RELIABILITY-BASED EVALUATION OF BRIDGE LIVE LOAD CARRYING CAPACITY IN THE UNITED STATES

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Abstract

In accordance with the National Bridge Inspection Standards (NBIS), each bridge must be load rated as to its live-load carrying capacity following the method and procedure specified in the AASHTO Manual for Bridge Evaluation (MBE). When the maximum unrestricted legal loads or State routine permit loads exceed that allowed, the bridge must be posted or restricted. This paper will (1) provide an overview of the federal requirements about load rating highway bridges; (2) present the basic concept of structural reliability used in calibration of the Load and Resistance Factor Design (LRFD) and Rating (LRFR) method; (3) summarize the LRFR provisions in the MBE that FHWA (Federal Highway Administration) is promoting; and (4) illustrate the LRFR procedure through an example.

Introduction

Bridges are aging, and truck weights and volumes are increasing. In addition to ensuring the safety of the travelling public, it is also important to protect bridges from over-loads that may cause premature or accelerated deterioration. When State's legal loads or routine permit loads exceed the safe live load allowed for a bridge, the bridge should be posted or restricted in accordance with the National Bridge Inspection Standards (NBIS) (23 CFR 650 Subpart C) [1]. The current American Association of State Transportation and Highway Officials (AASHTO) Manual for Bridge Evaluation (MBE) [2, 3] further defines the requirements and procedures for load rating and posting of bridges.

The current NBIS stipulates that each bridge is to be load rated in accordance with the AASHTO Manual for Bridge Evaluation (MBE), First Edition, 2008. The MBE replaces the old AASHTO bridge condition evaluation manuals and incorporates the state-of-the art load rating method: the Load and Resistance Factor Rating (LRFR) method. AASHTO publishes the 2nd Edition of the MBE in 2011.

On October 30, 2006, FHWA issued a Policy Memorandum regarding Bridge Load Ratings for the National Bridge Inventory. It clarifies the NBI reporting requirements as to what load rating methods should be used for different types of bridges. In accordance with the requirements, new bridges and totally replaced bridges designed after October 1, 2010 must be load rated and reported in the NBI with the LRFR method.

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Since the establishment of the national bridge inspection program in the Federal-Aid Highway Act of 1968 (23 U.S.C. 151) and the NBIS, AASHTO has published a series of manuals for bridge inspection and evaluation [2, 3, 4, 5, 6]. The major related publications are listed in Table 1.

TABLE 1: AASHTO MANUALS

Year	AASHTO Manual	Notes
1970	AASHO Manual for Maintenance Inspection of Bridges	This was the first manual by AASHTO and served as a standard to provide uniformity in the procedures and policies for determining the physical condition, maintenance needs and load capacity of highway bridges.
2003	AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges	This Guide Manual reflected the Load and Resistance Factor Design (LRFD) Specifications that AASHTO had already adopted. It was based on the NCHRP research project 12-46 (Calibration of Load Factors for LRFR Bridge Evaluation) during the period of 1997 to 2002. It superseded the previous AASHTO Manual and only the inspection and material testing sections in the previous manual were retained. New sections included Load and Resistance Factor Rating, Fatigue evaluation of bridges, Non-destructive load testing of bridges, and Introduction to Bridge Management System. Allowable stress rating and load factor rating were included as alternate rating methods.
2008	AASHTO Manual for Bridge Evaluation, 1st Edition	The First Edition MBE superseded the publications mentioned above and had been developed to assist bridge owners by establishing inspection procedures and evaluation practices that meet the NBIS. Section 6 discussed the load rating of bridges and included the Load and Resistance Factor (LRFR) method, the Load Factor (LFR) method and the Allowable Stress (ASR) method. The rating procedures presented for the LRFR method recognized a balance between safety and economics through a reliability-based calibration.
2011	AASHTO Manual for Bridge Evaluation, 2nd Edition	This manual contains essentially the same requirements as the 1st Edition MBE except for some minor formatting of subsections. Sections C6A.1.1 and C6B.1 allow assigning a load rating to a bridge based on its design load for the first time, however, a number of conditions that must be met in order to use this method.

In the MBE, there are three analytical load rating methods specified: ASR, LFR and LRFR method. Section 8 also includes the Non-Destructive Testing (NDT) as a valid load rating method to meet the NBIS's requirements for load rating (Table 2).

TABLE 2: LOAD RATING METHODS IN MBE

Load Rating Method	Corresponding Design Method	Design Specifications
ASR*	Allowable Stress Design (ASD)	AASHTO Standard Specs
LFR	Load Factor Design (LFD)	AASHTO Standard Specs
LRFR	Load and Resistance Factor Design (LRFD)	AASHTO LRFD
NDT	----------	----------
Engineering Judgment*	----------	----------
Assigned Load Rating*	LFD or LRFD	AASHTO Standard or LRFD

Note: * Special requirements must be met to be acceptable as a valid load rating.

In addition, the 2nd Edition MBE allows assigning a load rating to a bridge based on its design load. Even though the 2nd Edition MBE has not been incorporated in the current regulation (NBIS), FHWA issued a policy memo on September 29, 2011 and formally accepted the Assigned Load Ratings as valid if all the conditions set forth in Articles C6A.1.1 or C6B.1 are met.

The adoption of the LRFD by AASHTO in the first edition of the AASHTO LRFD Bridge Design Specifications [7] in 1994 was considered a significant break-through. The load and resistance factors are derived from probabilistic models. Strength limit states are calibrated to achieve a uniform reliability. The LRFR was the load rating method based on the LRFD methodology. Legal loads including AASHTO routine commercial vehicles and specialized hauling vehicles, and permit loads were also calibrated with Weight-in-Motion data through National Cooperative Highway Research Program (NCHRP) projects managed by Transportation Research Council. The structural redundancy and bridge condition such as deterioration resulting from corrosion or other structural degradation can be taken into account with the System Factor and Condition Factor in the LRFR.

As specified in FHWA Memorandum regarding Bridge Load Ratings for the National Bridge Inventory dated October 30, 2006, new bridges and totally replaced bridges designed after October 1, 2010 must be load rated with the LRFR method specified in the AASHTO MBE. The primary reason for FHWA to promote the LRFR method is the uniform reliability and potential benefits and advantages of this new methodology. A National LRFR Implementation Status Survey was conducted in September 2011. Survey results showed that at the time of the survey, 92% of States used LRFR to rate bridges designed with LRFD, 40% used LRFR to rate bridges designed under AASHTO Standard Specifications, and 52% of States have their own State-specific policies and procedures to implement LRFR.

Structural Reliability

During the development of AASHTO LRFD Bridge Design Specifications and calibration of the LRFR load rating method [9], there has been considerable research and data gathering in highway bridge loadings and component resistances.

The limit state function is defined as

$$\boldsymbol{g = R - D}$$

where $\boldsymbol{D}$ and $\boldsymbol{R}$ are the load effect and resistance, respectively. Both $\boldsymbol{D}$ and $\boldsymbol{R}$ are statistically distributed with the uncertainty of their values at the time that the component is designed or evaluated. The probability of failure can be written as

$$\boldsymbol{P_f = P[g < 0] = P[R < D]}$$

Alternatively, one can use the reliability index, β, to measure the safety margin,

$$\boldsymbol{\beta = \frac{\overline{g}}{\sigma_g}}$$

where $\boldsymbol{\overline{g}}$ and $\boldsymbol{\sigma_g}$represent the mean and standard deviation of the random number, $\boldsymbol{g}$. If $\boldsymbol{\overline{g}}$ is large (a positive value means safe) and/or $\boldsymbol{\sigma_g}$ is small, the probability that $\boldsymbol{g}$ will fall below zero or that failure will occur will be small. The greater the reliability index, $\boldsymbol{\beta}$, the greater the safety margin, or the smaller the probability of failure.

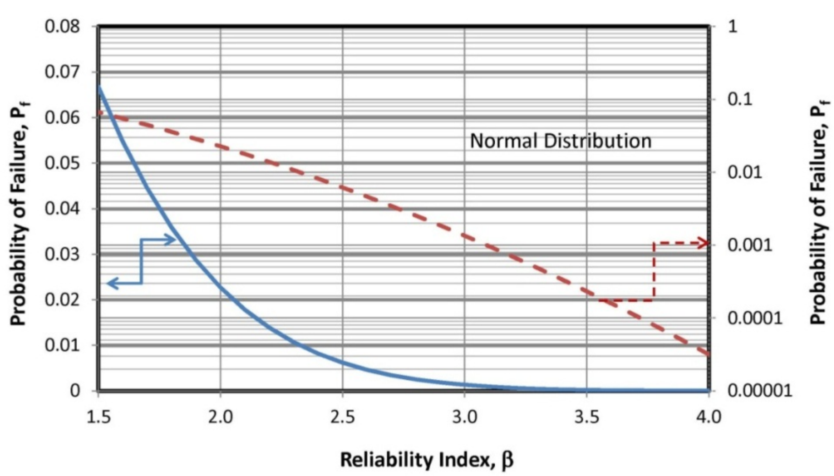


FIGURE 1: RELIABILITY INDEX VS. PROBABILITY OF FAILURE

The relationship between the reliability index and probability of failure is shown in Figure 1, assuming that $\boldsymbol{g}$ follows a normal distribution. Corresponding to a reliability index of 3.5 (target index for design), $\boldsymbol{P_f} \approx 0.00023$. For legal load ratings, $\boldsymbol{\beta}$ and $\boldsymbol{P_f}$ are 2.5 and 0.00621, respectively. Note that the duration of exposure for design is the design life of the bridge, however, the duration for legal load ratings is the inspection cycle.

Table 3 lists the target reliability indices for different levels of evaluation used in load and resistance factor design and rating during the calibration of the AASHTO LRFD and LRFR.

TABLE 3: TARGET RELIABILITY INDICES

Evaluation Level		Reliability Index $\boldsymbol{\beta}$
Design		3.5
Design Load Rating	Inventory Level	3.5
	Operating Level	2.5
Legal Load Rating		2.5
Permit Load Rating	Routine Permits	2.5
	Special Permits (Single Trip, Escorted)	2.5
	Special Permits (Single or Multiple Trip, Mixed in Traffic)	3.5

If $\boldsymbol{D}$ and $\boldsymbol{R}$ are normally distributed with a mean of $\overline{\boldsymbol{D}}$ and $\overline{\boldsymbol{R}}$, and a standard deviation of $\boldsymbol{\sigma_D}$ and $\boldsymbol{\sigma_R}$, $\boldsymbol{g}$ will be normally distributed too. $\boldsymbol{\beta}$ can be written as

$$\overline{\boldsymbol{g}} = \overline{\boldsymbol{R}} - \overline{\boldsymbol{D}}$$

$$\boldsymbol{\sigma_g} = \sqrt{(\boldsymbol{\sigma_R})^2 + (\boldsymbol{\sigma_D})^2}$$

$$\boldsymbol{\beta} = \frac{\overline{\boldsymbol{R}} - \overline{\boldsymbol{D}}}{\sqrt{\boldsymbol{\sigma_R^2} + \boldsymbol{\sigma_D^2}}}$$

If $\boldsymbol{D}$ and $\boldsymbol{R}$ follow a log-normal distribution, the reliability index can be computed with the following equation,

$$\boldsymbol{\beta} = \frac{\boldsymbol{ln}\left(\frac{\overline{\boldsymbol{R}}}{\overline{\boldsymbol{D}}}\right)}{\sqrt{\boldsymbol{V_R^2} + \boldsymbol{V_D^2}}}$$

where $\boldsymbol{V_R}$ and $\boldsymbol{V_D}$ are the coefficient of variation (COV) of $\boldsymbol{R}$ and $\boldsymbol{D}$, respectively, equal to the standard deviation divided by the mean.

If ***D*** and ***R*** follow other statistical distribution, a random simulation algorithm, such as Monte Carlo simulation, has to be utilized to compute the reliability index.

Different from new design, load ratings must consider the real physical condition of a bridge at the time of rating. Deteriorations may change the load distribution in the structure, and/or reduce the resistance of structural components. Therefore, LRFR introduces a condition factor to account for the physical condition of a bridge/member in computing its load ratings.

Figure 2 demonstrates the impact of structural condition change on the probability of failure during the life of a bridge. Figure 3 shows the reliability index vs. the condition factor (1.0 refers to no deterioration; 0.75 means 25% reduction in resistance.).

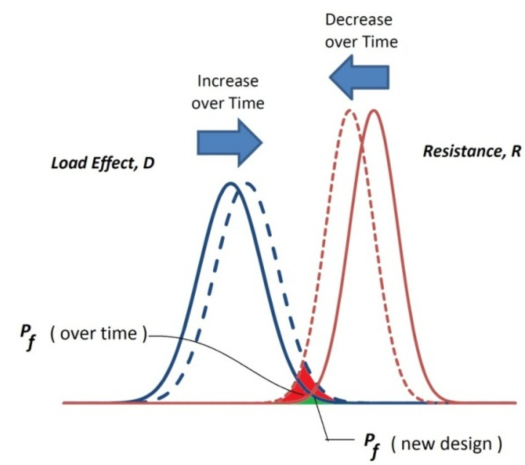


FIGURE 2: PROBABILITY OF FAILURE OVER TIME

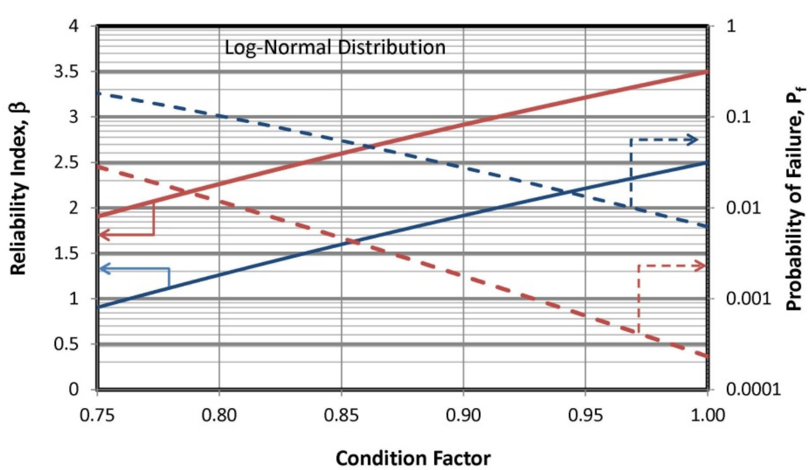


FIGURE 3: RELIABILITY INDEX AND PROBABILITY OF FAILURE OVER TIME

The computation of the reliability index is dependent of the statistics of load and resistance data. In calibrating the LRFR, Moses [9] used normal distribution models for dead loads and resistance and a log-normal distribution model for live loads (see Table 4).

TABLE 4: STATISTICS FOR RELIABILITY INDEX CALIBRATION [9]

Case	Bias	COV	Distribution
Dead Load	1.14	0.08	Normal
Live Load	1.00	0.18	Log-Normal
Resistance	1.12	0.10	Normal

Bias: the ratio of the mean value to nominal design value.
COV: the ratio of the standard deviation to mean value.

Load and Resistance Factor Rating Method

The LRFR method was first introduced in the AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges [6] in 2003. The Guide Manual further evolved into the AASHTO Manual for Bridge Evaluation (MBE), 1st Edition, 2008, and the 2nd Edition of the MBE published in 2011. Even though the MBE includes all three analytical load rating methods (ASR, LFR and LRFR), the LRFR method is considered the most advanced. It is a reliability-based method for bridge live load capacity evaluation.

1. Load rating methodology

Bridge design and rating are similar in the overall approach, but differ in several aspects. LRFD design method was calibrated for a reliability index of 3.5 for strength limit states and requires checking strength and service limit states to ensure serviceability and durability for a service life of 75 years with limited maintenance. Bridge ratings generally require the Engineer to consider a wider range of variables than bridge design.

The added cost of overly conservative evaluation standards would be prohibitive, since load restrictions, rehabilitation, and replacement would increase. Therefore, the LRFR method adopted two levels of reliability for different rating vehicles with different length of exposure duration (design life for design load rating and inspection interval for legal load rating). Design load rating (HL-93 live loading) includes inventory level rating with the same target reliability index of 3.5 as used in design. It is primarily used to compare an existing bridge to a new design. Operating level rating of the design load is based on a reduced reliability index of 2.5, mainly served as a screening tool for legal load rating.

Legal loads are the vehicles legally allowed to use on bridges in the United States or a specific State. The federal regulation Formula B defines the configuration and axle weight of a legal vehicle. AASHTO MBE includes some common vehicle types such as the Routine Commercial Vehicles Type 3, 3S2 and 3-3, and Specialized Hauling Vehicles SU4, SU5, SU6 and SU7. Most States also have their own State-specific legal vehicles.

Legal load rating recognizes a shorter duration of exposure corresponding to the routine inspection cycle. For a balance between reliability and economy, a lower target reliability of 2.5 has been chosen for legal load rating at the strength limit state. Application of serviceability limit states is done on a more selective basis than prescribed for design. The main purpose of legal load ratings is to determine load posting needs.

Permit load rating is to ensure the safe operation of highway bridges by evaluating the bridge capacities under over-weight vehicles requiring a permit. For annual routine permits and escorted single-trip permits, a reliability index of 2.5 was used. For single-trip and multiple-trip special permits allowing the permit vehicles to mix with traffic, a reliability index of 3.5 was selected.

2. Rating equation

The load rating formula is shown below.

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

For the Strength Limit States:

$$C = \varphi_c \, \varphi_s \, \varphi \, R_n$$
$$\varphi_c \, \varphi_s \geq 0.85$$

For the Service Limit States:

$$C = f_R$$

RF denotes the Rating Factor. C is the Capacity, equal to the allowable stress f_R or the factored member resistance. R_n represents the nominal member resistance in the LRFD code and computed from the as-inspected condition. DC, DW, P, LL and IM denote the load effects due to weight of structural components and attachments, weight of wearing surface and utilities, other permanent loads, live load, and dynamic allowance, respectively. γ_{DC}, γ_{DW}, γ_P and γ_{LL} are the corresponding load factors. φ_c, φ_s and φ are the condition factor, system factor and resistance factor, respectively.

3. Condition factor

The condition factor, φ_c is to account for the increased uncertainty in the capacity of deteriorated members and the likely increased future deterioration of these members between inspection cycles. φ_c varies from 0.85 to 1.0 depending on the structural condition.

TABLE 5: CONDITION FACTOR

Structural Condition of Member	Superstructure Condition Rating (SI&A Item 59)	Condition Factor, φ_c
Good or Satisfactory	6 or Higher	1.00
Fair	5	0.95
Poor	4 or Lower	0.85

4. System factor

The system factor, φ_s is to account for the level of redundancy of the complete superstructure system. φ_s corresponds to the load factor modifier for redundancy in the LRFD Specifications.

TABLE 6: SYSTEM FACTOR FOR FLEXURAL AND AXIAL EFFECTS

Superstructure Type	System Factor, φ_s
Welded Members in Two-Girder/Truss/Arch Bridges	0.85
Riveted Members in Two-Girder/Truss/Arch Bridges	0.90
Multiple Eyebar Members in Truss Bridges	0.90
Three-Girder Bridges with Girder Spacing 6 ft (1.83 m)	0.85
Four-Girder Bridges with Girder Spacing ≤4 ft (1.22 m)	0.95
All Other Girder Bridges and Slab Bridges	1.00
Floorbeams with Spacing >12 ft (3.66 m) and Noncontinuous Stringers	0.85
Redundant Stringer Subsystems between Floorbeams	1.00

5. Loads

All permanent loads shall be considered in the load ratings. In addition to dead loads, pre-stressing/post-tensioning and any locked-in forces during construction should be included in the calculation. If the secondary load effects from creep and shrinkage will reduce the load ratings, such effects should also be considered for some types of bridges such as segmental concrete bridges.

For design load rating, the design live load model of HL-93 specified in the LRFD Specifications shall be used. For legal load rating, load ratings should be conducted for AASHTO legal loads, as specified in MBE 2nd Edition Article 6A.4.4.2.1a, and the Notional Rating Load (NRL) as specified in MBE 2nd Edition Article 6A.4.4.2.1b, or State-specific legal loads. For permit load rating, the actual permit truck shall be used in the load rating analysis.

For different load ratings, different dynamic allowance may be used per the MBE, considering the riding surface roughness and vehicle travelling speed. However, a dynamic allowance of 0.3 shall not be reduced for design load rating. The load factors to be used in the load rating are specified in MBE 2nd Edition Table 6A.4.2.2-1.

TABLE 7: LIVE LOAD FACTORS

Traffic Volume (One direction)	Load Factor for Type 3, Type 3S2, Type 3-3 and Lane Loads	Load Factor for NRL, SU4, SU5, SU6, and SU7
Unknown	1.8	1.6
ADTT ≥ 5000	1.8	1.6
ADTT = 1000	1.65	1.4
ADTT ≤ 100	1.4	1.15

Linear interpolation is permitted for other *ADTT*.

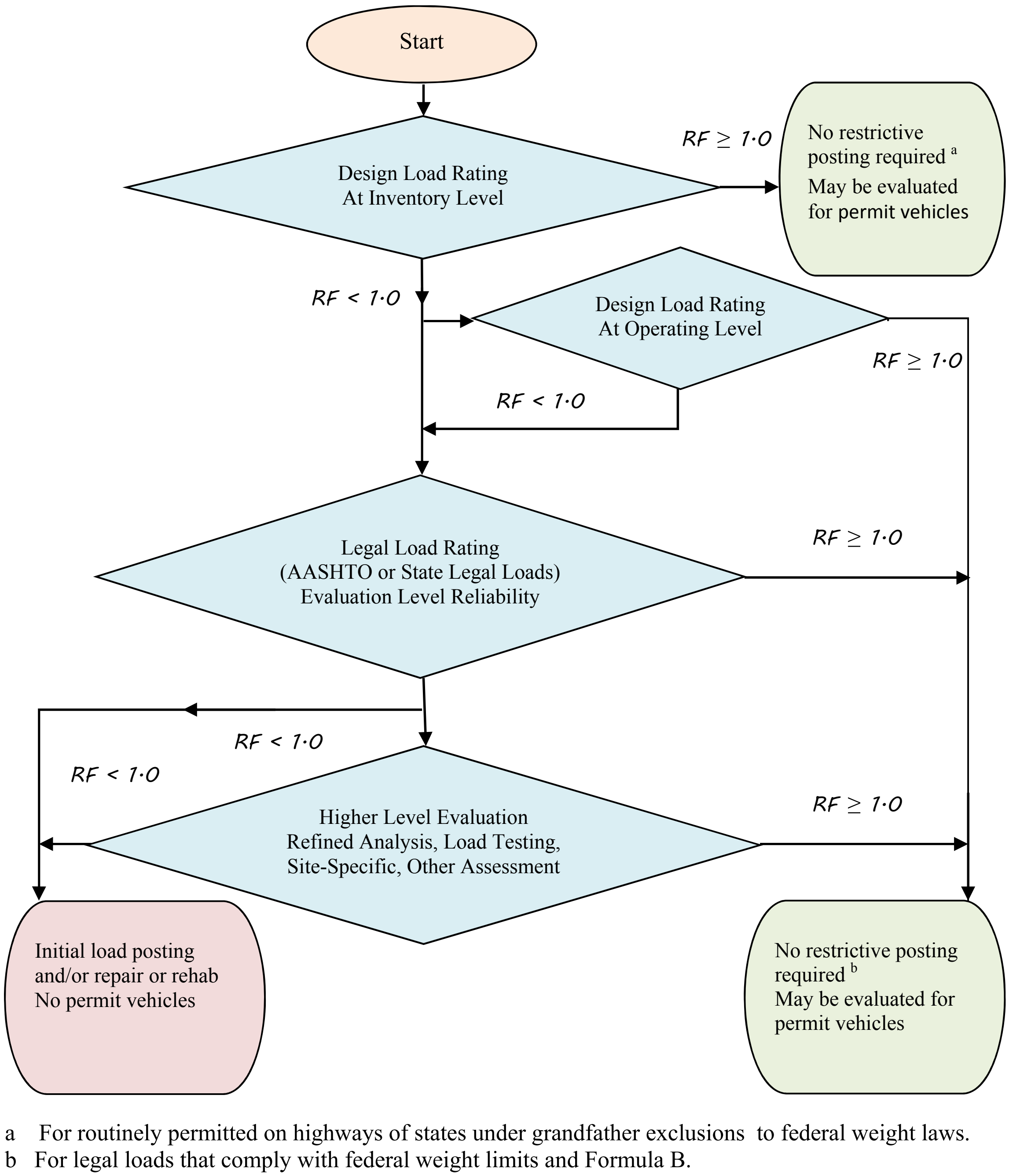
6. Limit states

Strength is the primary limit state for load rating. Service and fatigue limit states are selectively applied in accordance with the provisions of the MBE. The applicable limit states are summarized in MBE 2nd Edition Table 6A.4.2.2-1.

7. Rating procedure

In load rating a bridge, the structural condition and extent of deterioration of structural members should be considered in the computation of the load effects and the capacities. Whenever a change in structural condition or loadings occurs and the change reduces the live load carrying capacity of the bridge, a re-rating should be performed.

In the LRFR, the load rating procedures are structured to be performed in a sequential manner (the flowchart in MBE 2nd Edition Appendix A6A), starting with design load rating. In addition to fulfilling the NBI reporting required by the NBIS, it also serves as a screening. Load rating for AASHTO legal loads is required only when the load rating factor of the design load rating is lower than 1.0. Furthermore, only bridges that pass the load rating for AASHTO legal loads should be evaluated for overweight permits. Otherwise, the bridge should be posted or closed.

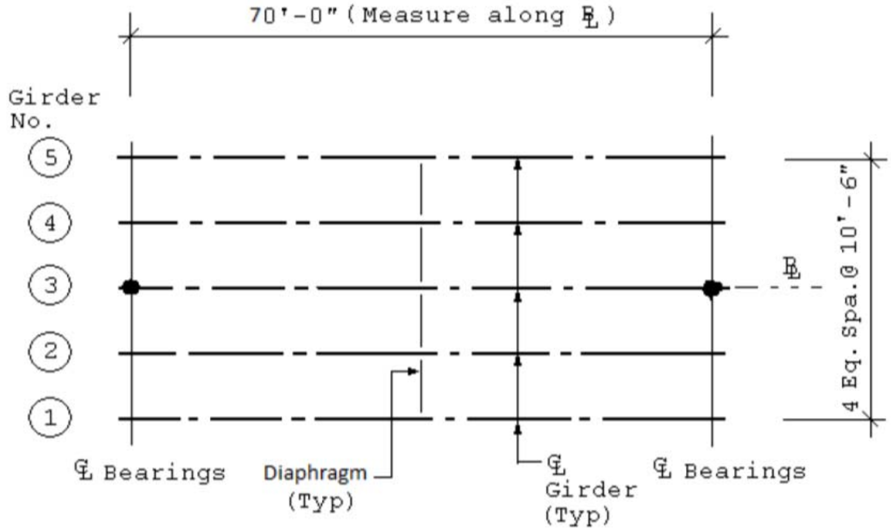


a For routinely permitted on highways of states under grandfather exclusions to federal weight laws.
b For legal loads that comply with federal weight limits and Formula B.

FIGURE 4: LOAD AND RESISTANCE FACTOR RATING FLOWCHAR

Illustrative Examples

This example is to demonstrate the LRFR through rating a simple span precast prestressed concrete AASHTO I girder bridge. Shears are not rated in this example. The bridge was built in 1975. From the most current inspection, Superstructure Condition (SI & A Item 59) was rated 4. The section loss is minimal. There is no shear distress noted. The thickness of overlay was field measured/verified. Figure 5 shows the framing plan and typical section of this bridge. The rating below calculation is for an interior girder.



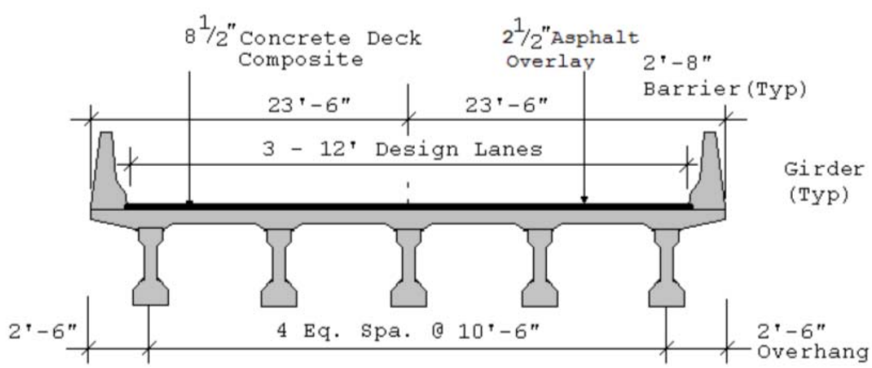


FIGURE 5: FRAMING PLAN AND TYPICAL SECTION
Unit Conversion: 1 k-ft = 1.356 kN.m; 1 ksi = 6.895 MPa; 1 ton = 8.896 kN.

- Span length: 70 ft (21.336 m).
- AASHTO Type III precast prestressed concrete I girders spaced at 10-6" (3.2 m).
- 8½" (216 mm) concrete deck and 2 ½" (64 mm) asphalt overlay.

- Prestressing steel: Low-relaxation 0.5"ϕ (ϕ12.5 mm) strands, Grade 270.
  Yield strength: f_{py} = 243 ksi (1675 MPa).
  Tensile strength: f_{pu} = 270 ksi (1862 MPa).
- Concrete – Precast I Girder: f'_c = 6000 psi (41.4 MPa).
- Concrete – Deck: f'_c = 4000 psi (27.6 MPa).

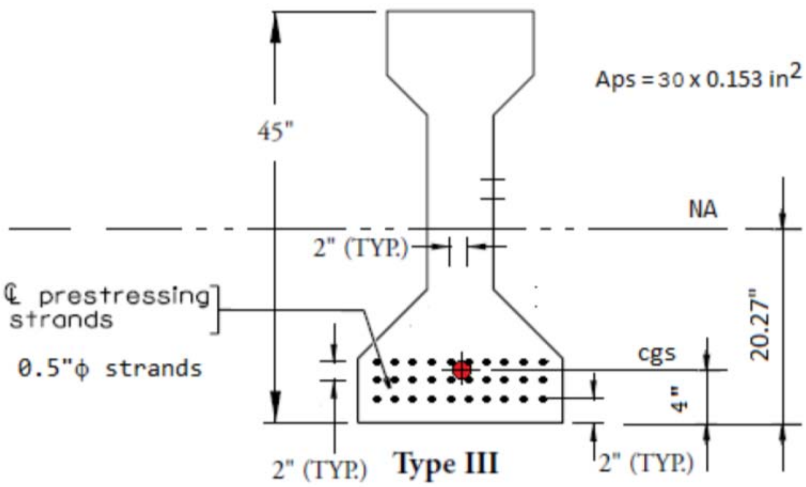


FIGURE 6: PRESTRESSING LAYOUT
Unit Conversion: 1 k-ft = 1.356 kN.m; 1 ksi = 6.895 MPa; 1 ton = 8.896 kN.

The design load, HL-93, and legal loads, AASHTO Type 3, 3S2 and 3-3, and specialized hauling vehicles, SU4, SU5, SU6 and SU7, are considered in the calculation.

As an illustrative example, only flexural capacity for Strength I and flexural stress for Service III limit states are included. A condition factor of 0.85, corresponding to the superstructure condition rating of 4, is included in Strength I. The live load factors are as follows,

γ_{LL} = 1.75, for Inventory Level of design load rating

γ_{LL} = 1.35, for Operating Level of design load rating

γ_{LL} = 1.8, for unknown ADTT and AASHTO Type 3, 3S2 and 3-3

γ_{LL} = 1.6, for unknown ADTT and SU4, SU5, SU6 and SU7

The results are shown in Table 8 below. Note that the shaded boxes are optional. Based on the results, there is no need to post this bridge for strength. However, State may post it in accordance with the serviceability (Service III).

TABLE 8: LOAD RATING RESULTS

Load Rating Type	Load Type		Live Load Effects		Flexure RF		Controlling Rating	
			M_{LLIM} (k-ft)	f_{LLIM} (ksi)	Strength I	Service III	RF	RT (tons)
Design Load Rating	HL-93	Inventory	1415.0	-1.544	0.98	0.77	0.77	-
		Operating	1415.0	-1.544	1.27		1.27	-
Legal Load Rating	Routine Commercial Vehicles	Type 3	795.3	-0.868	1.69	1.09	1.09	27.3
		Type 3S2	875.6	-0.955	1.54	0.99	0.99	35.7
		Type 3-3	818.9	-0.893	1.64	1.06	1.06	42.4
	Specialized Hauling Vehicles	SU4	893.3	-0.975	1.69	0.97	0.97	26.2
		SU5	988.2	-1.078	1.53	0.88	0.88	27.2
		SU6	1100.2	-1.200	1.38	0.79	0.79	27.4
		SU7	1200.0	-1.309	1.26	0.72	0.72	28.0

Unit Conversion: 1 k-ft = 1.356 kN.m; 1 ksi = 6.895 MPa; 1 ton = 8.896 kN.

Closing Remarks

LRFR is a reliability-based method for evaluating the bridge live load capacity. A majority of States in the United States have developed guidelines and policies to implement the LRFR method, and have started to utilize this method to rate their highway bridges. The LRFR method offers greater consistency and uniformity in reliability.

Acknowledgements

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