	170.0	1.10
16	244.4	1.10	203.6	1.10	173.0	1.10
17	272.6	1.10	232.4	1.10	182.8	1.10
18	283.4	1.10	241.6	1.10	200.0	1.10
19	277.2	1.10	234.4	1.10	200.8	1.10
20	264.0	1.10	225.8	1.10	191.4	1.10

Table 4a-6

Span Length	Load Effect	Legal Trucks GVW ≤ 100-kips	Legal-Heavy Trucks GVW > 100-kips and Permit Trucks
L≤200-ft	Positive Moment and Reactions at Exterior Supports	Truck + Impact	Truck + Impact
	Negative Moment and Reactions at Interior Supports	0.75*(Two Trucks Spaced 30-ft Apart + Impact) + 0.2-klf	(Truck + Impact) + 0.2-klf
200-ft<L≤400-ft	Positive Moment and Reactions at Exterior Supports	0.75*(Truck + Impact) + 0.2-klf	(Truck + Impact) + 0.2-klf
	Negative Moment and Reactions at Interior Supports	0.75*(Two Trucks Spaced 30-ft Apart + Impact) + 0.2-klf	(Truck + Impact) + 0.2-klf

Table 4a-7
LRFR Loading Configurations for Legal, Legal-Heavy and Permit Loads

References

1. Lwin, M. (2006). *INFORMATION: Bridge Load Ratings for the National Bridge Inventory*. Federal Highway Administration. October 30, 2006. http://www.fhwa.dot.gov/bridge/nbis/103006.cfm.

2. AASHTO (2002). *Standard Specifications for Highway Bridge Design, 17th Edition*. Washington, DC.

3. AASHTO (2008). *LRFD Bridge Design Specifications, 4th Edition*. Washington, DC.

4. AASHTO (1994). *Manual for Condition Evaluation of Bridges, 4th Edition*. Washington, DC.

5. Curtis, R., and Till, R. (2008). *Recommendations for MI Specific Load and Resistance Factor Design Loads and Load and Resistance Factor Rating Procedures*. R-1511. Michigan Department of Transportation. http://www.michigan.gov/documents/mdot/MDOT_Research_Report_R1511_233374_7.pdf.

6. AASHTO (2008). *The Manual for Bridge Evaluation*. American Association of State Highway and Transportation Officials. Washington, D.C.

Chapter 5

ANALYSIS VEHICLE SELECTION

June 30, 2006

ANALYSIS VEHICLE SELECTION

Summary of Vehicle Selection Concepts

The intent of this chapter is to aid in vehicle selection and vehicle placement in order to generate maximum live load moments and shears as part of the load rating process.

Determining the appropriate vehicle for load rating of bridges can be a time consuming effort. In general, for short span bridges, individual axle loads and spacings are very critical. As spans increase in length, the individual axles of a vehicle become less significant while the vehicle's gross weight becomes more critical in generating maximum effects. Chapter 4 of this Guide addresses the placement of vehicles to create maximum moments and shears. In addition, many structural engineering text books give a methodology for placement of moving loads.

Vehicle Selection Guidelines

There are five general categories of bridge rating discussed in the Guide. These five categories use three different groups of live loads.

Inventory Rating and Federal Operating Rating.

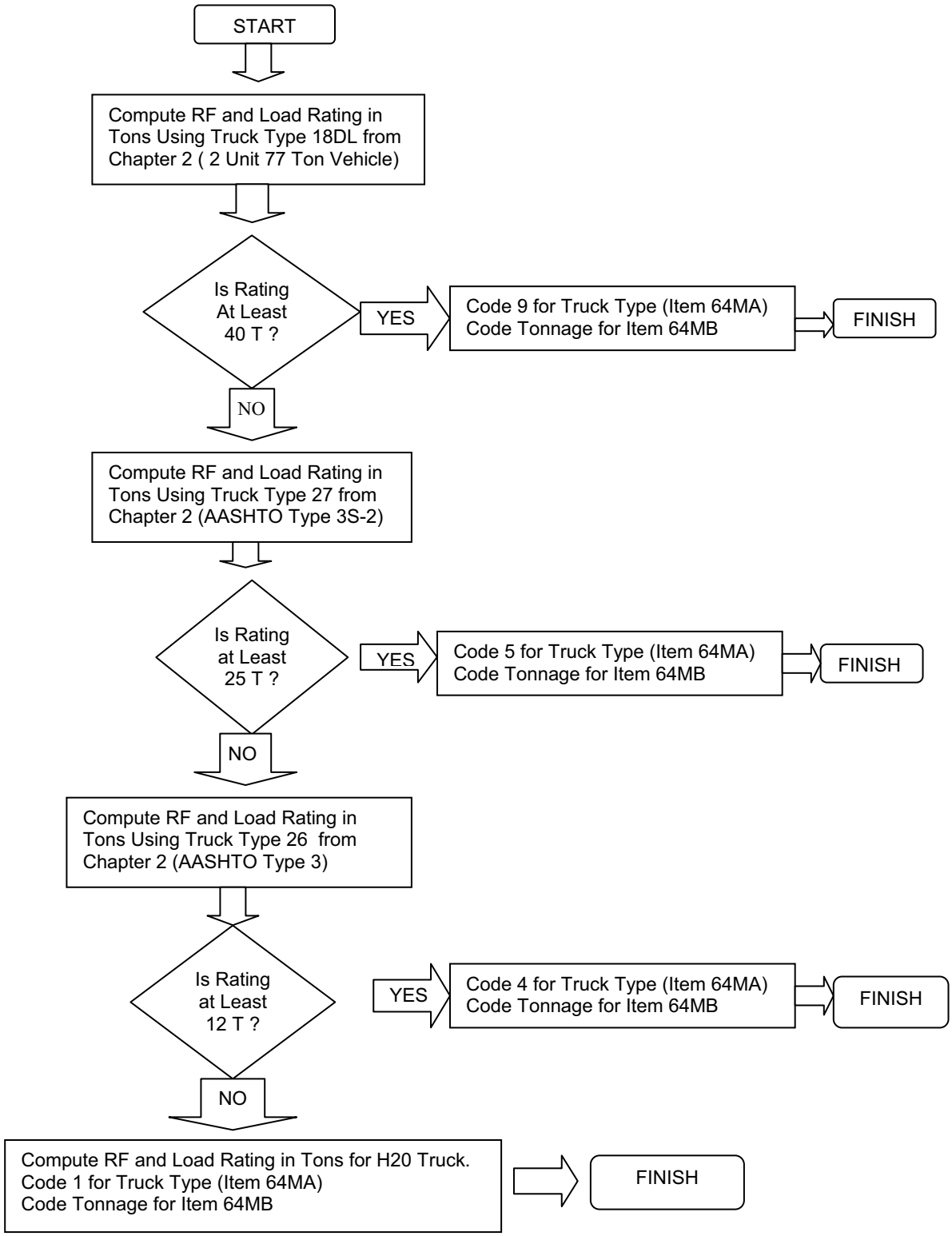
For both of the above ratings, the live load used to rate each structure is to be HS20 truck or lane load as defined in the AASHTO Design Specifications, and as shown in Figure 2.2.

In general, the truck load controls for shorter span lengths and lane load controls for longer lengths. Lane loadings may be continuous or discontinuous. Only one standard truck per lane is allowed on a span. As many lanes may be loaded as is required to produce the maximum desired affect. See Chapter 10 for a complete listing of maximum moments and shears for all span lengths between 5' and 300'.

Michigan Operating Rating.

The purpose of the Michigan Operating Rating is to provide a fairly uniform performance measure of the structure's load carrying capacity relative to the unique legal loads in Michigan. A convention has been used to determine which vehicle to select for reporting this bridge capacity in the Michigan Bridge Inventory. This convention is more easily understood by following the flowchart on the following page.

TRUCK SELECTION FOR MICHIGAN OPERATING RATING



For spans less than 200' in length, the vehicles shall be applied one per lane, with as many lanes loaded as is required to produce the maximum desired affect.

For spans 200' and greater, one lane shall be occupied by a train of any of the legal vehicles described above with a nose to tail spacing of 30 feet. This train can be idealized as a distributed load specific to each vehicle type. See Figure 2.2 for distributed load values of the equivalent train load for each vehicle. Additional lanes shall be loaded with one legal vehicle (the same legal vehicle as is used for the equivalent train load) per lane, with as many lanes loaded as is required to produce the maximum desired affect. For the circumstance where live load varies between adjacent lanes, standard live load distribution factors for interior beams are not applicable. See chapter 6 for live load distribution for this circumstance.

Posting Load Rating.

The live load used to rate each structure is to be any and all of the state legal vehicles and the three AASHTO legal vehicles, as shown in Figure 2.1.

The methods presented in this Bridge Analysis Guide contain a significant change in process for calculating the Posting Loads for bridges. This is due to a careful examination of the effects caused by the large number of legal axles configurations and axle weights allowed by Michigan law. The truck figures shown in Chapter 2 illustrate the legal configurations of 1-unit, 2-unit and 3-unit vehicles allowed in Michigan.

The analyst must determine the legal loads allowed by the jurisdiction for the bridge being investigated. In general, counties and cities in Michigan allow Designated Loading on their roads and bridges, so the following discussion is limited to Designated Loading. If a particular agency allows only Normal Loading, or allows Special Designated Loading, the process described below remains the same, however tables for Normal Loads or Special Designated Loads would be used.

When calculating the Posting Load Rating for a particular structure, after finding the live load capacity of a particular bridge, it may be found that many, or even all of the legal loads can not be safely carried by that bridge.

Using 1-unit vehicles shown in Chapter 2 as an example, the analyst will note that there are five different configurations of Michigan Legal Loads and an AASHTO 1-unit load (which is also legal in Michigan) for a total of six configurations. If for a particular bridge, it is found that any of these trucks can not be safely carried, it is then important to find which Michigan Legal Load should be used to calculate the Posting Load Rating. Each of the legal vehicles could be used to calculate this Rating Load and the Rating Load calculated based on each vehicle would be different.

A study has shown that for every span and capacity circumstance there is one truck that will yield the lightest Posting Load Rating. It is important to identify and use this particular “controlling vehicle” to calculate the Posting Load. This is important since

truck operators, in general, do not know which of the 6 legal 1-unit vehicles they are driving, nor should they be asked to stop and make this determination before crossing a posted bridge. It would also be impractical to prepare posting signs for all six 1-unit vehicles, plus all 15 2-unit vehicles, plus all seven 3-unit vehicles.

To aid in determining which of the 1-unit trucks is the “controlling” vehicle, tables are available in Chapter 10 which list the moment and shear for every legal vehicle and for all span lengths between 5' and 300'. In addition to the live load moment, a value for Moment divided by Weight has been calculated for each of these combinations. To determine the “controlling” vehicle, the analyst should examine the values for the variable Moment divided by Weight for all vehicles which exceed the capacity of the section in question. The vehicle with the largest value for Moment/Weight is the “controlling” vehicle and should be used to determine the Posting Load. The same statements are true for shear analysis.

The same statements and methods apply to 2-unit and 3-unit vehicles. See the general example included in Chapter 9 for more clarity regarding the method for determining the “controlling” vehicle.

In the circumstance where all vehicles in a particular category (1-unit, 2-unit, 3-unit) can be safely carried by a bridge, the Posting Load will be the largest legal load in that category. In this circumstance, Posting would only be required if all vehicles in another category could not be safely carried by the bridge.

It must be noted that the above method is only applicable for simply supported beams. For bridges with continuous beams, it will be necessary to evaluate the effects caused by each of the legal vehicles in order to determine which vehicle will control the Posting Loads.

For spans less than 200' in length, the vehicles shall be applied one per lane, with as many lanes loaded as is required to produce the maximum desired affect.

For spans 200' and greater, one lane shall be occupied by a train of any of the legal vehicles described above with a nose to tail spacing of 30 feet. This train can be idealized as a distributed load specific to each vehicle type. See Figure 2.2 for distributed load values of the equivalent train load for each vehicle. Additional lanes shall be loaded with one legal vehicle (the same legal vehicle as is used for the equivalent train load) per lane, with as many lanes loaded as is required to produce the maximum desired affect. For the circumstance where live load varies between adjacent lanes, standard live load distribution factors for interior beams are not applicable. See chapter 6 for live load distribution for this circumstance.

Permit Load Rating.

This capacity rating is used when a request has been made to transport a load that is not included in the Michigan legal loads. The load to be carried may have heavier axles or more closely spaced axles than allowed by law, larger gross weight than allowed by law, or a combination of these features. The load to be used for analysis should be the exact load requested to be transported, with that one vehicle placed so as to produce the maximum desired effect. For permit rating, the bridge capacity can be evaluated at the operating level.

See Chapter 8 for a chart illustrating the more common permit type vehicle configurations. See Chapter 10 for tables for all maximum moments and shears for these loads, for span lengths between 5' and 300'.

Chapter 6

LIVE LOAD DISTRIBUTION

April 3, 2009

LIVE LOAD DISTRIBUTION

General

The intent of this chapter is to provide the user with guidance in the selection and application of live load distribution factors for the purpose of determining design shears and moments in stringers and beams providing support for bridge deck systems. This chapter has been developed on the premise that the user has an understanding of the AASHTO bridge code(s) and that these references are readily available.

These recommendations utilize current AASHTO guidelines supplemented by existing MDOT- approved practice for structure types not specifically covered in the bridge code. Distribution factors provided within this document are in accordance with the provisions of Chapter 6 of the AASHTO *Manual for Condition Evaluation of Bridges, 1994 Second Edition* with current interim specifications and the AASHTO *Standard Specifications for Highway Bridges, Sixteenth Edition, 1996* with current interim specifications, References 1 and 2, respectively.

Load Factor rating procedures are implemented to obtain ratings consistent with established MDOT practice and to comply with FHWA National Bridge Inventory (NBI) requirements. Load and Resistance Factor Rating procedures are still being studied and developed by AASHTO at this time, and should not be implemented beyond the scope as prescribed below. For other information on this topic, see Chapters 4 and 5 of Reference 3, References 4, and Reference 10.

The analyst may be confronted with situations where live load distribution factors derived in accordance with Article 3.23 of the AASHTO LF Code will lead to an analysis that shows that the supporting members can not safely carry all legal loads at the operating level (rating factor < 1.0). In that case, the analyst, and/or agency, may choose to implement one or a combination of other more refined methods to obtain load distribution factors that more accurately reflect the true behavior of the structure. These alternate methods are listed and described below.

Although the primary method illustrated in this Guide is Load Factor, for the circumstances mentioned here, live load distribution by LRFD is also discussed in this chapter. Recommendations to utilize LRFD derived distribution factors in conjunction with LF rating procedures are supported by research conducted by the University of Michigan Department of Civil Engineering for the Michigan Department of Transportation.

Applicability

Application of the information and methods in this chapter is limited to structures for which load distribution takes place mainly through flexure and torsion in the longitudinal and transverse directions, with deflections due to shear being negligible. Bridge types that satisfy this criteria are defined as *shallow superstructure* bridges, and include the solid slab, voided slab, and slab-on-girder bridges. In contrast, multicell box girder

bridges exhibit significant shear deformation, which is accompanied by bending of the top and bottom flanges about their own centerlines. For this reason, if similar orthotropic plate theory is to be implemented in determining structural behavior, a provision must be included to account for shear deformation.

The simplified method of applying a factor to determine the transverse distribution of live load, known as the D-Type Method, was developed by idealizing bridges as orthotropic plates. To satisfactorily idealize a bridge as an orthotropic plate, it must reasonably satisfy the following conditions:

1. The width is constant.
2. Line support conditions exist.
3. Skew angle does not exceed 20 degrees.
4. Curvature is negligible; $L^2/bR < 1.0$

where: L = Bridge Length

R = radius of curvature measured to the bridge centerline, and
b = (½)(Deck Width).

5. A solid or voided slab bridge is of uniform depth across the section.
6. Slab-on-girder bridges are made up of at least four parallel prismatic beams of similar stiffness.
7. The deck overhang for slab-on-girder bridges does not exceed 60 percent of the spacing between the girders.

For more information on this topic see Reference 24.

Limitations/Exclusions

The AASHTO LF code prescribed methods used to determine the transverse distribution of wheel loads are empirically derived and have been developed to *conservatively* encompass a broad range of basic superstructure types and geometry. Analysis of structurally and/or geometrically complex bridges is beyond the scope of this report. For examples of complex bridge types see Ref 1, section 6.1.6. These structures must be evaluated on a case-by-case basis using advanced modeling techniques or other owner approved methods. As noted above, should it become necessary to predict structural capacity with greater precision to evaluate marginal structures, those with a rating factor slightly less than 1.0, the AASHTO LRFD Bridge Design Specifications provide a more refined approach to accomplish this objective. Guidelines and limitations for the implementation of the LRFD specifications are presented in the final section of this chapter. Other, still more highly refined methods, which include three-dimensional modeling or field testing may be utilized to more accurately determine capacity for structures deemed marginal.

Alternate Methods for Determining Live Load Distribution

- **LRFD Live Load Distribution Factors**. MDOT has sponsored load testing of several bridges on the trunkline system, with one objective being to obtain live load distribution factors that more accurately reflect how loads are distributed in the transverse direction. Full reports of these research efforts are contained in References 27, 28 and 29. The structures examined were all composite slab-on-steel beam bridges with skew angles not exceeding 30 degrees. Beam spacing for these bridges ranged from 4'-4" to 9'-4", and span lengths ranged from 32 feet to 140 feet.

  One of the conclusions and recommendations provided by this series of reports is that AASHTO LRFD live load distribution methods may be used in conjunction with LFD analytic techniques for rating those bridges which are similar in structure type and fall within the skew, span length, and beam spacing limits considered in the studies. MDOT supports, and has adopted the above live load distribution recommendation.

- **Refined Analytical Methods**. Other analytical methods which may be implemented to obtain results that more accurately reflect the true bridge capacity include Finite Element Analysis and Grillage Analysis. Great care must be exercised when creating these models to ensure that the boundary conditions and model geometry are correct and that loads are place at positions that produce the maximum response in the components being investigated. Guidelines for detailed analysis of bridge decks and sample problems to illustrate their application are given in Appendix H of NCHRP Project 12-26 final report. Reference 17.

- **Load Testing**. In some cases, it may prove to be more economical to load test a particular bridge (or group of bridges) rather than to post the bridge for restricted loads, or to reconstruct the bridge in question. The analyst should confer with the owning agency to determine if load testing is economically appropriate for marginal structures. References 26 and 31 may prove useful in understanding the load testing process.

Distribution of Loads - Load Factor

General

The fraction of vehicle load effect transferred to a single member should be selected in accordance with the current AASHTO LFD Code (Ref 2, Article 3.23). These values represent a possible combination of diverse circumstances. The option exists to substitute field measured values, analytically calculated values or those determined from advanced structural analysis methods utilizing the properties of the existing span(s). During the implementation of any one of these methods, the position of loading shall be investigated to provide the condition causing the maximum response in the components being evaluated.

Impact, I, shall be added to the live load used for rating in accordance with the current AASHTO LFD Code. Specification impact may be reduced when conditions of alignment, enforced speed posting, and similar situations require a vehicle to substantially reduce speed in crossing the structure.

Distribution of Live Load - Inventory Loads

Inventory loads shall be distributed in accordance with Tables 6.1 and 6.2 below.

Distribution of Live Load - Operating Loads

In general, operating loads shall be distributed in accordance with Tables 6.1 and 6.2 below. In that circumstance where spans greater than 200' are to be rated, and an equivalent distributed load occupies one lane and a vehicle load occupies one or more adjacent lanes, standard live load distribution factors for interior beams are not applicable. For this case live load moment must be calculated by either distributing the equivalent distributed load and the adjacent vehicle loads using the lever rule or by more detailed analytical methods.

Distribution of Live Load - Permit Loads

Permit loads shall be distributed in accordance with Tables 6.1 and 6.2 below. The use of the live load distribution factor for one loaded lane (clear deck width less than 18') is appropriate.

Live Load Distribution Factors - General

The information provided in Tables 6.1 and 6.2 that follow has been derived from Article 3.23 of the AASHTO LF code and supplemented by the 1983 MDOT Bridge Analysis Guide for structure types common to the state of Michigan that are not specifically addressed by AASHTO. *The live load distribution factors provided herein are in terms of number of lanes per girder as opposed to the wheel lines per girder convention used in the AASHTO LF code; i.e. (S/5.5 wheel lines per girder) x (1 lane/2 wheel lines) = S/11.0 lanes per girder.*

The user is cautioned to refer to AASHTO Articles 3.11 and 3.12 for guidelines defining the application of live load and reductions in load intensity. Regarding the latter, Article 3.12.2 of the 1999 interim specifications states that reductions in load intensity shall not be applied when the distribution factors of Table 6.1 are used to determine moments in longitudinal beams.

For the purpose of this document, and in accordance with the AASHTO code, the following definitions apply:

Concrete Box Girder:
a. Precast solid, voided or cellular adjacent concrete boxes with shear keys and a cast-in-place concrete overlay.

b. Precast solid, voided or cellular adjacent concrete boxes with shear keys, no concrete overlay, and with or without transverse post-tensioning.

Concrete Spread Box Beams: Closed precast concrete boxes positioned with a space between interior webs supporting a cast-in-place concrete slab.

Floor Beam: Transverse beam spanning between main longitudinal members.

Longitudinal: In the direction of traffic flow.

Longitudinal Beam: Primary load carrying member supporting the floor system.

Stringer: Longitudinal beam spanning between floor beams.

Distribution of Live Load to Interior Stringers and Beams

In calculating bending moments in longitudinal stringers or beams, no longitudinal distribution of axle or truck loads shall be assumed, i.e. axle loads are considered to be “point” loads. The lateral distribution of load used to determine live load bending moment shall be determined by applying to the stringer or beam the fraction of truck or lane loads determined in Table 6.1 that follows.

The distribution values contained in Table 6.1 pertain to inventory, operating and permit ratings.

DECK TYPE	BEAM TYPE	CLEAR DECK WIDTH LESS THAN 18'	CLEAR DECK WIDTH 18' AND GREATER
Timbera plank[b]	All beam types	S/8	S/7.5
Timber[a] nail laminated[c] 4" thick or multiple layer[d] floors over 5" thick		S/9	S/8
Timber[a] nail laminated[c] 6" or more thick		S/10 If S>5' use footnote f	S/8.5 If S>6.5' use footnote f
Glued laminated[e] panel 4" thick	Glued laminated stringer	S/9	S/8
Glued laminated[e] panel 6" or more thick		S/12 If S>6' use footnote f	S/10 If S.7.5' use footnote f
Glued laminated[e] panel 4" thick	Steel stringer	S/9	S/8
Glued laminated[e] panel 6" or more thick		S/10.5 If S>5.5' use footnote f	S/9 If S>7' use footnote f
Concrete	Steel I-Beam stringers[g] and prestressed concrete girders	S/14 If S>10' use footnote f	S/11 if S>14' use footnote f
	Concrete T-Beams	S/13 If S>6' use footnote f	S/12 If S>10' use footnote f
	Timber stringers	S/12 If S>6' use footnote f	S/10 If S>10' use footnote f
	Concrete box girders[h]	S/16 If S>12' use footnote f	S/14 If S>16' use footnote f
	Steel box girder	See AASHTO Std. Spec. Section 10.39.2	
	Prestressed concrete spread box beams	See AASHTO Std. Spec. Section 3.28	
Steel grid less than 4" thick	All beam types	S/9	S/8
Steel grid 4" or more thick		S/12 If S>6' use footnote f	S/10 if S>10.5' use footnote f
Steel bridge corrugated plank[i] (2" minimum depth)	All beam types	S/11	S/9
Concrete Jack Arch or Encased Beams[j] with or without tie rods	Steel Stringer	S/10	S/8

TABLE 6.1
Distribution of Lane Loads in Interior Longitudinal Beams

Table 6.1 Notes:

S = Average Girder Spacing in Feet

a. Timber dimensions shown are nominal thickness.

b. Plank floors consist of pieces of lumber laid edge to edge with the wide faces bearing on the supports.

c. Nail laminated floors consist of pieces of lumber laid face to face with the narrow edges bearing on the supports, each piece being nailed top the preceding piece.

d. Multiple layer floors consist of two or more layers of planks, each layer being laid at an edge angle to the other.

e. Glued laminated panel floors consist of vertically glued laminated members with the narrow edges of the laminations bearing on the supports.

f. In this case the load on each stringer shall be the reaction of the live load assuming the flooring between the stringers to act as a simple beam.

g. “Design of I-Beam Bridges” by N. M. Newmark–Proceedings, ASCE, March 1948.

h. The sidewalk live load shall be omitted for interior and exterior box girders designed in accordance with the wheel load distribution indicated herein.

i. Distribution factors for Steel Bridge Corrugated Plank set forth above are based substantially on the following reference:Journal of Washington Academy of Sciences, Vol. 67, No. 2, 1977 “Wheel Load Distribution of Steel Bridge Plank,” by Conrad P. Heins, Professor of Civil Engineering, University of Maryland. These distribution factors were developed based on studies using 6"x2" steel corrugated plank. The factors should yield safe results for other corrugated configurations provided primary bending stiffness is the same or greater than the 6"x2" corrugated plank used in the studies.

j. Table 1 of the 1983 MDOT Bridge Analysis Guide. (Ref 8)

Distribution of Live Load to Exterior Stringers and Beams (Ref. 2, Article 3.23.2.3)

Steel - Timber - Concrete T-Beams

The live load bending moment for outside stringers or beams shall be determined by applying to the stringer or beam the reaction of the wheel load obtained by applying the Lever Rule. Note that computations should be carried out in terms of number of wheels per girder and multiplied by a factor of 1/2 (1 lane/2 wheels) to obtain number of lanes per girder. The requirement of an exterior stringer having at least the carrying capacity equal to that of an interior stringer is an important design consideration, but is optional for load rating calculations.

Concrete Box Girders

The factor for the lane load distribution to the exterior girder shall be $W_e/14$, where W_e is the width of exterior girder that shall be taken as top slab width, measured from the midpoint between girders to the outside edge of the slab.

Distribution of Live Load to Transverse Floor Beams

In calculating bending moments in transverse floor beams, no transverse distribution of wheel load shall be assumed in a manner similar to the assumption that no longitudinal distribution of wheel load is considered in computing bending moments in longitudinal beams (Ref 2, Article 3.23.2.1).

If longitudinal stringers are omitted and the floor is supported directly on the floor beams, the beams shall be designed for loads determined in accordance with Table 6.2. The longitudinal distribution of wheel load used to determine live load bending moment shall be determined by applying to the beam the fraction of wheel load determined in Table 6.2. Refer to Chapter 9 of this guide for an example calculation. *Note the departure from the lane load convention used in this guide;* ***wheel, not lane, loads*** *are used in calculating moments in transverse floor beams.*

DECK TYPE	FRACTION OF WHEEL LOAD TO EACH BEAM
Plank[a,b]	S/4
Nail laminated[c] or glue laminated[e], 4" in thickness, or multiple layer[d] floors more than 5" thick.	S/4.5
Nail laminated[c] or glue laminated[e], 6" or more in thickness	S[f]/5
Concrete	S[f]/6
Steel grid(less than 4" thick)	S/4.5
Steel grid (4" or more thick)	S[f]/6
Steel bridge corrugated plank (2" minimum depth)	S/5.5

TABLE 6.2
Distribution of Wheel Loads in Transverse Floor Beams

Table 6.2 Notes:

S = Longitudinal Spacing of Floor Beams in Feet

a-e For footnotes a through e, see Table 6.1

f If S exceeds the denominator, the load on the beam shall be the reaction of the wheel loads assuming the flooring between beams to act as a simple beam.

Distribution of Loads - Load and Resistance Factor Design

Application

As noted above, application of the LRFD live load distribution methodology shall be limited to slab-on-steel beam bridges of the type and geometry considered in the University of Michigan studies. The analytical requirements for other structure types is beyond the scope of this document and must be addressed on a case-by-case basis using a more rigorous owner-approved approach.

Beam spacing shall be checked to ensure compliance with the ranges specified in Tables 4.6.2.2.2b-1 and 4.6.2.2.3a-1. Note that the range of beam spacings for structures considered in the University of Michigan studies falls within the range of applicability as specified in these articles.

The multiple presence factors, defined in Table 3.6.1.1.2-1, have been included in the approximate equations for distribution factors in Articles 4.6.2.2 and 4.6.2.3 for both single and multiple lanes loaded; these factors, m, do not need to be applied to distribution factors determined in accordance with the provisions of these articles. Where use of the lever rule is specified, the engineer must determine the number of vehicles and lanes and, therefore, must include the multiple presence (see Ref 3, Commentary Article C3.6.1.1.2).

In addition to the requirements defined by the University of Michigan study for structure type, skew, span length, and beam spacing, the distribution of live load, specified in Articles 4.6.2.2.2 and 4.6.2.2.3, may be used for beams that meet, at least, the following conditions:

- Deck width is constant;
- Unless otherwise specified, the number of beams is not less than four;
- Beams are parallel and have approximately the same stiffness;
- Unless otherwise specified, the roadway part of the overhang, d_e, does not exceed 3.0 ft;
- Curvature in plan is less than the limit specified in Article 4.6.1.2; and
- Cross-Section is consistent with one of the cross sections shown in Table 4.6.2.2.1-1

Procedure

Distribution factors determined by LRFD methodology are calculated as a function of superstructure section properties, material properties, and bridge longitudinal and transverse geometry. A general approach for the computation of these factors is outlined below. A numerical example, complete with code references, for a composite slab on steel I-beam bridge is provided in Chapter 9 of this guide.

1. Compile beam and superstructure data for both interior and exterior beams:
   a. Deck width.
   b. Deck thickness.
   c. Number of beams.
   d. Beam spacing.
   e. Cantilever length.
   f. Beam non-composite section properties.
   g. Beam modulus of elasticity.
   h. Deck modulus of elasticity.

2. Using the above data compute the following:
   a. Distance from exterior web of exterior beam to curbline, d_e.
   b. Longitudinal Stiffness Parameter, K_g.
   c. Distance between CG non-composite girder and CG deck, e_g.
   d. Beam/Deck Modular Ratio, $n = E_B/E_D$.

3. Using the parameters calculated in Item 2, compute:
   a. Interior beam shear and moment distribution factor for one lane loaded.
   b. Interior beam shear and moment distribution factor for multiple lanes loaded.
   c. Exterior beam shear and moment distribution factor for one lane loaded.
   d. Exterior beam shear and moment distribution factor for multiple lanes loaded.

4. Evaluate distribution factors for each of the cases investigated in Item 3 above to determine the governing (greatest) shear and moment distribution factors to apply to the interior and exterior beams respectively.

Supplemental Research

For more information about recent research related to live load distribution, the following references are suggested:

1. *Distribution of Wheel Loads on Highway Bridges, Phase III* (Ref 17)

   Development of simplified wheel load distribution criteria for five common bridge types namely, slab on girder, slab, box girder, spread box beam and multibox beam.

2. *Load Testing of Bridges. 1996* (Ref 26)

   Load tests of five bridges, three reinforced concrete T-beam and two slab-on-steel beam bridges, to develop an efficient proof load testing procedure. Proof load testing data are valuable in that they can be used to verify load carrying capacity.

3. *Development of a Guide for Evaluation of Existing Bridges. 1998* (Ref 27)

   Load tests of five steel beam bridges to determine safe load limits, response to dynamic loads and actual live load distribution factors.

4. *Development of a Guide for Evaluation of Existing Bridges Phase 2. 2000* (Ref 28) .

   A continuation of the 1998 test program, load tests were performed on six steel beam bridges to determine safe load limits, response to dynamic loads and actual live load distribution factors.

5. *Verification of Girder Distribution Factors for Steel Girder Bridges. 2001* (Ref 28)

   A continuation of the above testing programs, load tests were performed on six steel beam bridges with span lengths ranging up to 139' to determine actual live load distribution factors.

Chapter 7

POSTING PROCEDURES

April 3, 2009

POSTING PROCEDURES

When to Post a Bridge

As noted in Chapter 5, Analysis Vehicle Selection, all bridges will be examined for their ability to safely carry all legal load configurations at the Operating Rating level. If the load carrying capacity of a bridge is insufficient for all legal loads, the bridge must be posted to restrict vehicles that are too heavy from crossing the bridge. When the load carrying capacity is less than 3 tons, the bridge must be closed to traffic. If the Operating Rating indicates that the bridge can carry all legal loads, then posting is not required.

A bridge owner may also elect to post a bridge for lower bridge weights than those determined by calculations. Lower postings can extend the life of a bridge.

Load Posting Process

The load posting process includes the following steps:

- Analysis discovers that posting is necessary.
- The coding for NBI Item 41 is changed to “B” using the Michigan Bridge Inspection System (MBIS).
- A load posting order is signed by the responsible individual within the agency.
- Bridge is posted correctly for reduced loads. The posted capacity must be no more than the calculated capacity.
- The coding for NBI Item 41 is changed to “P” using the Michigan Bridge Inspection System (MBIS).
- Submit photo of posted bridge to MDOT.

The process required by the Michigan Department of Transportation for posting a bridge includes properly coding the Structure Inventory and Appraisal forms. When a load rating is performed and the bridge capacity is deficient for legal loads, item 41 of the SI&A form must be coded properly. Three of the nine possible codes for item 41 that are shown below are taken from the Michigan Structure Inventory and Appraisal Coding Guide (Ref 10) :

Code	Description
A	Open, no restriction
B	Open, posting recommended but not legally implemented (All signs not in place or do not show the correct information or are not in the correct location)
P	Posted for load (may include other restriction such as temporary bridges which are load posted).
K	Bridge closed.

If a particular bridge is currently not posted and a load rating shows the capacity to be insufficient for legal loads, item 41 should have its coding changed from an “A” to a “B.” Only after the bridge is posted, can the coding be changed from a “B” to a “P.”

It is imperative that corrective action be taken when the requirement for load posting is known. When a bridge requires posting (item 41 coded as “B”), a person or persons having authority over the bridge in question must give signed approval for the sign installation. After the approval, the posting sign can be ordered and then installed. See example #6 (Simple Span Composite Prestressed Concrete Box Beam) in Chapter 9 for a load rating that results in load posting.

In addition to load posting the bridge and updating NBI Item 41 with the appropriate coding via MBIS, a photo showing both the bridge and the load posting sign is to be submitted to the MDOT Bridge Operations Unit of the Construction and Technology Division.

Sign Configurations

The Michigan Manual of Uniform Traffic Control Devices-1994 Edition (MMUTCD), Part 2B Regulatory Signs, gives examples of typical signs used for posting bridges. As with any road sign, the information shown on the signs must be clear and concise so that the operator of a vehicle can understand the meaning quickly.

Figure 7.1 illustrates examples of various posting signs. Sign type R12-5 is the most common bridge load posting sign. Signs R12-1 and R12-2 may be useful in situations where severe load restrictions apply to a bridge or to a bridge component. Sign R12-4 can be used to combine the information contained on R12-1 and R12-2. In any case, careful analysis of the structure will determine the types of loading that control and will, therefore, dictate the information required on the posting signs.

After a load rating has been completed and it is determined that the bridge can not support legal axle loads, the bridge owner must order the fabrication of posting signs. The signs should be installed in advance of each end of the bridge. Advance sign locations and locations of signs near the bridge are both described in the MMUTCD.

Posting Routes With Multiple Posted Bridges

When multiple bridges on the same route require posting, it may be appropriate to post the entire section of road based on the bridge with the lowest capacity. Some typical scenarios are as follows:

- Two or more posted bridges are in immediate succession. If it is not physically possible to cross one bridge and not cross the other, then both bridges should be posted with the most restrictive posting. Advance warning signs should be placed so that overweight vehicles can take a detour route.
- Two posted bridges are separated by non-commercial driveways and/or intersections with roads with little commercial traffic. In this case, both bridges should be posted with the most restrictive posting. Advance warning signs should be placed so that overweight vehicles can take a detour route.
- Two posted bridges are separated by commercial/industrial facilities and/or intersections with roads with significant commercial traffic. In this case, the bridges should be posted individually to allow trucks to use the bridge with the higher posting. Advance warning signs should be placed before each bridge so that overweight vehicles can take a detour route.

When posting two or more bridges for the most restrictive posting, it is possible that the result will be more restrictive than either bridge posted individually. Example, the one unit – two unit – three unit posting for bridge #1 is 12-40-45 and the posting for bridge # 2 is 10-42-47, Posting the bridges the same would require a posting of 10-40-45. It is important that no bridge shall be posted to allow any load which exceeds its computed capacity.

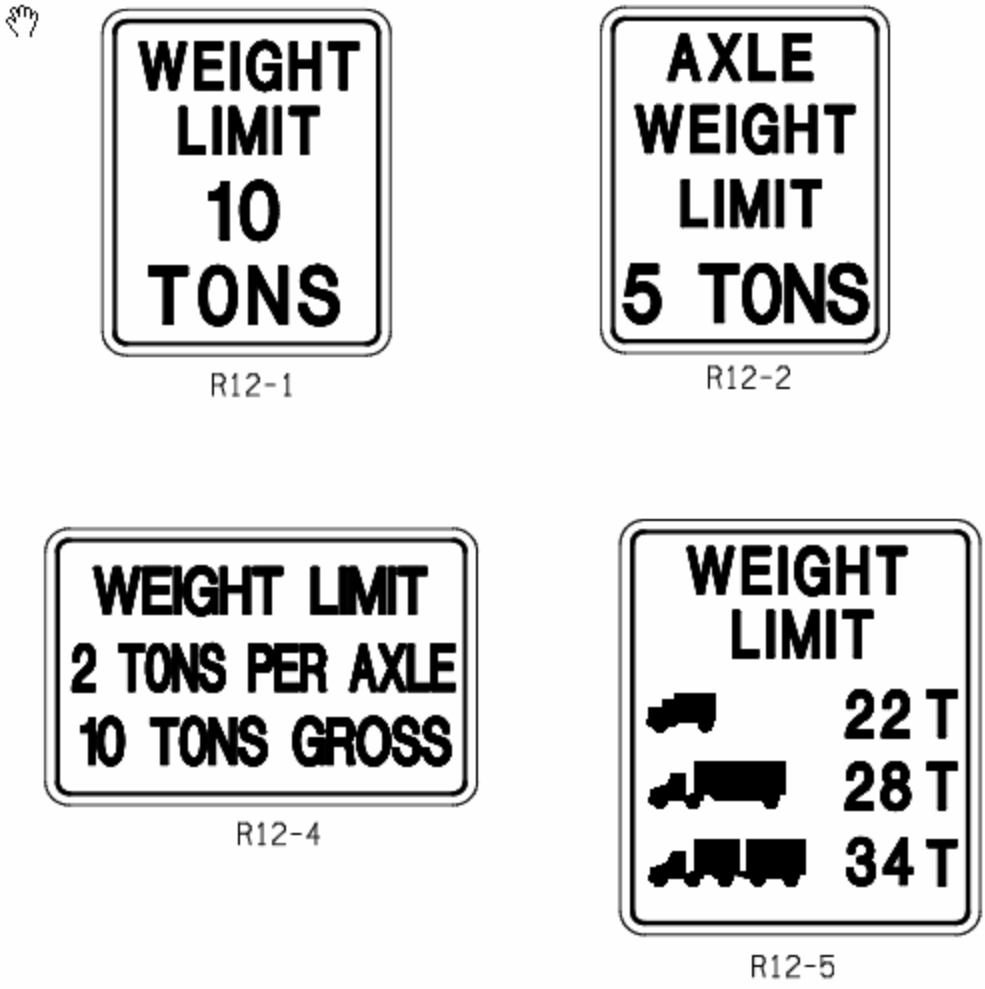


FIGURE 7.1
Sign Posting Examples

Chapter 8

OVERLOAD PROCEDURES

January 3, 2002

OVERLOAD PROCEDURES

The majority of vehicles that travel on Michigan roads and bridges are configured such that they are classified as legal and conform to the Michigan Vehicle Code. Occasionally vehicles with unusually heavy loads and/or non-standard axle configurations are required. Overload vehicles are those vehicles having axle spacings and/or axle weights that exceed what is permitted under the Michigan Vehicle Code.

Load rating of bridges for overloads is always performed at the Operating rating level.

MDOT Vehicle and Route System

The Michigan Department of Transportation (MDOT) has established a list of 20 different common overload vehicle configurations (see Figure 8.1). Each one of the overload configurations can be further classified as Class A, Class B or Class C, based on maximum allowable axle loads. The vehicle configurations shown in Figure 8.1 represent a majority of the overload vehicles on Michigan roads. Also note that Figure 8.1 is intended for out-to-out tire gauges of 8 ft, but larger gauges can be evaluated using the adjustment method included.

For overload permit purposes, all Michigan trunkline bridges have been classified as Class A, B, C or Restricted. The bridge classification is dependant on the overload capacity of that structure. Restricted bridges are those that are not capable of carrying all Class C overloads. The loads shown in Figure 8.1 have been computed by the MDOT, for bridges on their system.

Local Authority Systems

Local authorities, such as cities and counties, may or may not maintain an overload class system that mimics that of the state. However, local authorities are encouraged to adapt the Class A, Class B and Class C system for consistency throughout the state. Engineers performing load rating for bridges owned by local agencies should contact the appropriate local authority for information regarding overload classifications.

Permitting Procedures

MDOT Procedures

Owners of vehicles that do not conform to the Michigan Vehicle Code must apply for a permit with the Michigan Department of Transportation to utilize trunkline roads and bridges. There are a variety of overweight permit types available for objects and/or loads that cannot be divided to create legal configurations (non-divisible loads). See Chapter 13 to view common MDOT permit applications. The applications require information pertaining to axle weights, axle spacings, tire widths and in some cases origins and destinations. Upon review of the permit application, the state may issue a permit suitable for the specific load and routes requested.

The Michigan Department of Transportation, through the Utilities Coordination and Permits Section of the Real Estate Division, has produced a map and list entitled *Table of Bridges With Restricted Load Limits,* of the entire state that color codes all trunkline bridges as being either Class A, Class B, Class C or Restricted. This map pertains only to state owned roads and bridges. Individual bridges along all routes have been analyzed for load carrying capacity and given a classification that correlates with the permit class system.

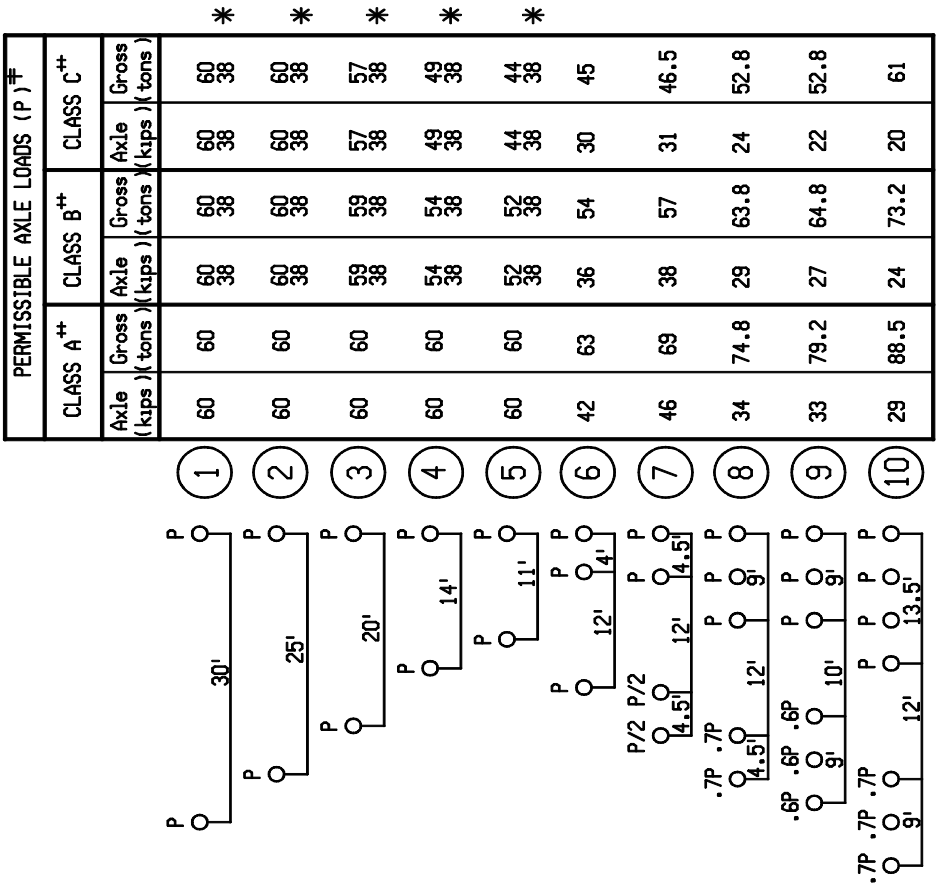
Local Authority Procedures

Like MDOT, the local authorities throughout the state have procedures for the issuance of overweight vehicle permits. The individual local authorities should be contacted to gain an understanding of their permitting process. Some of this information can be obtained from the Internet. The County Road Association of Michigan has a website (www.micountyroads.org) that lists all of the county road commissions in Michigan. The list also includes contact people and links to the websites (if available) of individual road commissions. Some of the individual road commission websites includes information regarding permits. Two county overload permit applications are shown in Chapter 13.

Load Rating Using Overload Vehicles

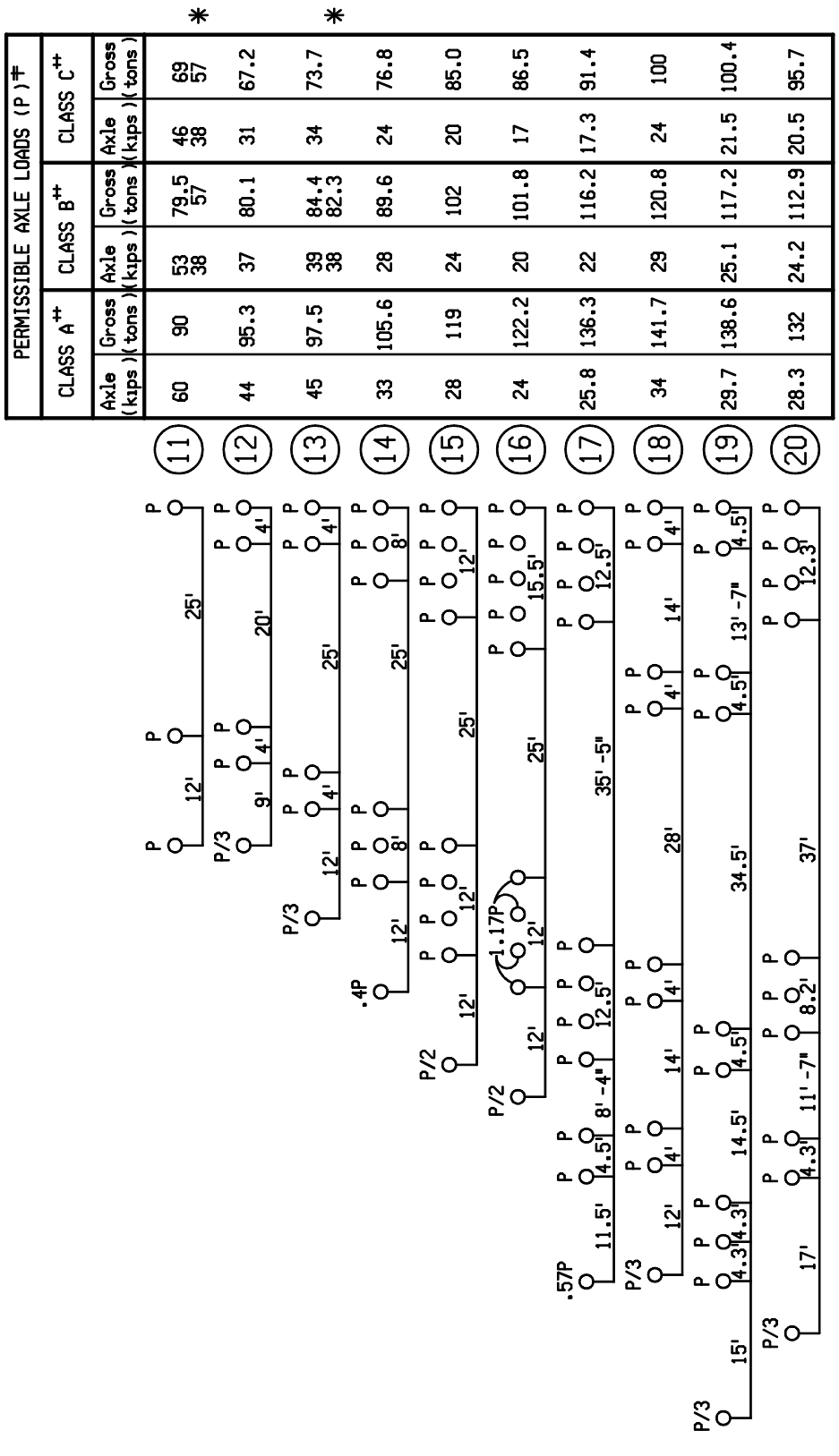
Load rating for overload vehicles may occur for two primary reasons. A bridge may be overload rated for all the normal overload vehicle classes prior to any overload application, so that the bridge capacity is known and permits can be issued or denied in an expeditious manner. MDOT has done this for all of the trunkline bridges in the state and as a result was able to produce the above referenced map. Tables of moments and shears for the MDOT Classes A, B and C overload vehicles are located in Chapter 10.

Another common reason for overload rating of a bridge is to respond to an application for a specific overload vehicle. The specific vehicle may be one that has a unique axle configuration and/or axles loads, or simply one which has not previously been considered. In this case, all of the bridges along the route, requested in the permit application, would have to be analyzed for this specific vehicle. This analysis would then be considered in the approval or denial of the permit application. Load rating calculations for overload vehicles are identical to normal load ratings for operating level ratings.



PERMISSIBLE AXLE LOADS (P)#	CLASS A++		CLASS B++		CLASS C++	
	Axle (kips)	Gross (tons)	Axle (kips)	Gross (tons)	Axle (kips)	Gross (tons)
1	60	60	60 38	60 38	60 38	60 38
2	60	60	60 38	60 38	60 38	60 38
3	60	60	59 38	59 38	57 38	57 38
4	60	60	54 38	54 38	49 38	49 38
5	60	60	52 38	52 38	44 38	44 38
6	42	63	36	54	30	45
7	46	69	38	57	31	46.5
8	34	74.8	29	63.8	24	52.8
9	33	79.2	27	64.8	22	52.8
10	29	88.5	24	73.2	20	61

FIGURE 8.1
Permissible Overload Classes on State Bridges



PERMISSIBLE AXLE LOADS (P)≠							
	CLASS A++		CLASS B++		CLASS C++		
	Axle (kips)	Gross (tons)	Axle (kips)	Gross (tons)	Axle (kips)	Gross (tons)	
11	60	90	53 38	79.5 57	46 38	69 57	*
12	44	95.3	37	80.1	31	67.2	
13	45	97.5	39 38	84.4 82.3	34	73.7	*
14	33	105.6	28	89.6	24	76.8	
15	28	119	24	102	20	85.0	
16	24	122.2	20	101.8	17	86.5	
17	25.8	136.3	22	116.2	17.3	91.4	
18	34	141.7	29	120.8	24	100	
19	29.7	138.6	25.1	117.2	21.5	100.4	
20	28.3	132	24.2	112.9	20.5	95.7	

FIGURE 8.1 (Continued)
Permissible Overload Classes on State Bridges

+ Loads exceeding these values must be checked out for individual bridges

++ For bridge class, refer to "Table of Bridges with Restricted Load Limits".

* For bridges designed for H15 between 1965 and 1972, the slab controls

Where W is not 8 feet, adjust axle load by the factor:

$$\frac{W+8}{16},$$

providing the axle load does not exceed 60,000 lbs and except for restricted bridges with "R" following number on map. This formula is only valid for multi-stringer bridges with stringer spacing not greater than 10'.

FIGURE 8.1 (continued)
Permissible Overload Classes on State Bridges

Chapter 9

CALCULATION EXAMPLES

April 03, 2009

Example 9-1 LFR General

A simply supported bridge with a span length of 40-ft requires load rating. The structure is located in an agency that allows designated loading. The design loading is HS-20. Structural analysis finds the total moment capacity of the controlling beam is 1000 k*ft. The dead load moment is 100 k*ft. The live load distribution factors are 0.5 for multiple lanes loaded, and 0.39 for a single lane loaded. The shear and service capacities do not control. The analysis was done using the LFR method.

The design load is greater than H15 and therefore the slab does not require analysis (See BAG, Chapter 4). The substructure is in good condition, and therefore the substructure does not require analysis.

Federal Inventory Rating, Item 66

The Impact for a span of 40-ft is 0.3. The weight of an HS-20 vehicle is 36-tons.
From Table 10.9 of the BAG, the live load moment for a 40-ft span is 450 k*ft

$$RF = \frac{C - A_1 * D}{A_2 * L * GDF * (1 + I)}$$ Eq 6B.5.1-1 The Manual for Bridge Evaluation

where:

RF	Rating Factor
C	Capacity
D	Dead Load Effect
L	Live Load Effect
GDF	Girder Distribution Factor
I	Impact
A_1	Dead Load Effect Factor
A_2	Live Load Effect Factor

$$RF = \frac{1000 - 1.3 * 100}{2.17 * 450 * 0.5 * (1 + 0.3)} = 1.37$$

It is acceptable to enter the Federal Inventory Rating as a Rating Factor. However, the Rating Factor (RF) can be converted to Metric Tons, as shown in the following equations.

Multiply the RF by the weight of the HS20 truck

$$1.37 * 36 tons = 49.32 tons$$

Convert to metric tons

$$49.32 tons * 0.907 \frac{metrictons}{tons} = 44.7 metrictons$$

Federal Operating Rating, Item 64F

The Impact for a span of 40-ft is 0.3
From Table 10.9 of the BAG, the live load moment for a 40-ft span is 450 k*ft

$$RF = \frac{C - A_1 * D}{A_2 * L * GDF * (1 + I)}$$

$$RF = \frac{1000 - 1.3 * 100}{1.3 * 450 * 0.5 * (1 + 0.3)} = 2.29$$

Once again, the RF could be submitted or the Rating in Metric Tons can be found.

Multiply the RF by the weight of the HS20 truck

$$2.29 * 36 tons = 82.44 tons$$

Convert to Metric Tons

$$82.44 tons * 0.907 \frac{metrictons}{tons} = 74.8 metrictons$$

Note: Metric tons greater than 99.9 need to be coded as 99.9. Entering a rating of 125.1 metric tons, for example, would be recorded as 12.5 metric tons.

Michigan Operating Rating (Legal or Posting Load Rating), Item 64M

The Impact for a span of 40-ft is 0.3
From Table 10.5 of the BAG, the maximum live load moment for a Designated Loading, 40-ft span, is 680-kip*ft for Truck #17:

$$RF = \frac{C - A_1 * D}{A_2 * L * GDF * (1 + I)}$$

$$RF = \frac{1000 - 1.3 * 100}{1.3 * 680 * 0.5 * (1 + .3)} = 1.51$$

As the rating factor is greater than 1, no posting is required.

For most structures, the #5, #18, and #23 vehicles will produce load effects close to the maximum ***when analyzed by LFR***. For structures where these three vehicles produce ratings significantly greater than 1, engineering judgement may be used to determine if the other twenty-five vehicles need to be analyzed.

MDOT Overload Class, Item 193

From Table 10.10 of the BAG, the maximum live load moment for a Class A loading, 40-ft span is 964 k*ft. The GDF for this rating is taken as 0.39 as Overloads are analyzed as single lane loading in ASR and LFR.

$$RF = \frac{C - A_1 * D}{A_2 * L * GDF * (1 + I)}$$

$$RF = \frac{1000 - 1.3 * 100}{1.3 * 964 * 0.39 * (1 + 0.3)} = 1.37$$

The RF>1 for all Overload trucks and therefore the Overload Class is A.

A sample summary sheet is shown in Figure 9-1.

BRIDGE ANALYSIS SUMMARY

Bridge ID B01-00001

The above structure was analyzed using: Hand Calcs

Version or Other:

The analysis is based on field inspection dated: 1/1/1998

The controlling component and failure mode are:

Moment at Midspan

NEW INVENTORY CODING

NBI Item 63- Operating Rating Method	6-LF Rating Factor	
NBI Item 64F- Federal Operating Rating	2.29	Rating Factor
MDOT Item 64MA- Michigan Operating Method	6-LF Rating	
MDOT Item 64MB- Michigan Operating Rating	1.51	Rating Factor
MDOT Item 64MC and D- Michigan Operating Truck	17	D - Designated
NBI Item 65- Inventory Rating Method	6-LF Rating Factor	
NBI Item 66- Federal Inventory Rating	1.37	Rating Factor
NBI Item 41- Open Posted Closed	A-Open	
NBI Item 70- Bridge Posting	5 - 100% or more	
NBI Item 141- Posted Loading		US Tons
MDOT Item 193A- Michigan Overload Class	A	
MDOT Item 193C- Overload Status	- No Restriction	

Analyzed By- Signature and Date ABC 1-2-98

Checked By- Signature and Date DEF 1-3-98

Database Updated By- Initials and Date GHI 1-4-98

Figure 9-1

Example 9-2 LFR with Deterioration

10 years later, the same structure is inspected and significant deterioration of the beam is found. The maximum moment capacity is reduced to 400 k*ft based upon the inspection. The deck and substructure are both in good condition. All other information remains the same.

The design load is greater than H15 and therefore the slab does not require analysis (See Chapter 4 of the BAG). The substructure is in good condition, and therefore the substructure does not require analysis.

Federal Inventory Rating, Item 66

$$RF = \frac{400 - 1.3*100}{2.17*450*0.5*(1+0.3)} = 0.43$$

Federal Operating Rating, Item 64F

$$RF = \frac{400 - 1.3*100}{1.3*450*0.5*(1+0.3)} = 0.71$$

Michigan Operating Rating (Legal or Posting Load Rating), Item 64M

$$RF = \frac{400 - 1.3*100}{1.3*680*0.5*(1+0.3)} = 0.47$$

The RF is less than 1.00, and so posting must be considered. It is helpful to calculate the Capacity Available for Live Load (L_A). This is found by rearranging the load rating equation.

Calculate the Live Load Capacity assuming an Operating Rating of 1.0

$$L_A = \frac{C - 1.3*D}{1.3*RF*GDF*(1+I)}$$

$$L_A = \frac{400 - 1.3*100}{1.3*1*.5*(1+0.3)} = 319.5kft$$

As this is designated loading, Tables 10.4, 10.5, and 10.6 of the BAG will be checked.

For 1-Unit, Designated Load vehicles, check Table 10.4 for a 40-ft span. Trucks 2, 3, 4 and 5 have live load moments greater than 319.5k*ft. Truck #2 has the highest Moment to Weight ratio (7.96), and therefore controls. The Live Load Moment for Truck #2 is 377k*ft and it weighs 23.7tons.

$$\frac{319.5}{7.96} = 40.1kips \approx 20tons$$

For continuous span configurations that are not provided in the BAG, the following steps may be taken to identify the posting load.

Calculate the rating factor for all trucks of that Unit Type. For all vehicles with Rating Factors less than 1.00, multiply the Rating Factor by the Truck Weight to find the Posting Load. The lowest Posting Load should be selected.

Truck Number	Moment (k*ft)	RF	Truck Weight (Ton)	Posting Load (Ton)
1	268	1.19	16.7	NA (RF>1)
2	377	0.85	23.7	**20.1**
3	406	0.79	27.2	21.5
4	488	0.65	33.7	21.9
5	463	0.69	42.0	29.0

Table 9-1

For 2-Unit, Designated Load vehicles, check Table 10.5 of the BAG for a 40-ft span. Trucks 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 27 have live load moments greater than 319.5k*ft. Truck #9 has the highest Moment to Weight ratio (7.08), and therefore controls. The Live Load Moment for Truck #9 is 364k*ft and it weighs 25.7tons.

$$\frac{319.5}{7.08} = 45.1 kips \approx 22 tons \text{ (rounding down)}$$

For 3-Unit, Designated Load vehicles, check Table 10.6 of the BAG for a 40-ft span. All of the 3-unit trucks have live load moments greater than 319.5k*ft. Truck #20 has the highest Moment to Weight ratio (4.71), and therefore controls. The Live Load Moment for Truck #20 is 411k*ft and it weighs 43.7tons.

$$\frac{319.5}{4.71} = 67.8 kips \approx 33 tons \text{ (rounding down)}$$

The posting for this structure would be:

1-Unit	20*tons*
2-Unit	22*tons*
3-Unit	33*tons*

While the Posting Load gives us the lowest tonnage for signing purposes, this does not always correspond to the lowest Rating Factor for that truck type. Looking at Table A-1, we find that the lowest 1-Unit Truck Rating Factor is 0.65, Truck #4, although the Posting Tonnage was controlled by Truck #2 with a Rating Factor of 0.85. From the Michigan Operating Calculation above, we know that the controlling 2-Unit Rating Factor is 0.47. Looking in Table 10.6 of the BAG, we find the maximum moment of the 3-Unit Trucks to be 601-k*ft for the #23 Truck with a corresponding Rating Factor of 0.53. These values will be recorded on the Summary Sheet.

MDOT Overload Class, Item 193

From Table 10.10 of the BAG, the maximum live load moment for a Class A loading, 40-ft span is 964 k*ft.

$$RF = \frac{C - A_1 * D}{A_2 * L * GDF * (1 + I)}$$

$$RF = \frac{400 - 1.3 * 100}{1.3 * 964 * 0.39 * (1 + 0.3)} = 0.42$$

The RF<1 for maximum Class A Overload truck. The engineer could next check Class B loading from Table 10.11 followed by Class C and Table 10.12 using the method outlined for Class A above. Alternatively, the Permit Live Load Capacity assuming single lane distribution and an Operating Rating of 1.0 can be found and compared to the Class B and C loading.

$$L_{APermit} = \frac{C - 1.3 * D}{1.3 * RF * GDF_{Permit} * (1 + I)}$$

$$L_{APermit} = \frac{400 - 1.3 * 100}{1.3 * 1 * 0.39 * (1 + 0.3)} = 409.6kft$$

From Table 10.11, the maximum live load moment for a Class B loading, 40-ft span is 822 k*ft and from Table 10.12, the maximum live load moment for a Class C loading, 40-ft span is 666 k*ft. The Permit Live Load Capacity is 409.6 k*ft, which is less than the Class B and Class C loadings and therefore the bridge is Class D. The Permits section may require the allowable axle load for each Overload Vehicle. This may be found by comparing the axle weights and maximum moment for each truck to the Permit Live Load Capacity, as shown in Table 9-2, and sample steps are outlined below.

Find the axle load from Figure 8.1 in the BAG.

$$Axle_{Truck1} = 60kips$$

Find the live load moment from Table 10.10 in the BAG.

$$Moment_{Truck1} = 600kft$$

Compare the Permit Live Load Capacity to the axle load and live load moment for the truck.

$$AllowableAxle_{Truck} = \frac{L_{APermit}}{Moment_{Truck}} * Axle_{Truck}$$

$$AllowableAxle_{Truck1} = \frac{409.6kft}{600kft} * 60kips = 41.0kips$$

Class C			Allowable
Truck	Axle (kips)	Moment (k*ft)	Axle (kips)
1	60	600	41.0
2	60	600	41.0
3	57	641	36.4
4	49	666	30.1
5	44	655	27.5
6	30	664	18.5
7	31	645	19.7
8	24	656	15.0
9	22	625	14.4
10	20	645	12.7
11	46	665	28.3
12	31	615	20.6
13	34	657	21.2
14	24	645	15.2
15	20	660	12.4
16	17	653	10.7
17	17.3	647	11.0
18	24	561	17.5
19	21.5	589	15.0
20	20.5	655	12.8

Table 9-2

A sample Summary Sheet is shown in Figure 9-2.

BRIDGE ANALYSIS SUMMARY

Bridge ID B01-00001

The above structure was analyzed using: Hand Calcs

Version or Other:

The analysis is based on field inspection dated: 1/1/2008

The controlling component and failure mode are:

Moment at Midspan including deterioration

NEW INVENTORY CODING

NBI Item 63- Operating Rating Method	6-LF Rating Factor	
NBI Item 64F- Federal Operating Rating	0.71	Rating Factor
MDOT Item 64MA- Michigan Operating Method	6-LF Rating	
MDOT Item 64MB- Michigan Operating Rating	0.47	Rating Factor
MDOT Item 64MC and D- Michigan Operating Truck	17	D - Designated
NBI Item 65- Inventory Rating Method	6-LF Rating Factor	
NBI Item 66- Federal Inventory Rating	0.43	Rating Factor
NBI Item 41- Open Posted Closed	B-Requires Posting	
NBI Item 70- Bridge Posting	0 - 59% or less	
NBI Item 141- Posted Loading	20-22-34	US Tons
MDOT Item 193A- Michigan Overload Class	D	
MDOT Item 193C- Overload Status	- No Restriction	

Analyzed By- Signature and Date	ABC	1-2-2008
Checked By- Signature and Date	DEF	1-3-2008
Database Updated By- Initials and Date	GHI	1-4-2008

Figure 9-2

Example 9-3 LRFR General

A simply supported bridge with a span length of 40-ft requires load rating. The structure is located in an agency that allows designated loading. The design loading is HL-93. Structural analysis finds the total moment capacity (Strength I and II) of the controlling beam is 1000 k*ft. The capacity for Service II is 950 k*ft. The dead load moment is 100 k*ft. The live load distribution factors are 0.56 for multiple lanes loaded, and 0.44 for a single lane loaded. The shear and service capacities do not control. The ADTT of this structure is unknown, and so 5000 will be assumed. The analysis was done using the LRFR method.

The design load is according to HL-93 and therefore the slab does not require analysis (See Chapter 4 of the BAG). The substructure is in good condition, and therefore the substructure does not require analysis.

Federal Inventory Rating, Item 66

From Table E6A-1 of The Manual for Bridge Evaluation (MBE), the HL-93 Design Load (including Impact) is 722.0-k*ft per lane.

$$RF = \frac{C - \gamma_{DC} * DC - \gamma_{DW} * DW \pm \gamma_p * P}{\gamma_L * (LL + IM)}$$ Eq 6A.4.2.1-1 MBE

where:

RF	Rating Factor
C	Capacity
DC	Dead Load Effect due to structural components
DW	Dead Load Effect due to wearing surface and utilities
P	Permanent Loads other than dead loads
LL	Live Load Effect (including girder distribution)
IM	Dynamic Load Allowance (33% of tandem or truck allowance)
γ_{DC}	LRFD load factor for structural components
γ_{DW}	LRFD load factor for wearing surface and utilities
γ_P	LRFD load factor for permanent loads other than dead loads (γ_P=1)
γ_L	LRFD load factor for live load

In load rating, wearing surfaces that have been field verified may be treated as structural components (DC). In this structure, there are no terms for DW or P.

$$RF = \frac{1000 - 1.25 * 100}{1.75 * 722 * 0.56} = 1.24$$ Strength I

$$RF = \frac{950 - 1.00 * 100}{1.30 * 722 * 0.56} = 1.62$$ Service II

It is acceptable to enter the Federal Inventory Rating as a Rating Factor. However, the Rating Factor (RF) can be converted to Metric Tons, as shown in the following equations.

Multiply the RF by the weight of the HS20 truck

$$1.24 * 36 tons = 44.64 tons$$

Convert to metric tons

$$44.64 tons * 0.907 \frac{metrictons}{tons} = 40.5 metrictons$$

Federal Operating Rating, Item 64F

For Operating Rating, the γ_L changes to 1.35 for the Strength Limit State.

$$RF = \frac{1000 - 1.25 * 100}{1.35 * 722 * 0.56} = 1.60$$ Strength I

$$RF = \frac{950 - 1.00 * 100}{1.00 * 722 * 0.56} = 2.10$$ Service II

Once again, the RF could be submitted or the Rating in Metric Tons can be found.

Multiply the RF by the weight of the HS20 truck

$$1.60 * 36 tons = 57.60 tons$$

Convert to Metric Tons

$$57.60 tons * 0.907 \frac{metrictons}{tons} = 52.2 metrictons$$

Note: Metric tons greater than 99.9 need to be coded as 99.9. Entering a rating of 125.1 metric tons, for example, would be recorded as 12.5 metric tons.

Michigan Operating Rating (Legal or Posting Load Rating), Item 64M

The maximum ***factored with impact*** live load moment for the Strength Limit State, 5000 ADTT, Designated Loading, 40-ft span, is 1.80*1.33*488k*ft = 1168-kip*ft for Truck #4. This is found by combining Tables 10.4, 10.5 and 10.6 from the BAG and Table 4a-1 to find the controlling effect.

$$RF = \frac{C - \gamma_{DC} * DC - \gamma_{DW} * DW \pm \gamma_p * P}{\gamma_L * (LL + IM)}$$ Eq 6A.4.2.1-1 MBE

$$RF = \frac{1000 - 1.25 * 100}{1168 * 0.56} = 1.34$$ Strength I

The maximum ***factored with impact*** live load moment for the Service Limit State, 5000 ADTT, Designated Loading, 40-ft span, is 1.00*1.33*680k*ft = 904-kip*ft for Truck #17:

$$RF = \frac{950 - 1.00 * 100}{904 * 0.56} = 1.68$$ Service II

As the rating factor is greater than 1, no posting is required.

MDOT Overload Class, Item 193

The maximum ***factored with impact*** live load moment for the Strength Limit State, Class A loading, 5000 ADTT, 40-ft span is 1666 k*ft. This is found from combining Table 10.10 from the BAG with Table 4a-4 to find the controlling effect. As the MDOT Overload Class refers to routine, annual permits, the multi-lane distribution will be applied.

$$RF = \frac{C - \gamma_{DC} * DC - \gamma_{DW} * DW \pm \gamma_p * P}{\gamma_L * (LL + IM)}$$ Eq 6A.4.2.1-1 MBE

$$RF = \frac{1000 - 1.25 * 100}{1666 * 0.56} = 0.94$$

The RF<1 for maximum Class A Overload truck and therefore try Class B.

The maximum ***factored with impact*** live load moment for the Strength Limit State, Class B loading, 5000 ADTT, 40-ft span is 1571 k*ft.

$$RF = \frac{1000 - 1.25 * 100}{1571 * 0.56} = 1.00$$

Service Checks are optional for Permit Trucks and will not be checked for this structure.

The RF=1 for maximum Class B Overload truck and therefore the bridge is Class B.

A sample summary sheet is shown in Figure 9-3.

BRIDGE ANALYSIS SUMMARY

Bridge ID B01-00001

The above structure was analyzed using: Hand Calcs

Version or Other:

The analysis is based on field inspection dated: 10/1/2020

The controlling component and failure mode are:

Moment at Midspan including deterioration

NEW INVENTORY CODING

NBI Item 63- Operating Rating Method	8-LRF Rating Factor (HL-93)	
NBI Item 64F- Federal Operating Rating	0.50	Rating Factor
MDOT Item 64MA- Michigan Operating Method	8-LRF Rating	
MDOT Item 64MB- Michigan Operating Rating	0.42	Rating Factor
MDOT Item 64MC and D- Michigan Operating Truck	4	D - Designated
NBI Item 65- Inventory Rating Method	8-LRF Rating Factor (HL-93)	
NBI Item 66- Federal Inventory Rating	0.39	Rating Factor
NBI Item 41- Open Posted Closed	B-Requires Posting	
NBI Item 70- Bridge Posting	0 - 59% or less	
NBI Item 141- Posted Loading	5-8-14	US Tons
MDOT Item 193A- Michigan Overload Class	D	
MDOT Item 193C- Overload Status	- No Restriction	

Analyzed By- Signature and Date ABC 10/2/2020

Checked By- Signature and Date DEF 10/3/2020

Database Updated By- Initials and Date GHI 10/4/2020

Figure 9-4

BRIDGE ANALYSIS SUMMARY

Bridge ID B01-00001

The above structure was analyzed using: Hand Calcs

Version or Other:

The analysis is based on field inspection dated: 10/1/2010

The controlling component and failure mode are:

Moment at Midspan

NEW INVENTORY CODING

NBI Item 63- Operating Rating Method	8-LRF Rating Factor (HL-93)	
NBI Item 64F- Federal Operating Rating	1.60	Rating Factor
MDOT Item 64MA- Michigan Operating Method	8-LRF Rating	
MDOT Item 64MB- Michigan Operating Rating	1.34	Rating Factor
MDOT Item 64MC and D- Michigan Operating Truck	4	D - Designated
NBI Item 65- Inventory Rating Method	8-LRF Rating Factor (HL-93)	
NBI Item 66- Federal Inventory Rating	1.24	Rating Factor
NBI Item 41- Open Posted Closed	A-Open	
NBI Item 70- Bridge Posting	5 - 100% or more	
NBI Item 141- Posted Loading		US Tons
MDOT Item 193A- Michigan Overload Class	B	
MDOT Item 193C- Overload Status	- No Restriction	

Analyzed By- Signature and Date	ABC	10/2/2010
Checked By- Signature and Date	DEF	10/3/2010
Database Updated By- Initials and Date	GHI	10/4/2010

Figure 9-3

Example 9-4 LRFR with Deterioration

10 years later, the same structure is inspected and significant deterioration of the beam is found. The maximum moment capacity is reduced to 400 k*ft based upon the inspection. The deck and substructure are both in good condition. All other information remains the same.

The design load is according to HL-93 and therefore the slab does not require analysis (See Chapter 4 of the BAG). The substructure is in good condition, and therefore the substructure does not require analysis. From the previous rating, it is known that Service does not control.

Federal Inventory Rating, Item 66

$$RF = \frac{400 - 1.25 * 100}{1.75 * 722 * 0.56} = 0.39$$ Strength I

Federal Operating Rating, Item 64F

$$RF = \frac{400 - 1.25 * 100}{1.35 * 722 * 0.56} = 0.50$$ Strength I

Michigan Operating Rating (Legal or Posting Load Rating), Item 64M

$$RF = \frac{400 - 1.25 * 100}{1168 * 0.56} = 0.42$$ Strength I

The RF is less than 1.00, and so posting must be considered. It is helpful to calculate the LRFR Capacity Available for Live Load (LL_A). The LL_A for LRFR is different than LFR. In LFR, the L_A should be compared to the unfactored load effect without impact. For LRFR, LL_A is compared to the factored load effect including impact. This is found by rearranging the load rating equation.

Calculate the Live Load Capacity assuming an Operating Rating of 1.0

$$LL_A = \frac{C - \gamma_{DC} * DC - \gamma_{DW} * DW \pm \gamma_p * P}{RF * GDF}$$

$$LL_A = \frac{400 - 1.25 * 100}{1 * 0.56} = 491 kft$$

As this is Designated Loading and 5000 ADTT, Tables 10.4, 10.5 and 10.6 from the BAG are combined with Table 4a-1 to find the controlling effect.

For 1-Unit, 5000 ADTT, Designated Load vehicles, check Tables 10.4 and 4a-1 for a 40-ft span. All trucks have factored with impact live load moments greater than 491-k*ft.

Calculate the rating factor for all trucks of that Unit Type. For all vehicles with Rating Factors

less than 1.00, calculate the Posting Load as:

$$PostingLoad = \frac{W*(RF-0.3)}{0.7}$$ Eq 6A.8.3-1 MBE

Truck Number	Moment (k*ft)	RF	W=Truck Weight (Ton)	Posting Load (Ton)
1	642	0.76	16.7	11.0
2	903	0.54	23.7	8.1
3	972	0.51	27.2	8.2
4	1168	**0.42**	33.7	5.8
5	1079	0.46	42.0	9.6

Table 9-3

For 2-Unit, 5000 ADTT, Designated Load vehicles, check Tables 10.5 and 4a-1 for a 40-ft span. All trucks have factored with impact live load moments greater than 491-k*ft. A spreadsheet was created to select the correct posted load similar to the method described for the 1-Unit Truck.

Minimum RF: 0.44 (Truck #16)
Minimum Posting Load: 8.7 (Truck #11)

For 3-Unit, 5000 ADTT, Designated Load vehicles, check Table 10.6 and 4a-1 for a 40-ft span. All trucks have factored with impact live load moments greater than 491-k*ft. A spreadsheet was created to select the correct posted load similar to the method described for the 1-Unit Truck.

Minimum RF: 0.51 (Truck #23)
Minimum Posting Load: 14.1 (Truck #20)

The posting for this structure would be:

1-Unit	5*tons*
2-Unit	8*tons*
3-Unit	14*tons*

While the Posting Load gives us the lowest tonnage for signing purposes, this does not always correspond to the lowest Rating Factor for that truck type. Looking at the 2-Unit trucks, we find that the lowest Rating Factor is 0.44, Truck #16, although the Posting Tonnage was controlled by Truck #11 with a Rating Factor of 0.76. The lowest Rating Factors will be recorded on the Summary Sheet. Please note that this bridge was analyzed using artificial numbers similar to the LFR process. Posting limits as low as this may require engineering judgement regarding further action such as reducing the bridge to a single lane or closing it until repairs are made.

MDOT Overload Class, Item 193

From Tables 10.10 and 4a-6, the maximum ***factored with impact*** live load moment for the Strength Limit State, Class C loading, 5000 ADTT, 40-ft span is 1478 k*ft. This is much greater than the Capacity Available for Live Load, 491-k*ft, as calculated above.

The RF<1 for maximum Class C Overload trucks and therefore the bridge is Class D. The Permits section may require the allowable axle load for each Overload Vehicle. This may be

found by comparing the axle weights and maximum moment for each truck to the Permit Live Load Capacity, as shown in Table 9-4, and sample steps are outlined below.

Find the axle load from Figure 8.1 in the BAG.

$$Axle_{Truck1} = 60kips$$

Find the live load moment from Table 10.12 in the BAG.

$$Moment_{Truck1} = 600kft$$

Find the live load factor from Table 4a-4.

$$\gamma_{LL_Truck1} = 1.39$$

Compare the Permit Live Load Capacity to the axle load and live load moment for the truck.

$$AllowableAxle_{Truck} = \frac{LL_{APermit}}{Moment_{Truck} * \gamma_{LL} * 1.33} * Axle_{Truck}$$

$$AllowableAxle_{Truck1} = \frac{491kft}{600kft * 1.39 * 1.33} * 60kips = 26.6kips$$

Class C, 5000 ADTT				Allowable Axle (kips)
Truck	Axle (kips)	LL Factor, γ_L	Unfactored Moment (k*ft)	
1	60	1.39	600	26.6
2	60	1.39	600	26.6
3	57	1.43	641	23.0
4	49	1.58	666	17.2
5	44	1.7	655	14.6
6	30	1.67	664	10.0
7	31	1.64	645	10.8
8	24	1.5	656	9.0
9	22	1.5	625	8.7
10	20	1.37	645	8.4
11	46	1.28	665	20.0
12	31	1.3	615	14.3
13	34	1.23	657	15.5
14	24	1.2	645	11.4
15	20	1.14	660	9.8
16	17	1.13	653	8.5
17	17.3	1.1	647	9.0
18	24	1.1	561	14.4
19	21.5	1.1	589	12.3
20	20.5	1.1	655	10.5

Table 9-4

A sample Summary Sheet is shown in Figure 9-4.