NCHRP Web Document 28 (Project C12-46): Contractor's Final Report

Manual for Condition Evaluation and Load Rating of Highway Bridges Using Load and Resistance Factor Philosophy

Prepared for:

National Cooperative Highway Research Program
Transportation Research Board
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Submitted by:

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SECTION 1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

The AASHTO *LRFD Bridge Design Specifications* introduce a limit states design philosophy, based on structural reliability methods, to achieve a more uniform level of safety (reliability) throughout the system. The Specification is also a state-of-the-art document that advances new developments in structural forms, structural behavior, live load and resistance models, and methods of analysis. The current AASHTO *Manual for Condition Evaluation of Bridges* (MCE) contains provisions for only the conventional (deterministic) Allowable Stress and Load Factor methods of load rating existing bridges. Hence there is an acute need for a comprehensive new evaluation manual that will not only be consistent in philosophy and approach with the LRFD Specifications but will also be technologically current.

The new LRFD code introduces the philosophy of limit states design, which in essence is a systematic way of considering all applicable limit states in the design of new bridges. This philosophy is now to be extended to the evaluation of existing bridges. Bridge design and evaluation, though similar in overall approach, differ in important aspects. In the design stage there is greater uncertainty in loading over the life of the bridge whereas in evaluation there is greater uncertainty on the resistance side, especially in the case of degraded bridges. Upgrading an in-service bridge is far more costly than incorporating extra capacity at the design stage. Therefore, a more refined approach to evaluating the load capacity of an existing bridge can be economically justified.

Structural reliability methods contain the necessary ingredients to provide a more rational, a more flexible, and a more powerful evaluation strategy for existing bridges. In a reliability based approach the evaluation could provide a uniform safety level, without resorting to traffic restrictions or strengthening, by reducing uncertainties. This can be done by obtaining improved resistance data, site-specific traffic data, and improved load distribution analysis. In evaluation, uncertainties can be reduced based upon site-specific considerations that were unavailable to the designer.

1.2 SCOPE OF THE PROJECT

NCHRP Project 12-46 was initiated in March 1997 to develop a new AASHTO Load and Resistance Factor Rating Manual for highway bridges. A Lichtenstein led Research Team was awarded the contract for the project. Mr. Charles Minervino was the Principal Investigator and Mr. Bala Sivakumar was the Co-Principal Investigator. Dr. Fred Moses and Dr. Dennis Mertz served as consultants to Lichtenstein.

The objective of the project was to develop a manual with supporting commentary and illustrative examples for the evaluation of highway bridges by the Load and Resistance Factor Method. The new Manual will be consistent with the LRFD Specifications in using a reliability based limit states philosophy. This Manual will serve as a standard for determining the physical condition, maintenance needs and load capacity of the Nation’s highway bridges.

The primary goal of the Research Team was to produce a practical manual that is easy to understand and use, which builds upon past experience. The reliability aspects remain invisible to the evaluation engineer through the use of calibrated load and resistance factors, as was done in the LRFD Specifications. The new load rating procedures are presented in a way that allows their use in a deterministic manner, making them appear almost as an extension of the Load Factor rating method.

In the LRFD Specifications much of the emphasis and calibration of design factors was based on multi-girder steel and concrete bridges that were considered representative of current and future trends in bridge design. In developing a compatible evaluation manual it was important to recognize that the existing

inventory of bridges is comprised of a wide array of bridge types, structural systems, material types, and physical conditions. Additionally, the evaluation criteria pertaining to reliability indices, limit states, and load and resistance models could be different

The Research Team recognizes the wide range of potential users, and just as importantly the large number of structure types and range of conditions that must be reflected to facilitate implementation of the manual as a comprehensive all inclusive document. The Research Team's goal was to produce a manual that will not only meets the evaluation needs of our inventory of bridges but will also receive broad support for adoption and distribution by the AASHTO Subcommittee on Bridges and Structures.

1.3 OVERVIEW OF THE RECOMMENDED MANUAL

The recommended Manual represents a major overhaul of the existing AASHTO *Manual for Condition Evaluation (MCE)*. All but two sections of the current MCE have been entirely rewritten. The new Manual advances many new technologies and state-of –the art procedures to bridge evaluation, just as it was done in the LRFD Specification for new bridge design. Some of the important changes include:

- A new section on load rating bridges using the Load and Resistance Factor philosophy.
- Numerous illustrative load rating examples to demonstrate the use of the Manual.
- Load rating procedures that are contingent upon the live load model and the intended use of evaluation results.
- Procedures to determine site-specific live load factors for load rating.
- Customized load factors by permit type for overload permit review.
- A new section on fatigue evaluation of steel bridges.
- A new section on non-destructive load testing of bridges.
- Parallel commentary

The Manual has been divided into nine sections:

1. Introduction
2. Bridge File (Records)
3. Bridge Management Systems
4. Inspection
5. Material Testing
6. Load and Resistance Factor Rating
7. Fatigue Evaluation of Steel Bridges
8. Non-Destructive Load Testing
9. Special Topics

Appendix A: Illustrative Examples

Section 1 contains introductory and background information on the maintenance inspection of bridges as well as definitions of general interest terms. Key components of a comprehensive bridge file are defined in Section 2. The record of each bridge in the file provides the foundation against which changes in physical condition can be measured. Changes in condition are determined by field inspections. A Bridge Management System is an effective tool in allocating limited resources to bridge related activities. An overview of Bridge Management Systems is included in Section 3. The types and frequency of field inspections are discussed in Section 4, as are specific inspection techniques and requirements. Conditions at a bridge site or the absence of information from original construction may warrant more elaborate material tests, and various testing methods are discussed in Section 5. Section 6 sets forth

procedures for the evaluation of bridges using the Load and Resistance Factor method. The evaluation of existing bridges for fatigue is discussed in Section 7. Field load testing is a means of supplementing analytical procedures in determining the live load capacity of a bridge and for improving the confidence in the assumptions used in modeling the bridge. Load test procedures are described in Section 8. Section 9 is entitled Special Topics, and deals with the evaluation of masonry bridges and other bridge related issues.

1.4 PROJECT HISTORY AND SUBMISSIONS

Research activities on NCHRP Project 12-46 commenced in March 1997. Submission of the Interim Report in September 1997 marked the completion of Tasks 1 through 5 of this project. The main focus of this initial research was to identify and define the key technical issues and evaluation criteria to be applied in evaluating existing bridges by the Load and Resistance Factor method. Once this was accomplished a proposed evaluation procedure was developed that was philosophically consistent with the LRFD Specifications and provides flexibility while maintaining a uniform level of reliability. A plan for calibrating load and resistance factors that achieve uniform reliability was developed. Potential changes and revisions to the current MCE were identified and an outline for the new Manual was prepared. An updated Work-plan for Tasks 6 through 11 was also included in the Interim Report.

In accordance with the approved work-plan, the Research Team commenced work on the preparation of the Manual and supporting commentary, calibration of evaluation factors for uniform reliability, and the development of illustrative examples to demonstrate the use of the Manual. An early draft of the Manual was submitted for Panel reviews in August 1998. Review comments were incorporated into a pre-final Draft Manual completed in March 1999. The Manual was then subjected to widespread reviews and testing through trial ratings by fifteen volunteer States. The final Draft of the Manual, containing extensive revisions to the load rating section and examples resulting from the testing phase results and review comments, was completed in March 2000 and distributed to the fifty States by NCHRP.

The purpose of this Final Project Report is to provide supporting information for the proposed AASHTO *Manual for Condition Evaluation and Load and Resistance Factor Rating of Highway Bridges*. This report also contains the details of the project history; this includes the testing phase that was part of the project and comments by the States and responses by the Research Team (in section 3).

Project deliverables for NCHRP Project 12-46 consist of the Interim Report (Sept. 1997), the Final Draft Manual (March 2000), the Calibration Report (March 2000), and this final project report. This final report gathers background information used in the development of the Manual that is not otherwise published and summarizes the work performed under the project. The calibration report, included as an Appendix to this report, addresses the determination of the load and resistance factors that have been developed for use with legal and permit traffic in evaluating the continuing use of existing bridges. All statistical data and reliability modeling details for the project are contained within the calibration report.

Maintaining an interactive approach between the Research Team the Project Panel, AASHTO Technical Committee T18, and State DOTs and industry experts was considered vital to ensure the success of this project. Ongoing communications were made through periodic submissions to NCHRP, meetings with the Project Panel and AASHTO, and presentations by the Research Team at the AASHTO Bridge Engineers' Conference and other major bridge forums. Two draft versions of the Manual were prepared and submitted for review prior to the completion of the final draft in March 2000. The project chronology given below summarizes the project milestones/submissions and meetings history:

Project Chronology

		Start of Project	March	1997
	Task 1			
	Task 2			
	Task 3			
	Task 4			
		Presentation AASHTO T-18	June 1997	
Submit	Task 5	Interim Report	September	1997
		Review Meeting w/ Panel & T-18	October, 14	1997
		Begin Manual Preparation	December	1997
	Task 6			
	Task 7			
	Task 8			
		Presentation to AASHTO T-18	June 1998	
Submit		Draft 1 of Manual	August	1998
		Review Meeting w/ Panel & T-18	December, 1	1998
Submit	Task 9	Draft 2 of Manual	February	1999
		Presentation to AASHTO T-18	June	1999
		Begin State DOT Testing Phase	June	1999
		Receive Trial Ratings & Comments from States	July to October	1999
		Review Meeting w/Panel & T-18	December 6,7	1999
Submit	Task10	Final Draft Manual	March	2000
Submit		Calibration Report	March	2000
		Presentation to AASHTO T-18	May	2000
Submit	Task11	Draft Final Project Report	July	2000
Submit		Final Report	Aug	2000

SECTION 2.0 EXECUTION OF THE PROJECT WORK PLAN

The project was organized into eleven specific tasks by the NCHRP Research Project Statement and the approved work plan. Tasks 1 through 4 were focused on identifying and defining key technical issues and evaluation criteria to be applied to the evaluation of existing bridges by the load and resistance factor method. The findings of this research were presented in an Interim Report developed under Task 5. Manual development and calibration studies were performed under Tasks 6 through 10. This final report constitutes the work performed under the final task, Task 11. The work performed under each task is described in the following paragraphs.

TASK 1: *Review relevant practice, literature, existing guidance, and research findings from foreign and domestic sources. This information shall be assembled from both technical literature and unpublished experiences of bridge owners, bridge engineers, inspectors, maintenance personnel, consultants, and others.*

1) Literature Search

The Research Team performed a search, assembly, and review of technical papers, research reports, and foreign bridge evaluation codes considered relevant to the current project. Many NCHRP research reports pertaining to bridge evaluation and management were reviewed. A search of published technical papers was performed through the Transportation Research Information Services (TRIS), ASCE Linda Hall Library Search Service, and the Worldwide Web and GOPHER (INTERNET). Over two thousand citations were obtained. The list was narrowed to a few hundred citations closely related to the project. The publications were from both domestic and foreign sources. Full text versions of many technical papers relevant to the key issues to be addressed were obtained and reviewed.

2) Review of Foreign Bridge Evaluation Codes

Most of the major structural codes in the world are moving toward probabilistic methodologies. The Research team reviewed leading bridge design and evaluation codes from Canada, the United Kingdom, Australia, and Switzerland to better understand recent developments in bridge specifications.

3) Survey of States

The Research Team prepared and mailed a comprehensive survey questionnaire to the State Bridge Engineers. The purpose of the questionnaire was to obtain State DOT comments on the current AASHTO MCE, AASHTO Guide Specifications, and solicit opinions on technical issues pertaining to the inspection, evaluation, and load rating of bridges. The responses were most valuable in developing the Load and Resistance Factor evaluation criteria, proposed load rating procedures, improvements needed to the current MCE, and in ascertaining the current state of bridge evaluation practice in the U.S. A complete tabulation of Questionnaire responses was prepared as a separate document.

The Questionnaire explored the following nine topics considered relevant to this project:

1. Inspection
2. Load Rating
3. Load Posting and Overload Permit Checking
4. Nondestructive Load Testing of Bridges
5. Bridge Management System
6. Past-Performance of Bridges
7. 1994 AASHTO Manual for Condition Evaluation (MCE)
8. 1989 AASHTO Guide Specifications for Strength Evaluation
9. 1990 AASHTO Guide Specifications for Fatigue Evaluation

4) Review of AASHTO Specifications for Bridge Evaluation

Of particular relevance to this project are the following AASHTO bridge evaluation documents:

1) 1989 GUIDE SPECIFICATIONS FOR STRENGTH EVALUATION OF EXISTING STEEL AND CONCRETE BRIDGES.
2) 1990 GUIDE SPECIFICATIONS FOR FATIGUE EVALUATION OF EXISTING STEEL BRIDGES
3) 1994 MANUAL FOR CONDITION EVALUATION OF BRIDGES.

The Research Team conducted a thorough review of these documents. The 1989 AASHTO *Guide Specifications for Strength Evaluation* was the first implementation of a structural-reliability-based specifications for bridge evaluation in the US. Despite the advances in reliability methods and bridge engineering in the intervening years many elements of the supporting research and calibration methodologies are still relevant. Similarly, the 1990 AASHTO *Guide Specifications for Fatigue Evaluation* provide probabilistic methods for the calculation of remaining fatigue-life of existing bridges. The Interim report for this project contains a critique of these documents. It is expected that once the new Manual is adopted these documents will be sunset after a transition period. Fatigue evaluation provisions consistent with the LRFD Specifications have been developed and incorporated into the new Manual. The proposed Manual is envisioned to gradually replace the current AASHTO *Manual for Condition Evaluation.*

TASK 2: *Identify and discuss areas in current bridge inspection, evaluation, and load-rating procedures requiring interpretation, clarification, or modification for the development of a condition-evaluation manual that is consistent with the AASHTO LRFD bridge specifications.*

The objective of this research was to develop a bridge evaluation manual that is philosophically consistent with the LRFD Specifications. To this end, it was necessary to define certain key issues that relate to the differences between design and evaluation, and develop a rationale and approach to their resolution. The following key issues were identified as being central to the development of the new Manual:

- Exposure Period
- Reliability Indices
- Limit States
- Live Load Models
- Resistance Modeling
- System redundancy
- Ductility
- Connections and Splices
- Load Posting
- Permit Review
- Data Collection for Load Rating

Detailed discussions on these issues, available options for their resolution, and suggested evaluation criteria prepared by the Research Team are contained in Chapter 5 of the project Interim Report (Sept. 1997).

Task 3: *Recommend a load model(s) for rating and develop a plan for calibrating load and resistance factors for the appropriate strength and serviceability limit states in the manual. Provide a rationale and approach for the development and inclusion of appropriate provisions for the manual. Issues to be addressed include the definition of limit states, selection of one or more appropriate reliability indices, and development of load and resistance models for evaluation.*

The nominal live load effect and the load and resistance factors must be selected in the code calibration process to achieve pre-assigned goals, including uniform reliability. In a design specification, such as the AASHTO LRFD Bridge Specification, the selection of these factors is fixed based on information available to the specification writers. In the bridge evaluation activity, however, calibration is more complex due the added knowledge about an existing span that may be available to the evaluator and the greater variety of decisions that may have to be made. The product of a calibration process is a series of load factors to be used for checking at different levels including non-permit traffic, posting loads, and overweight permits.

The methodology for calibration was formulated and carried-out by Dr. Fred Moses (under Task 6). The steps include:

1) Define the limit state conditions that should be controlled by the code.
2) Assemble the relevant data-base on the various load and resistance variables.
3) Establish the target safety indices based on existing performance experience.
4) Formulate a checking model.
5) Calibrate the load and resistance factors that achieve uniform reliability levels.

A report on the calibration work prepared by Dr Fred Moses has been published as *NCHRP Report 454*. This report provides the derivations of the live load factors, and presents traffic models and data-bases used in the calibration process. It is intended to serve as a reference for Manual users and for future developments and modifications of the LRFR methodology as more data and improved analysis methods become available.

Task 4: *Prepare a detailed outline for the manual based on the findings of Tasks 1 through 3. As a minimum, the outline will include chapter and topical headings along with a description of the intent of each topic and the data, references, or information sources that will be used to complete each section.*

The goal of this task was to prepare a proposed presentation format for the new Manual and commentary based upon the findings of Tasks 1 through 3. The research objective was to produce a practical Manual that is easy to understand and use that will receive broad-based support for adoption and distribution by AASHTO.

A proposed outline of the new manual with section and topical headings were provided in the Interim Report. Based on the findings of Tasks 1 through 3 several significant changes were proposed throughout the manual. Changes to several non-load rating sections were proposed to improve the Manual's applicability, usefulness, and organization. At the time of preparing the Interim Report the **major revisions** envisioned to the existing MCE were as follows:

- The current load rating section should be replaced in its entirety. A new section on evaluation of bridges using the Load and Resistance Factor philosophy should be included.
- A new section on fatigue evaluation of existing steel bridges should be included.
- The existing section on non-destructive load testing of bridges should be revised and expanded to provide additional coverage and guidance.

- A new section on Bridge Management Systems (BMS) that provides an overview of BMS used nationally should be included.
- The inspection section in the existing MCE should be revised to include inspection data collection requirements for load rating using LRFR.
- The commentary and illustrative examples in the existing MCE should be replaced with new material applicable to the Load and Resistance Factor methodology.
- Remaining sections of the existing MCE should be carried over into the new Manual with revisions and modifications as necessary to ensure consistency.

A discussion of these proposed changes is contained in project the Interim report.

Task 5: *Submit an interim report that documents the results of Tasks 1 through 4 and includes a detailed work plan and budget for the remainder of the project. The report must also describe the number and type of illustrative examples to be developed in Task 7, a proposed format for the final manual and commentary, and a preliminary discussion of the implementation plan described in Special Note A. NCHRP approval of the interim report will be required before proceeding with the remaining tasks.*

A detailed Interim Report that documents the results of tasks 1 through 4 was completed in September 1997 and submitted to NCHRP for review by the Project Panel and AASHTO Technical Committee T18. The topics covered in the report are as follows:

CHAPTER 1	INTRODUCTION
CHAPTER 2	LOAD AND RESISTANCE FACTOR PHILOSOPHY
CHAPTER 3	RESEARCH
CHAPTER 4	REVIEW OF AASHTO GUIDE SPECIFICATIONS
CHAPTER 5	DEVELOPMENT OF EVALUATION CRITERIA
CHAPTER 6	PROPOSED LOAD RATING PROCEDURE
CHAPTER 7	PLAN FOR CALIBRATION
CHAPTER 8	MANUAL OUTLINE
CHAPTER 9	WORK PLAN FOR TASKS 6 - 10
CHAPTER 10	ADDITIONAL CONSIDERATIONS AND SUGGESTED RESEARCH

A review meeting was held in Chicago on October 14, 1997. It was a joint meeting attended by AASHTO Committee T18 and the Project Panel. Several important decisions made at this meeting established a clear direction for the remaining research and Manual development. Written review comments on the Interim Report were later submitted to the Research Team. A point-by-point response to the review comments was prepared by the Research Team and submitted to the Program Manager. As directed by the Program Manager a revised Interim Report was not reissued. Work on the remaining tasks commenced in December 1997, in accordance with the approved work plan for tasks 6 through 10.

Task 6: *According to the approved work plan, conduct any necessary calibration and other analytical work, and prepare the manual with supporting commentary.*

Tasks 6 thru 11 comprised the “production” phase of the Manual and the project deliverables. The work under Task 6 included calibration of evaluation factors necessary to support the proposed LRFR evaluation procedures. The Research Team incorporated the comments and directives resulting from the panel’s review of the Interim Report into the calibration process outlined in the Interim Report.

Procedures to calibrate evaluation load factors for dead load, live load truck models, and posting and permit live loads, are described in the Calibration Report (March 2000) prepared by Dr. Fred Moses (*NCHRP Report 454*). The calibration effort utilized a number of variables that affect bridge safety. These include: resistance and loading data-base, definitions of limit states, site specific load models, incorporation of redundancy, testing, performance, inspection, and deterioration information. The data-base of truck weights from the LRFD Design Specifications was reviewed and compared to current weigh-in-motion data obtained by the Research Team. The truck multiple-presence model was refined to allow the derivation of load factors for a variety of traffic volumes commonly encountered at bridge sites. The product of the calibration process is a series of load factors to be used for load rating at different levels, including non-permit traffic, posting and permit loads. The live load factors were calibrated to provide a reliability level at least equivalent to the present levels associated with Operating rating levels of safety (Load Factor rating at Operating). Adjustment factors on the resistance factors have been specified to reflect deterioration, inspection, and system or multiple load paths.

Task 7: *Develop a sufficient number of illustrative examples to demonstrate the use of the manual for conducting load ratings for a variety of structure types, materials, and conditions. Provide comparative load ratings, based on current load-rating procedures, for the illustrative examples.*

Load rating examples are important to demonstrate the practical applications of the proposed LRFR methodology and to highlight the differences and compare the increased flexibility of the proposed procedure as compared to current methods. The examples can also be helpful in comparing the impact of the proposed methodology on current load rating and load posting practice. Due to the extensive changes proposed to current load rating practice added emphasis was placed on the illustrative examples during the preparation of the Manual.

The following load rating examples are included in the Manual:

Example	Bridge Summary		
A1	Simple Span	Composite Steel Stringer Bridge (Interior and Exterior Stringers)	65 FT
A2	Simple Span	Reinforced Concrete T-Beam Bridge	26 FT
A3	Simple Span	Prestressed Concrete I-Girder Bridge	80 FT
A4	Simple Span	Timber Stringer Bridge	17 FT 10 IN
A5	Four-Span Continuous	Welded Plate Girder Bridge	112 FT / 140 FT / 140 FT / 112 FT
A6	Single Span	Through Pratt Truss Bridge	175 FT
A7	Simple Span	Reinforced Concrete Slab Bridge	21 FT 6 IN
A8	Simple Span	Two-Girder Steel Bridge	94 FT 8 ¼ IN
A9	Simple Span	Prestressed Concrete Adjacent Box-Beam Bridge	70 FT

Table 2-1. Final Draft Manual Example Load Ratings

Task 8*: Develop a summary document that describes the major deviations from current practice resulting from the use of the manual developed in Task 6.*

The research team's proposed method of load and resistance factor evaluation of bridges is described in Chapter 6 of the Manual. We believe the procedures presented are highly consistent with the LRFD Bridge Design Specifications. On the other hand, the procedures are considerably different than the current bridge rating methods contained in the MCE. However, in many ways the LRFR approach may be viewed as an extension of the Load Factor method of rating than a radical new procedure.

A detailed discussion of the key differences and major deviation from current practice is contained in Section 5 of this report. This discussion is tied to the results of the trial rating phase, which provided a convenient basis for comparing and contrasting the LRFR methodology with LFR and its potential impact on current load ratings and postings.

Task 9: *Submit the complete manual with commentary, along with the illustrative examples and the summary document describing major deviations from current practice, for review by the NCHRP and AASHTO. Following review of these items, meet with the panel to discuss the task deliverables and the remaining research. The contractor will formally address written panel comments, as well as any issues raised at the panel meeting. NCHRP approval of the task deliverables will be required before proceeding with the remaining tasks.*

A first draft of the Manual with parallel commentary and illustrative examples was completed and submitted for Panel review in August 1998. A review meeting to discuss the draft Manual was held on December 1, 1998, in Washington D.C. and was attended by the Project Panel and AASHTO Committee T18. At this meeting it was agreed to expand the project to include broader testing of LRFR procedures by the States to better ascertain their impact on current ratings and postings. It was also realized that testing by potential end users would also reveal if the Manual was clear and being understood and interpreted correctly.

Task 10: *Based on the review comments emanating from Task 9, prepare and submit a revised manual with commentary, illustrative examples, and summary document describing the major deviations from current practice for review and subsequent revision.*

Numerous comments received during the review of the first draft Manual were addressed in writing by the Research-Team. Section 6 of the Manual was revised to reflect these comments as appropriate. Several additional load rating examples were prepared at the request of the Panel. A pre-final Draft Manual and a draft Calibration Report were completed and submitted for review in March 1999. In May 1999, Modification No. 1 was authorized, which provided additional funding in the amount of $50,000 to allow further testing of the Manual by various State DOTs. The contract completion date was extended from August 31, 1999, to September 30, 2000.

The purpose of the trial ratings is to test the applicability of the new Manual for Condition Evaluation and Load and Resistance Factor Ratings on a larger inventory of existing bridges of varied bridge types and to better ascertain the impact of the proposed LRFD methodology on current practice. The testing was done by 15 volunteer states. The states were requested to select bridges previously rated by the Load Factor method and re-rate same using the new Manual procedures and to compare the results. States are invited to select bridges of their choice from the list of bridge types provided. States may also select other bridge types of interest not included in the table. Over 75 bridges were load rated. The testing phase extended from June 1999 to January 2000. As a result of the state trial ratings a large number of revisions were being made to the Draft LRFR manual and load rating examples.

Wide-ranging comments generated during the testing phase were instrumental in effecting changes in content and organization of Section 6 (Load Rating). The Final Draft Manual was completed in March 2000 and submitted to NCHRP for distribution. The final draft incorporates extensive revisions to the March 1999 draft. Changes included: reorganization of load rating procedures for ease-of-use, recalibration of Special permit factors, revisions to concrete shear provisions, revisions to system and condition factors, and extensive revisions to the load rating examples.

Task 11: *Submit a final report describing the entire research project. Include the manual with commentary, illustrative examples, the document describing major deviations from current practice, and the implementation plan, as separate appendices.*

This final report is prepared to satisfy the requirements of this task.

SECTION 3.0 - MANUAL CONTENT SUMMARY

3.1 GENERAL LOAD RATING EQUATION

Unlike design where all applicable loads and load combinations are considered in the design process, in rating there is special interest in the live load and in the capacity of a member relative to the live load. The rating factor format allows the engineer to report the results of the evaluation in a compact form of the quantity of interest for bridge rating and posting, the live load rating factor.

The load rating is generally expressed as a rating factor for a particular live load model, using the general load rating equation. In LRFR the rating procedure is carried out at each applicable limit state and load effect with the lowest value determining the controlling rating factor. The following general expression is used in determining the load rating of each component and connection subjected to a single force effect.

$$\mathbf{RF} = \frac{C - \gamma_{DC}\, DC - \gamma_{DW}\, DW \pm \gamma_{p}\, P}{\gamma_{L}\, LL\,(1 + IM)}$$

For the Strength Limit States:
$C = \phi_c \phi_s \phi\, R$

Where the following lower limit shall apply:
$\phi_c\, \phi_s \geq 0.85$

For the Service Limit States:
$C = f_R$

Where:

RF	=	Rating Factor
C	=	Capacity
f_R	=	Allowable stress specified in the LRFD code
R_n	=	Nominal member resistance (as-inspected)
DC	=	Dead-load effect due to structural components and attachments
DW	=	Dead-load effect due to wearing surface and utilities
P	=	Permanent loads other than dead loads
LL	=	Live-load effect
IM	=	Dynamic load allowance
γ_{DC}	=	LRFD Load factor for structural components and attachments
γ_{DW}	=	LRFD Load factor for wearing surfaces and utilities
γ_p	=	LRFD Load factor for permanent loads other than dead loads
	=	1.0
γ_L	=	Evaluation live load factor
ϕ_c	=	Condition factor
ϕ_s	=	System factor
ϕ	=	LRFD resistance factor

Components subjected to combined load effects should be load rated considering the interaction of load effects (i.e., axial-bending interaction or shear-bending interaction), as provided in the Manual.

The load modifiers (η) relating to ductility, redundancy, and operational importance contained in the *LRFD Bridge Design Specifications* (Article 1.3.2.1) are not included in the general load rating equation. In load rating, ductility is considered in conjunction with redundancy and incorporated in the system factor ϕ_s. Operational importance is not included as a factor in the load rating provisions of the new Manual.

Secondary effects from prestressing of continuous spans and locked-in force effects from the construction process are included as permanent loads other than dead loads, P, in the load rating equation.

Condition Factor ϕ_c

Only sound material based on a recent thorough inspection should be considered in determining the nominal resistance of a section. Resistance factor ϕ used in rating is the same as for new design in LRFD. This approach is valid for existing members in good or satisfactory condition. Once the member experiences deterioration and begins to degrade the uncertainties and resistance variabilities are greatly increased (scatter is larger) and the resistance factor ϕ for new design would not be reflective of the increased uncertainties.

The condition factor specifies the estimated reduction to account for the increased uncertainty in the resistance of deteriorated members and the likely increased future deterioration of these members during the period between inspection cycles. Condition factor ϕ_c varies from 0.85 for members in poor condition to 1.0 for members in good or satisfactory condition.

The intent of the condition factor is to account for the increases in uncertainty and anticipated future accelerated loss. It does not account for the observed change in the actual physical dimensions. The specified approach is to take the as-inspected member information and apply it in finding the member resistance and then apply the condition resistance factor to decrease the deteriorated resistance for reasons previously noted.

System Factor ϕ_s

Structural members interact with other members to form one structural system. Bridge redundancy is the capability of a bridge structural system to carry loads after damage to or the failure of one or more of its members. System factors are multipliers applied to the nominal resistance, and are related to the level of redundancy of the complete superstructure system. Bridges that are less redundant will have their factored member capacities reduced so they will have lower ratings. Non-redundant bridges are penalized by requiring their members to provide higher safety levels than those of similar bridges with redundant configurations. The aim of ϕ_s is to add a reserve capacity such that the overall system reliability is increased from approximately an Operating level (for redundant systems) to a more realistic target for non-redundant systems corresponding to Inventory levels.

The simplified system factors presented in the Manual are for steel and concrete bridges of typical spans and geometries. For bridges with configurations that are not covered by the table in the Manual, a direct redundancy analysis approach may be used, as described in NCHRP Report 406.

3.2 THE LOAD AND RESISTANCE FACTOR LOAD RATING SYSTEM

Live loads to be used in the rating of bridges are selected based upon the purpose and intended use of the rating results. Live load models for load rating include:

Design Load: HL93 Design Load per LRFD Specifications

Legal Loads : AASHTO Legal Loads (Type 3, Type 3S2, Type 3-3), State legal having only minor variations from the AASTO legal loads.

Permit Load: Actual Permit Truck

The Manual provides three load rating procedures that are structured in a tiered approach using the live load models outlined above:

1. Design Load Rating

Design load rating is a first-level rating of bridges using the HL-93 loading and LRFD design standards with dimensions and properties for the bridge in its present as-inspected condition. It is a measure of the performance of existing bridges to new bridge design standards. Under this check existing bridges are screened at the design level reliability (Inventory Level) or at a second lower level reliability (comparable to the Operating Level reliability in past practice) for the strength limit state.

2. Legal Load Rating

This second level evaluation provides a single safe load capacity applicable to AASHTO and State legal loads. Live load factors are selected based upon the traffic conditions at the site. Strength is the primary limit state for evaluation. Service and fatigue limit states are selectively applied. The results of the load rating for legal loads could be used as a basis for decision-making relating to load posting or bridge strengthening.

3. Permit Load Rating

Procedures are provided for checking the safety and serviceability of bridges for the issuance of permits for the passage of vehicles above the legally established weight limitations. Calibrated load factors by permit type and traffic conditions at the site have been provided for use in checking the load effects induced by the passage of the overweight truck. Guidance is also provided on the serviceability criteria that should be checked when reviewing permit applications. These procedures apply only to bridges that have adequate capacity to carry legal loads.

Figure 3-1 below demonstrates the general procedure for performing a load rating using LRFR.

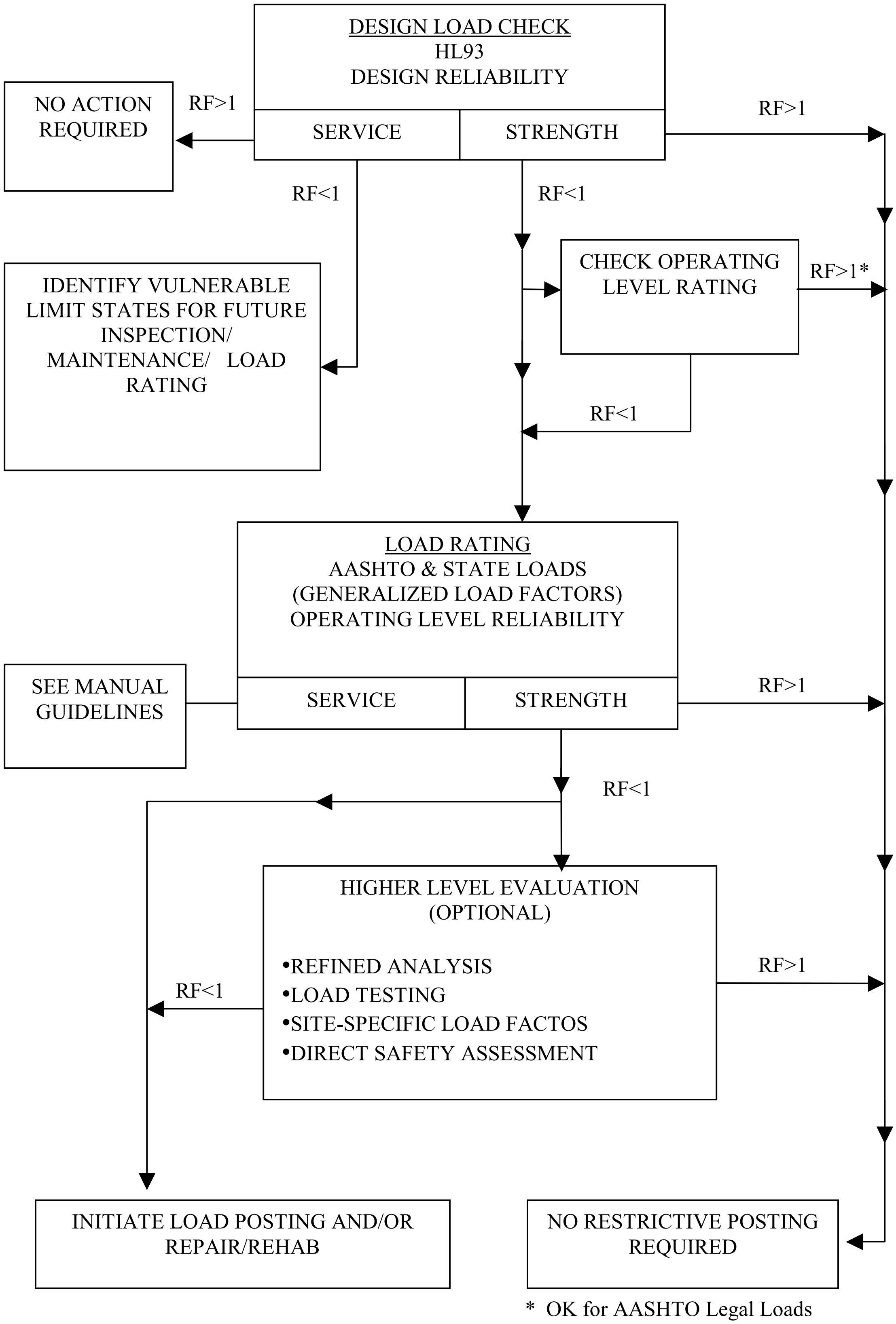

Figure 3-1. LRFR Flow Chart for Non-Permit Loads

LRFR has implemented a tiered approach to load rating as described in the flow chart in Figure 3-1. An initial check is performed based upon the LRFD Design Code's HL93 loading in the same manner as was done for the HS20 loading and provides a value for reporting to FHWA. The difference is that the HL93 loading provides a screening check for all of the AASHTO trucks and the State legal exclusion vehicles in the United States. If a bridge has a rating factor greater than 1.0 for the Inventory HL93 check then it is known that the bridge is satisfactory for all State legal vehicles that fall within the exclusion limits described in the LRFD calibration studies. After performing the Inventory level design load check agencies that restrict legal traffic to the level of the AASHTO legal loads have another screening check available with the Operating level check. If heavier vehicles or vehicles with very different configurations are allowed, the Operating HL93 will not envelope the load effects. The Inventory HL93 envelopes all exclusion traffic in the United States as of 1993.

While this notional load (HL93) provides a convenient and uniform basis for design, it bears no resemblance or correlation to any legal vehicle type on the roads. Practical difficulties are therefore bound to arise in using HL93 rating results for load posting. Additionally, the local live load environment is often less severe than the prescribed design loading. The LRFR Manual proposes procedures for load rating when a bridge does not pass the initial design load check. Load factors to be applied to the AASHTO legal loads are provided as well as combinations of limit states that are to be evaluated for different types of bridges. LRFR takes advantage of the differences between design and evaluation by using calibrated live load factors, based on various Average Daily Truck Traffic (ADTT) levels. Finally, the LRFR provides limit states and live load factors specific to permit vehicles for bridges that pass the legal load checks.

3.3 SAFETY CRITERIA FOR LOAD AND RESISTANCE FACTOR RATING

3.3.1 Reliability Indices for Evaluation

In LRFD code calibrations, the target reliability index (beta) of 3.5 for the strength limit state was selected as it was considered indicative of the reliability indices inherent in girder bridges designed by the AASHTO Standard Specifications. The reliability indices were calculated for concrete and steel bridges with varying span lengths and girder spacings. Timber and masonry bridges were not included. The beta values were widely dispersed generally ranging from a low of 2.0 to a high of 4.5. Bridges with short spans and smaller girder spacings were commonly observed in the lower end of the reliability range. The target reliability index of 3.5 selected for the LRFD code corresponds to the calculated reliability of existing 60 ft. girder spans with a girder spacing of 6 feet. It is important to note that the bridges considered for calibration were all redundant load path structures as they were considered indicative of current and future trends in bridge design. The beta of 3.5 represents the reliability of an individual member and the true system reliability or safety will be considerably higher.

For design, a relatively high target reliability index was chosen as the cost of compliance is only marginal. For evaluation, a lower bound on acceptable reliability is more appropriate as the cost impact due to bridge strengthening or traffic restrictions could be quite significant. A reliability index was selected based on calibrating with past load rating practice, which generally allows up to operating stress levels to be used for redundant bridges. The operating level (beta = 2.5) has served as an acceptable safety level for posting and permit decisions for redundant systems in the past and was selected as an acceptable basis for the new Manual calibrations. A lower reliability for evaluation can be justified on many grounds including the fact that evaluation is performed for a much shorter exposure period of two to five years compared to the 75 year exposure period assumed for design. Moreover, the HL93 is a conservative design load with only a very small probability of occurrence on most bridges.

Load factors in the new Manual are derived for load rating under legal loads, routine and special permits, and incorporation of site-specific traffic data, using a methodology consistent with the calibration of the *LRFD Bridge Design Specifications*. The calibration of load factors was done, based on member reliability only, at an Operating level of safety for redundant bridges. System redundancy considerations should be introduced to ensure that higher reliability indices are achieved for non-redundant superstructure components. Non-redundant systems will have their ratings lowered through reduced resistance factors (increased reliability index). The operating level has served as an acceptable safety level for posting and permit decisions for redundant systems in the past and would serve as an acceptable basis for code calibrations. The operating level of safety is also economically justifiable as existing bridges are required to meet this minimum safety standard for the applied service loads.

The two most important parameters which determine the reliability index for multi-girder bridges were shown to be the girder spacing and the span length. Concerns have been expressed that many existing bridges in our current inventory may not meet the high reliability level established for newer bridge designs. Limited trial ratings done on various existing bridge types using the LRFR Manual indicates that bridges with close girder spacings and short span lengths (such as T-Beam bridges) are at risk and may not pass screening for the design load at the Inventory level. A major reason for this is the high load effects resulting from the tandem plus lane loading; with a smaller contribution attributed to the slightly higher distribution factor (compared to the S/N distribution factor). Bridges outside the span range governed by tandem loading should prove to have adequate performance. The other bridge types that may also be vulnerable are nonredundant two-girder, and truss bridges. They do not benefit from the improved distribution factors that apply to multi-girder bridges. They also have their resistance reduced for increased reliability. The conservative bias inherent in these bridge designs could offset the higher load effects and reduced resistance.

3.3.2 Maintaining Uniform Reliability in Legal Load Rating

The objective of producing a new LRFD code that will yield designs having a uniform safety over all span lengths for the various force effects required as its basis a new live load model with a uniform bias when compared to the exclusion vehicles permitted by the grandfathered rights. (Grandfather provisions in the federal statutes allow states to retain higher load limits if such limits were in effect when the applicable federal statutes for load limits were first enacted. Many states have increased their legal loads above the 80,000 lb. federal limit, such as Michigan at 154,000 lb., and most Western states at 131,000 lb). The large variations in bias factors over varying span lengths indicated that HS20 loading was not representative of current loads on the highways. The live load model consisting of either the HS20 truck plus the uniform lane load or the tandem plus the uniform lane load (designated as HL93 loading) resulted in a tight clustering of data around a 1.0 bias factor for all force effects over all span lengths.

A characteristic of the AASHTO family of legal loads (TYPE 3, TYPE 3S2, TYPE 3-3) is that the group satisfies the Federal Bridge Formula adopted by Congress. The AASHTO legal loads model three portions of the Bridge Formula which control short, medium, and long spans. Therefore, the combined use of these three AASHTO legal loads results in uniform reliability over all span lengths, as was achieved with the HL93 notional load model. These vehicles are presently widely used for load rating and load posting purposes. As such they are appropriate for use as rating vehicles in the new Manual and they also satisfy the major aim of providing uniform reliability over all span lengths. Additionally, these vehicles are familiar to engineers and will provide continuity with current practice. The HS-20 truck when used as the sole live load model does not provide uniform reliability over varying span lengths.

Load rating for legal loads determines a single safe load capacity of a bridge for the AASHTO family of legal loads and state legal loads, using more optimum safety and serviceability criteria considered appropriate for evaluation. The results are suitable for determining the need to load post or strengthen a

bridge. Evaluation procedures are provided in the Manual to establish a safe load capacity for an existing bridge that recognizes a balance between safety and economics. The previously existing distinction of Operating and Inventory level ratings is no longer maintained when load rating for legal loads. The single safe load capacity produced by the guidelines presented in the Manual will provide a level of reliability corresponding to the Operating level reliability for redundant bridges in good condition.

This Manual provides live load factors for load rating that have been calibrated to provide a uniform and acceptable level of reliability. The calibration of live load factors to achieve the target reliability uses the same traffic statistics used in calibrating the *LRFD Bridge Design Specifications.* Live load factors are sensitive to the ADTT of the site. Load factors appropriate for use with the AASHTO and State legal vehicles are defined based upon the traffic and load data available for the site. The load factors are characterized as generalized load factors and site-specific load factors.

Generalized Live Load Factors - Traffic conditions at bridge sites are usually characterized only by traffic volume. Generalized load factors apply when only the ADTT at a site is known or can be estimated. Generalized load factors are representative of bridges nationwide with similar traffic volumes.

Traffic Volume	Limit State	Load Factor
Unknown	STRENGTH	1.8
ADTT > 5000	STRENGTH	1.8
ADTT = 1000	STRENGTH	1.6
ADTT < 100	STRENGTH	1.4

Table 3-1. Generalized Live Load Factors for Legal Loads

Site-Specific Live Load Factors
Live load varies systematically from site-to-site. More refined load factors appropriate for a specific bridge site may be estimated if more detailed traffic and load data are available for the site. ADTT and truck loads through weigh-in-motion measurements recorded over a period of time allow the estimation of site-specific load factors that are characteristic of a particular bridge site. The new Manual provides a simplified procedure for calculating site-specific load factors that follow the same format used in the derivation of live load factors contained in the AASHTO *LRFD Bridge Design Specification.*

3.3.3 Reliability-based Permit Load Rating

Bridge owners usually have established procedures which allow the passage of vehicles above the legally established weight limitations on the highway system. These procedures involve the issuance of a permit which describes the features of the vehicle, its load, and route of travel. Permits are issued by states on a single trip, multiple trip or annual basis. Routine or annual permits are usually valid for unlimited trips over a period of time, not to exceed one year. The maximum gross weight of vehicles allowed by an agency under this permit category is usually not in excess of 150 KIPS. Special permits are usually valid for a single trip only, or for a limited number of trips. These permit vehicles are usually heavier than those vehicles issued annual permits. Depending upon the authorization, these permit vehicles may be allowed to mix with normal traffic or may be required to be escorted in a manner which controls their speed and/or lane position, and the presence of other vehicles on the bridge. These permit vehicles are usually heavier than those vehicles issued routine permits for multiple trips. Depending on the authorization, these special vehicles may be allowed to mix with random traffic or may be required to be escorted in a manner that controls speed and/or lane position, and the presence of other vehicles on the bridge. The new Manual provides procedures for checking overweight trucks that are analogous to load rating for legal loads except that load factors are selected based upon the permit type. The actual permit vehicle will be the live load used in the evaluation.

The target reliability level for routine permit crossings is established as the same level as for legal loads, consistent with traditional AASHTO Operating ratings. For single and multiple-trip special permits that are allowed to mix with traffic (no restrictions on other traffic) the live load factors were explicitly derived to provide a higher level of reliability consistent with AASHTO Inventory ratings and LRFD design level reliability. The higher target reliability is justified as a very heavy special permit or superload (200K) may represent the largest loading effect that a bridge has yet experienced in its lifetime. The increased risk of structural damage and associated benefit/cost considerations leads to higher safety requirements for very heavy special permit vehicles than other classes of trucks.

The permit live load factors were derived to account for the possibility of simultaneous presence of non-permit heavy trucks on the bridge when the permit vehicle crosses the span. Thus the load factors are higher for spans with higher ADTT and smaller for heavier permits. The live load factors for single trip escorted permits that are required to cross bridges with no other vehicles present have been calibrated to reliability levels consistent with traditional AASHTO Operating ratings. A target reliability at the Operating level is allowed because of the reduced consequences associated with allowing only the escorted permit vehicle alone to cross the bridge. An agency may also elect to check escorted permits at the higher design or Inventory level reliability by using an increased live load factor as noted in the manual commentary.

The following Table of permit load factors suitable for most commonly encountered permit situations is provided in the new Manual.

Permit Type	Frequency	Loading Condition	DF[a]	ADTT (one direction)	Load Factor by Permit Weight[b] Up to 100 KIPS	≥150 KIPS
Routine or Annual	Unlimited Crossings	Mix with traffic (other vehicles may be on the bridge)	Governing of One - lane or Two or more lanes	>5000	1.80	1.30
				=1000	1.60	1.20
				<100	1.40	1.10
					All Weights	
Special or Limited Crossing	Single-Trip	Escorted with no other vehicles on the bridge	One lane	N/A	1.15	
	Single-Trip	Mix with traffic (other vehicles may be on the bridge)	One lane	>5000	1.50	
				=1000	1.40	
				<100	1.35	
	Multiple-Trips (less than 100 crossings)	Mix with Traffic (other vehicles may be on the bridge)	One Lane	>5000	1.85	
				=1000	1.75	
				<100	1.55	

Notes

[a] DF = LRFD distribution factor. When one lane distribution factor is used the built-in multiple presence factor should be divided out.

[b] For routine permits between 100 KIPS and 150 KIPS interpolate the load factor considering also the ADTT value.

Table 3-2. Permit Load Factors -- γ_L

3.3.4 Reliability-based Posting

The aim of the new Manual is to maintain target uniform reliabilities, even for bridges that have been load posted. In a reliability-based evaluation the relationship between posting values and rating factors is not proportional. The new manual would provide guidance to the users on how to translate rating factors less than 1.0 into posting values that maintain the criteria of uniform reliability. This is achieved through a posting graph given in the Manual that presents posting weights for different vehicle types as a function of rating factors.

3.4 SERVICEABILITY CRITERIA FOR LOAD AND RESISTANCE FACTOR RATING

The new LRFD Specifications introduce the philosophy of limit states design, which in essence is a systematic way of considering all applicable design criteria by grouping them into limit states. This philosophy is now to be extended to the evaluation of existing bridges. Differences exist between the application of limit states to design vs. evaluation. The very nature of evaluation calls for different limit states to be applied. If the evaluator is concerned about accumulating excessive fatigue damage during normal usage, the fatigue-and-fracture limit state should be considered for evaluation. On the other hand, if the evaluator is only interested in precluding damage from more limited, perhaps single, passages of permit vehicles, the strength and service limit states would only be considered, not the fatigue-and-fracture limit states. Also, there may be a high cost penalty for imposing certain non-strength related limit states in evaluation compared to design where the cost impact may be negligible.

LRFD Design Specifications address serviceability of bridges from the perspective of durability, inspectability, maintainability, rideability, deformation control, and future widening. Clearly, most of these goals are a design function that are beyond the control of the evaluator and do not belong in an evaluation. Strength is the primary basis for evaluation. The focus of serviceability checks in evaluation is to identify and control live load effects that could potentially damage the bridge structure, and impair its serviceability and service life. Serviceability checks are necessary even though the live load may have been determined to be safe at the strength limit state. Consequently, serviceability considerations in evaluation are aimed at avoiding or minimizing bridge damage due to live loads by placing limits on service load stresses under normal use and controlling permanent inelastic deformations under authorized or unauthorized overloads.

In bridge evaluations, the past performance of a bridge is a good indicator of adequate serviceability. Traffic restrictions are difficult to justify if no serviceability related problems are evident. A bridge that has been in service for a number of years is very likely to have already experienced a load heavier than it is likely to experience in the next two to five years (exposure period for evaluation). If no past performance problems have been observed or reported, the bridge has in effect passed a proof test for serviceability. In such cases, restrictive load postings based upon calculated serviceability performance measures, such as stresses or deformations, are not warranted nor economically justifiable. The same logic does not apply to heavy permit loads, which may introduce a load greater than that imposed in the past. Service limit states checks are therefore stressed for permit reviews.

The importance of serviceability checks is not so much in their usefulness for posting but more in their role as indicators of performance of existing bridges under current loads and modern evaluation standards. Most maintenance problems in existing bridges are service related. They could be fatigue problems in steel bridges, cracking in concrete bridges, or excessive deflection in timber bridges. If ignored, serviceability problems could ultimately develop into strength and safety problems. Performing serviceability checks during load ratings can help identify these potential vulnerabilities and focus inspection efforts and preventive/maintenance strategies. This kind of decision-making requires the performance of serviceability checks on a routine basis during evaluation. As strength evaluation methods are continually improved and refined to produce increased load ratings it becomes increasingly important to pay closer attention to the service and fatigue limit states to avoid negative long term impacts.

Most existing bridges were designed by the Allowable Stress method, where designs are carried out at the service load level, and serviceability criteria are implicitly considered. Many older bridges were designed for much lower loads than used in modern codes and may not meet present criteria for either strength or serviceability. Bridges designed more recently by the Load Factor method were designed for factored loads that were compared to the ultimate strength. The designs were then checked for serviceability.

Compact members that were able to fully develop their plastic moment capacity would often be governed by the serviceability criteria under overloads, where flange stresses were limited to a value slightly less than yield. Prestressed concrete bridges continue to be designed for service loads and checked for factored loads, even under the Load Factor method. Load Factor rating methods in the MCE have included specific serviceability checks for steel and concrete bridges — though the use of serviceability considerations in setting posting weight limits and checking overweight permits have varied widely among bridge owners. A survey of State DOTs conducted by Lichtenstein indicates that only about a quarter of the responding states consider serviceability in load posting or permit review. Approximately half the States indicated that they check MCE serviceability criteria (i.e. overload limitations on steel bridges, crack control in prestressed concrete bridges) during load rating calculations. However, when it comes to load posting and permit reviews the States are currently using more discretion on the applicability of these serviceability checks. This points to the need for a continued flexible approach to incorporating serviceability checks in bridge evaluation.

LRFD Serviceability Checks

In the *LRFD Bridge Design Specifications* (AASHTO 1998) only the STRENGTH I limit state was calibrated based on structural reliability theory. The other strength limit states were not explicitly calibrated. The service limit states are material dependent and were calibrated to past practice. The fatigue and fracture limit state is geared toward controlling crack growth to prevent failure by fracture. The service limit states checks are aimed at two important considerations:

1) Control of permanent inelastic deformations in steel structures.
2) Crack control in concrete structures.

<u>Steel Bridges</u>**:** Steel structures must satisfy the overload permanent deflection check under the SERVICE II load combination. Maximum steel stress is limited to 95% and 80% of the yield stress for composite and non-composite compact girders respectively. In the context of the LRFD Specifications most composite steel girders would qualify as compact girders in the positive moment region. The code also includes an optional transient live-load deflection check designed to produce live-load deflections similar to those produced by the Standard Specifications. The live load deflection check is carried out using the live load portion of the SERVICE I load combination.

Material toughness requirements and restrictions on live load stress range under service conditions are specified to satisfy the fatigue and fracture limit state. A factored fatigue load equivalent to the current HS15 truck loading is used in the LRFD Specifications, producing a lower calculated stress range than obtained by the fatigue loading in the Standard Specifications. The reduced stresses produced by the LRFD fatigue loading, considered more reflective of actual stress conditions in ridges, is offset by an increase in the number of loading cycles.

<u>Concrete Bridges</u>: The provisions for reinforced concrete and prestressed concrete have been unified and combined into one section in the LRFD Specifications. SERVICE I limit state is applied to distribute tensile reinforcement to control crack width in concrete structures. For prestressed concrete bridges, LRFD provides a limit state check for cracking of concrete (SERVICE III) and crushing of concrete (SERVICE I) by limiting concrete tensile and compressive stresses respectively under service loads. SERVICE I load combination may also be applied to impose optional deflection criteria for vehicular live loads. SERVICE II load combination is not applicable for concrete bridges.

<u>Wood Bridges</u>: Optional deflection criteria are specified for vehicular and pedestrian loads. Wood structures that deflect excessively could loosen connections and cause wearing surfaces to crack and break.

Recently completed designs suggest that by the LRFD Specifications the strength limit states may seldom govern the design of composite steel girder bridges. They will be governed mostly by the SERVICE II limit state. A similar situation could be expected to arise in the Load and Resistance Factor Rating of existing bridges, if LRFD serviceability criteria for the design of new bridges are routinely used for evaluation. A more selective use of serviceability checks that consider the past performance history of a bridge and allow more flexible performance standards than design is warranted to achieve more optimal safety and economy in evaluations.

LRFR Serviceability Checks

The LRFR system is structured in a tiered approach. An initial check is performed based upon the LRFD Design Code's HL93 loading and design limit states. The HL93 loading provides a screening check for all of the AASHTO trucks and the State legal exclusion vehicles in the United States. Load rating for legal loads is required only when a bridge fails the design load rating. Strength is the primary limit state for load rating. Service and fatigue limit states are selectively applied in accordance with the provisions of the new Manual, summarized in Table 3-3.

Bridge Type	Limit State	Dead Load DC	Dead Load DW	Design Load		Legal Load	Permit Load
				Inventory	Operating		
				LL	LL	LL	LL
Steel	STRENGTH I	1.25	1.50	1.75	1.35	Table 6.4.4.2.3-1	-
	STRENGTH II	1.25	1.50	-	-	-	Table 6.4.5.4.2-1
	SERVICE II	1.00	1.00	1.30	1.00	1.30	1.00
	FATIGUE	0.00	0.00	0.75	-	-	-
Reinforced Concrete	STRENGTH I	1.25	1.50	1.75	1.35	Table 6.4.4.2.3-1	-
	STRENGTH II	1.25	1.50	-	-	-	Table 6.4.5.4.2-1
	SERVICE I	1.00	1.00	-	-	-	1.00
Prestressed Concrete	STRENGTH I	1.25	1.50	1.75	1.35	Table 6.4.4.2.3-1	-
	STRENGTH II	1.25	1.50	-	-	-	Table 6.4.5.4.2-1
	SERVICE III	1.00	1.00	0.80	-	1.00	-
	SERVICE I	1.00	1.00	-	-	-	1.00
Wood	STRENGTH I	1.25	1.50	1.75	1.35	Table 6.4.4.2.3-1	-
	STRENGTH II	1.25	1.50	-	-	-	Table 6.4.5.4.2-1

Table 3-3. Limit States and Load Factors for Load Rating

Note: Shaded cells of the table indicate optional checks. Table numbers denote Tables in the new manual.

Table 3-3 indicates that some optional checks are present. These checks are optional in the sense that a posting or permit decision does not have to be dictated by the result, not in the sense of whether the check should be performed. These service checks provide information for the engineer to use in the decision process that should be considered along with the service history of the bridge. A new SERVICE I limit state has been specified for concrete bridges. This check is applied to permit checks and uses a limiting criteria of 0.9 Fy in the extreme tension reinforcement. The same issue is dealt with in steel bridges with the traditional SERVICE II check for overloads. The same concern is not present for timber bridges as the members do not have any plastic capacity beyond the elastic limit.

Load rating of prestressed concrete bridges based upon satisfying limiting concrete tensile stresses under service loads at the SERVICE III limit state is considered optional. These provisions for evaluation of prestressed concrete bridges permit, but do not encourage, the past practice of limiting concrete tensile stresses at service loads. This check of the SERVICE III load combination may be appropriate for prestressed concrete bridges that exhibit excessive cracking under normal traffic. In design, limiting the tensile stresses of fully-prestressed concrete members based on uncracked section properties is considered appropriate. In evaluation, considering an existing concrete bridge that has been in service for a number of years to be uncracked is not reasonable. All existing concrete bridges should be assumed to be cracked and load rated as such. SERVICE III is applicable to only normal service loads and should not be checked for permit loads. Cracking in concrete bridges under occasional overloads is not considered detrimental to the longevity of the bridge. The cracks will close once the overload passes, as long as the steel stresses are in the elastic range.

To this end, SERVICE I load combination for reinforced concrete components and prestressed concrete components has been introduced to check for possible inelastic deformations in the reinforcing steel during permit crossings. During permit load rating, the stresses in the reinforcing bars and/or prestressing steel nearest the extreme tension fiber of the member should not exceed 0.90 of the yield point stress for unfactored loads. This check has been added as the low live load factors possible for permit vehicles operating under controlled crossing conditions (i.e. escorted with no other vehicles on the bridge), combined with an ultimate strength resistance check could result in the possibility of inelastic stresses in the tensile steel that would reduce the long-term serviceability and durability of a bridge without causing an immediate failure or collapse. Limiting steel stress to 0.9Fy will mean that cracks that develop during the passage of overweight vehicles will close once the vehicle is removed. It also ensures that there is reserve ductility in the member. This check is carried out using the SERVICE I combination where all loads are taken at their nominal values. For concrete members with standard designs and closely clustered reinforcement, the engineer may as an alternate to limiting the steel stress choose to limit unfactored moments to 75 percent of nominal flexural capacity. Where computations are performed in terms of moments rather than stresses it is often easier to check limiting moments than it is to check limiting stresses. It should be noted that in design SERVICE I is not used to investigate tensile steel stresses in concrete components. In this regard it constitutes a departure from the LRFD Bridge Design Specifications.

As most prestressed designs are designed for no cracking under full service loads fatigue in the reinforcement is not a concern. Hence, prestressed components need not be routinely checked for fatigue.

SERVICE II load combination check is provided for the control of permanent deflection in steel bridges. The flange stresses in bending should not exceed the limiting stresses specified in the LRFD Specifications for composite and non-composite sections. The reduced load factors for SERVICE II, compared to Load Factor design and rating, reflect a more liberalized approach to applying SERVICE II checks for evaluation. Load Factor design and evaluation procedures require the service behavior of steel bridges to be checked for an overload taken as 5/3 times the design load. Serviceability checks for evaluation need not be as stringent as in new designs as there is less uncertainty in traffic loads and the

bridges to be checked for an overload taken as 5/3 times the design load. Serviceability checks for evaluation need not be as stringent as in new designs as there is less uncertainty in traffic loads and the exposure period is reduced. During an overweight permit review the actual truck weight is available for evaluation. Also, past performance of the bridge under traffic conditions is known and is available to guide the evaluation. It is important to note that the live load factors for SERVICE II limit state were not established through reliability based calibration, but were selected based upon engineering judgment and expert opinion. The level of reliability represented by this serviceability check is unknown.

New fatigue-life evaluation procedures for existing steel bridges are specified in Section 7 of the new Manual, which combines aspects of the Guide Specifications for Fatigue Evaluation of Existing Steel Bridges (AASHTO 1990) and the fatigue design procedures of the LRFD Bridge Design Specifications (AASHTO 1998). The principles of reliability and uncertainty employed in the LRFD Specifications for design have been extended to fatigue-life evaluation in the new Manual. Load-induced fatigue-life evaluation procedures are divided into two-levels: infinite life check and finite-life estimate. Bridge details that fail the infinite-life check may be subject to the more complex finite-life fatigue evaluation. This is an optional check not intended for use in load posting decisions.

The total finite fatigue-life of a fatigue-prone detail, in years, is determined as:

$$Y = \frac{R_R\, A}{365\, n\, (ADTT)_{SL}\, ((\Delta f\,)_{eff}\,)^3}$$

where:

R_R = resistance factor specified for evaluation, minimum or mean fatigue life as given in Table 7.2.5.1-1 of the new Manual.

Three levels of finite fatigue life may be estimated:

- the minimum expected fatigue life (which equals the conservative design fatigue life),
- the evaluation fatigue life (which equals a conservative fatigue life for evaluation), and
- the mean fatigue life (which equals the most likely fatigue life).

Much scatter, or variability, exists in experimentally derived fatigue lives. For design, a conservative fatigue resistance two standard deviations below the mean fatigue resistance or life is assumed. This corresponds to the minimum expected finite fatigue life. Limiting actual usable fatigue life to this design life is very conservative and costly. As such, means of estimating the evaluation fatigue life and the mean finite fatigue life are also included in the Manual to aid the evaluator in the decision-making.

The resistance factors for fatigue life, specified in the new Manual, represent the variability of the fatigue life of the various detail categories, A through E'. As the stress-range estimate grows closer and closer to the actual value of stress range, the probability of failure associated with each level of fatigue life approaches 2%, 16% and 50% for the minimum, evaluation and mean fatigue lives, respectively. The minimum and evaluation fatigue-life curves are two and one standard deviations off of the mean fatigue-life S-N curves in log-log space, respectively.

Owners sometimes use fatigue evaluation results to set inspection policy and procedures. For instance, fatigue prone details that are found to have limited remaining fatigue lives are identified for future hands-on inspections. The evaluator should also bear in mind the economic consequences of restricting traffic based solely on fatigue. It may be more economical to repair any resulting fatigue cracks than to limit the

capacity of the bridge in order to avoid fatigue damage. However, if a bridge, or a series of bridges as in a viaduct, has a large number of fatigue areas the cost of repairing cracks and potential disruption of an important traffic route may as critical as the economic costs of load posting. In permit review, fatigue need not be routinely considered as the number of cycles resulting from permit trucks is usually a very small percentage of the overall stress cycles from all traffic.

Fracture of steel bridges is governed by total stress, not the stress range as is the case with fatigue. Older bridges probably have demonstrated that their fracture toughness is adequate for their total stresses, i.e., the dead-load stress plus the stress range due to the heaviest truck that has crossed the bridge. However, propagating fatigue cracks in bridges of questionable fracture toughness are very serious, and may warrant immediate bridge closure. A rehabilitation of a bridge of unknown fracture toughness that may significantly increase the dead-load stress must be avoided.

3.5 NON DESTRUCTIVE LOAD TESTING OF BRIDGES

The actual performance of most bridges is more favorable than conventional theory dictates. When a structure's computed theoretical safe load capacity or remaining fatigue life is less than desirable, it may be beneficial to the owner to take advantage of some of the bridge's inherent extra capacity that may have been ignored in conventional calculations. Load tests can be used to verify both component and system performance under a known live load and provide an alternative evaluation methodology to analytically computing the load rating of a bridge.

Section 8 of the new Manual provides guidance on the applicability and usefulness of load testing in bridge evaluation and procedures for incorporation of load test results into theoretical load ratings. The procedures outlined in this section for the non-destructive load testing of bridges were developed in NCHRP Project 12-28(13)A, and reported in NCHRP Research Results Digest, November 1998 — Number 234, *Manual for Bridge Rating Through Load Testing,* and include certain modifications necessary to ensure consistency with the load and resistance factor load rating procedures presented in the Manual.

An overview of load test types, associated analysis and general testing procedures, interpretation of test results, and application of test results to load rating are covered in Section 8 of the manual in order to provide much needed information on this very effective evaluation method. This method could be very valuable especially for evaluating heavily deteriorated bridges and bridges with unknown properties.

SECTION 4.0 TESTING OF PRE-FINAL DRAFT MANUAL (MARCH 1999)

4.1 TESTING OBJECTIVES AND PROCEDURES

The objective of the testing phase was to ensure that the project delivered a practical and workable Manual in the Load and Resistance Factor philosophy. In order for the delivered Manual to be workable it must be able to be understood and implemented by bridge engineers and it must address all significant concerns of bridge engineers in rating bridges. Additionally, the Manual must be acceptable to the state bridge authorities so that it will receive broad support for adoption as an AASHTO Specification. The testing phase was intended to ensure that the Manual is understandable, easy to use, and acceptable as an evaluation standard for rating, posting, and permit review.

The objective was achieved by two parallel approaches in the testing phase. The two approaches involved evaluation of the Manual by reviewers outside the research team and the project panel. First, technical reviews of the draft version of the Manual were made by a number of State DOTs and other industry experts. Their comments and observations were received and responded to in an interactive and iterative manner. Second, trial load ratings were conducted where state DOTs used the draft Manual to perform load ratings for design, legal, and permit traffic on a number of existing bridges of their choosing. A summary of the Manual Testing Phase methodology is given in Figure 4-1.

The result of the two evaluation approaches produced a number of revisions to the draft manual that resolve most of the issues of concern raised. For a few issues the testing and commentary revealed a difference between the proposed LRFR and the current LFR that could not be corrected in the manual either with the current state-of-the-art as it pertains to LRFD, or without deviating from the uniform safety requirements. These issues include:

- Low shear ratings for some prestressed concrete girder bridges
- Incomplete criteria for the analysis of buried culverts
- Low design load flexural ratings for timber bridges
- Ratings for HS20 loadings

The first and second items are currently under review for the LRFD code, changes there could resolve those issues for rating as well as new design. As an intermediate step, in Article 6.5.9 the LRFR does not require shear ratings for design and legal loads on in-service concrete bridges that do not show visible signs of shear distress. The concerns with culverts are not directly addressed but are acknowledged here. The third issue for wood bridges results from more recent research indicating that previous approaches for the analysis of wood stringer bridges (distribution factors) were unconservative combined with the higher load effect caused by HL93 on short spans. Since these bridges do not usually carry high traffic routes the legal load evaluations will have lower live load factors with LRFR than with LFR and the results may be equivalent. Inclusion of HS20 vehicle for rating purposes in LRFR was considered desirable by some agencies. Providing calibrated load factors for HS20 was not feasible while maintaining the uniform safety criteria set for all span lengths. Load factors for legal loads may be used with HS20 loading for rating purposes, yielding conservative results. This is addressed in the commentary to the Manual.

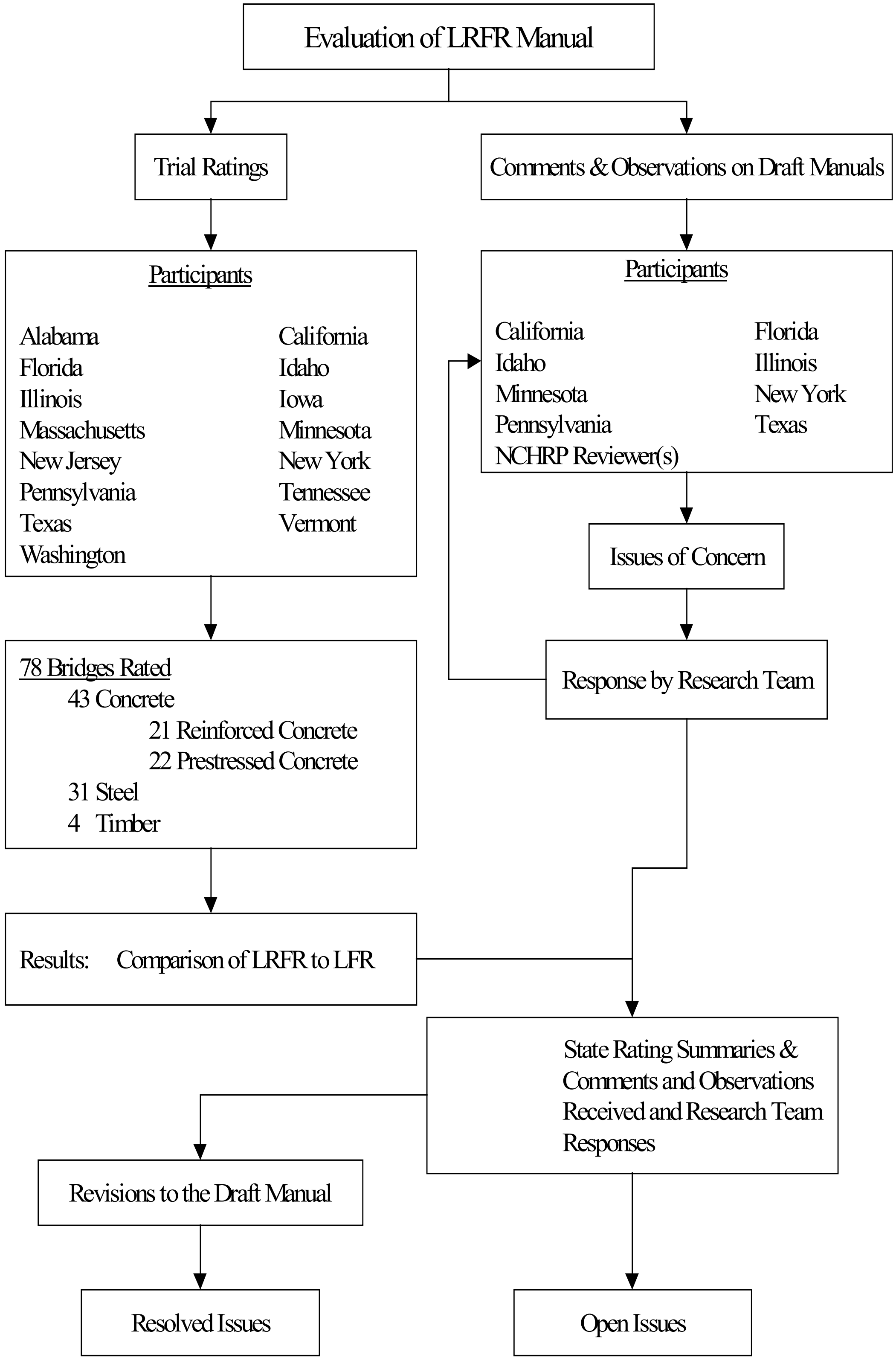

Figure 4-1. Flowchart of Draft Manual Testing

4.2 BRIDGE TYPES AND PARTICIPATING STATES

As shown in the flowchart on the evaluation of the LRFR Manual a number of states participated in both the trial ratings and in submitting comments and observations on the draft manual. In particular, California, Pennsylvania, and Florida raised issues and provided suggestions through frequent communications. Fifteen states volunteered to perform ratings on existing bridges using the draft Manual. A total of 78 bridges of varying complexity were rated. A summary of the more significant comments and their resolution is included under sections 4.4 and 4.5 of this report.

The testing matrix was designed so that approximately 90% of the main structural types in the United States would be represented with larger sample sets for the most common types. In addition to the common bridge types, a number of states performed ratings on less common bridges to investigate the general applicability of the manual. The type and number of bridges rated in the trial phase are given in the following table.

Material	Type	Total
Concrete	Slab	7
Concrete	Tee Beam	6
Concrete	Box Beam or Girders - Multiple	1
Concrete	Box Beam or Girders - Single or Spread	1
Concrete	Frame (except frame culverts)	1
Concrete	Culvert (includes frame culverts)	1
Concrete continuous	Slab	2
Concrete continuous	Tee Beam	2
Steel	Stringer/Multi-beam or Girder	18
Steel	Girder and Floorbeam System	3
Steel	Truss - Thru	3
Steel continuous	Stringer/Multi-beam or Girder	6
Steel continuous	Truss - Thru	1
Prestressed concrete	Slab	1
Prestressed concrete	Stringer/Multi-beam or Girder	8
Prestressed concrete	Box Beam or Girders - Multiple	6
Prestressed concrete	Box Beam or Girders - Single or Spread	2
Prestressed concrete	Segmental Box Girder	1
Prestressed concrete continuous	Stringer/Multi-beam or Girder	4
Wood or Timber	Stringer/Multi-beam or Girder	4
		Σ = 78

Table 4-1. Bridges Rated in the Testing Phase

4.3 RESULTS OF TRIAL RATINGS

Table 4-2 shows the results of the LRFR trial ratings in terms of the number of bridges that did not pass each check in the rating process. The number of bridges tested was not large enough for the trends in the table to be considered statistically representative of the national bridge inventory. In some cases most of the structures of a particular type were currently posted. However, it does demonstrate that a large number

of bridges can be eliminated from further rating after the first screening evaluation is performed (HL93 Inventory). This check also provides a uniform reporting basis for the FHWA. The second screening test (HL93 Operating) only applies to states where the legal vehicles do not exceed the federal bridge formula limits. This test can be seen to only remove a few bridges from the test population, however, the Operating rating is generally very easy to compute once the Inventory rating has been calculated. The final check of AASHTO legal vehicles with ADTT based live load factors is seen to fail far fewer bridges than the initial design level check.

Bridge			HL93 Check		Legal Load Check
Material	**Type**	**Total**	**RF Inv <1**	**RF Opr <1**	**RF Legal <1**
Concrete	Slab	7	6	6	4
Concrete	Tee Beam	6	5	4	1
Concrete	Box Beam or Girders – Multiple	1	1	1	0
Concrete	Box Beam or Girders – Single or Spread	1	1	1	0
Concrete	Frame	1	1	1	0
Concrete	Culvert	1	1	1	1
Concrete continuous	Slab	2	1	1	1
Concrete continuous	Tee Beam	2	1	1	0
Subtotals:		**21**	**17**	**16**	**7**
Steel	Stringer/Multi-beam or Girder	18	5	3	2
Steel	Girder and Floorbeam System	3	2	2	1
Steel	Truss - Thru	3	3	3	3
Steel continuous	Stringer/Multi-beam or Girder	6	1	1	0
Steel continuous	Truss - Thru	1	1	1	1
Subtotals:		**31**	**12**	**10**	**7**
Prestressed concrete	Slab	1	0	0	0
Prestressed concrete	Stringer/Multi-beam or Girder	8	6	6	5
Prestressed concrete	Box Beam or Girders - Multiple	6	2	1	0
Prestressed concrete	Box Beam or Girders - Single or Spread	2	0	0	0
Prestressed concrete	Segmental Box Girder	1	0	0	0
Prestressed concrete cont.	Stringer/Multi-beam or Girder	4	0	0	0
Subtotals:		**18**	**7**	**7**	**5**
Wood or Timber	Stringer/Multi-beam or Girder	4	4	4	2
Totals:		**71**	**37**	**35**	**19**

Table 4-2. Results for State DOT Ratings by LRFR Bridges Not Passing Rating Requirements

In addition to summarizing the results of the state load rating trials the ratings were also reviewed to determine areas where the Draft Manual was not adequately conveying the authors' intent or not being interpreted properly.

LRFR	Occurrences
0.75Mn not checked or used incorrectly	13
P/S Service I not checked	5
steel Service II not checked or incorrect	2
P/S Service III not checked	5
max reinforcement not checked	13
min reinforcement not checked	5
multiple presence not removed from permit distribution factor	1
reporting (Service as RF)	10
legal / permit IM incorrect	2
LRFR manual +M or –M lane load not checked or incorrect	6
Longitudinal reinforcement was not checked for M-V interaction	16
Fatigue check performed incorrectly	2
LRFD	
skew correction error	2
distribution factor error (including provisions for shear in timber bridges and strip widths for slabs)	13
steel section classification error	4
HL93 impact applied incorrectly	3
General	
moment or shear state not checked or important location not checked	9
-M not checked	3

Table 4-3. Errors in Trial Ratings

From this list the most problems encountered in using the LRFR were in areas of: concrete serviceability and reporting and use of service versus strength results. Problems based on the companion LRFD were distribution factors and the use of Modified Compression Field Theory (MCFT) for shear in concrete, including its check on longitudinal reinforcement yield under moment-shear interaction. The issues in the LRFD are expected to see improvements in future interim changes to the code and as users become more used to the format of the new code. The issue of concrete serviceability was also raised in the comments and the manual was revised to address it. The reporting issues were felt to be due to the format of Section 6. The section was extensively reordered and rearranged, and tables of limit states and load factors by material type were added, to make clear the differentiation between service and strength rating results and where each should be used in rating and posting decisions.

In general the DOT rating engineers were able to perform the LRFR evaluations without undue difficulty and with relatively few errors. This suggests that the technical foundation is established and that implementing the LRFR manual does not face any significant barriers.

4.4 REVIEW COMMENTS AND RESEARCH TEAM RESPONSES

The comments submitted on the Draft Manual (March 1999) and the changes to the Manual that arose from them were presented to the Panel and T-18 committee at the December 6th and 7th,1999 meeting. At this meeting final adjustments were agreed upon for the preparation of the Final Draft Manual. The

most significant of the issues brought up by the comments and the resolutions of those issues are discussed in this section. In some cases multiple reviewers commented upon the same issue. The example problems were updated to match the manual revisions, and additional calculations were included where necessary to make sure the Manual revisions were well illustrated. The following list summarizes the key comments that will be expanded upon:

- Manual Format
- Permit Live Load Factors
- Concrete Reinforcement Yield Limitation
- Continuous Span Legal Load

The format of Section 6 of the Manual has been reorganized to aid ease-of-use and to better conform with LRFD terminology and presentation. Inclusion of several summary tables of limit states and load factors for evaluation was a major enhancement. The system of load levels for rating have been more clearly identified and connected to the applicable limit states both in the text and in a table. These and other format changes were also made to comply with reviewer comments and to address misinterpretations noted in the trial rating calculations.

Permit Live Load Factors and their calibration are discussed in the Calibration Report (*NCHRP Report 454*). Overload permit review and decision making are an increasingly important concern for highway agencies. The consistency of the LRFR permit load factors for Routine permits with the strength load cases (STRENGTH I and STRENGTH II) of the LRFD Specifications is an important issue. The following figure shows the relation of the factored weight of Routine permit vehicles for the ADTT extremes of 100 and 5000 with the LRFD Strength I and Strength II load cases. It is evident that when both of the LRFD load cases are considered in design they provide an upper bound of the factored permit weights in the LRFR. This is an important concern since it shows that new bridges designed with permit vehicles as a load model will rate acceptably for those permits in evaluation. Reliability level for Routine permits is established the same as in AASHTO Operating ratings.

Revisions were also made to the permit live load factors for Limited-Crossing (Special) permits to comply with the comments and requests of several DOTs. To provide increased safety for “superload” crossings the live load factors given in the March 1999 draft were recalibrated to provide a higher level of reliability consistent with AASHTO Inventory ratings. These permits are checked based on a distribution factor for one lane due to the low probability of a vehicle of equivalent weight traveling alongside. As this probability increases with greater number of permit crossings and higher ADTT the live load factor increases. The table of load factors in the draft manual made use of changes in the vehicle weight as well as in the ADTT of the bridge to determine live load factors that resulted in the desired reliability index. At the request of reviewers the vehicle weight component was removed from the limited-crossing permits in the final Draft.

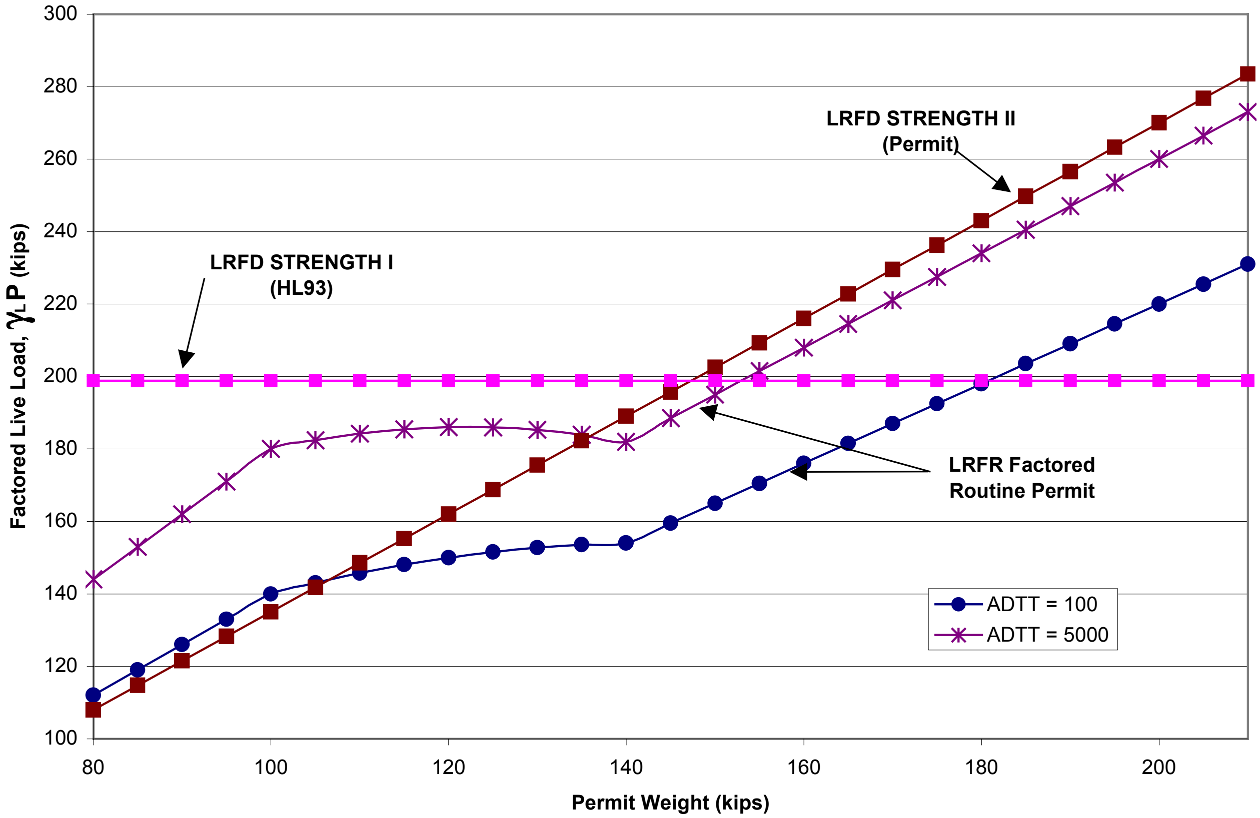

Figure 4-2 Evaluation of $\gamma_L P$ for Routine Permits Factored Live Load (No Impact)

The serviceability rating for concrete received a great deal of effort by participant reviewers; this was also one of the areas with the most misinterpretations of the draft Manual. This check was initially implemented as a subset of the strength rating for concrete bridges at an unfactored load level. The check has been moved to a serviceability check for permit loads as it represents the loading that could potentially cause permanent damage in concrete bridges. Other load levels may be checked for serviceability with the applicable LRFD limit states. The possibility of heavy permit loads causing damage is the basis for the check and it now applies only to permit crossings and is applied at the discretion of the owner.

A number of reviewers asked for clearer language on how to use the two lane type legal load models. To address the lack of clarity in the Manual Section 6.4.4.2.1 has been rewritten with more commentary and Appendix B6.2 now has schematics of the two lane type loads. Development of the lane type models is discussed here.

Longer simply supported spans may be governed by the combination of a single heavy vehicle with other moderately heavy vehicles. In the LRFD this is accommodated by the HL93 loading which includes a uniform loading for all cases. For many continuous span bridges the design loading is governed by a case of two vehicles in one lane. This is handled in the LRFD by using two design vehicles with fixed back axle spacings of 14 feet and a minimum headway between vehicles of 50 feet and reducing the entire load effect to 90%. In conjunction with the other loads in the HL93 model this produces the desired relationship of the design loading to the exclusion vehicle population.

The load models for evaluation of short to medium span simply supported bridges were taken as the AASHTO Legal Loads. Appendix B6.4 in the Manual shows a plot with the maximum moment bias for the exclusion vehicles to the AASHTO Legal Loads and the exclusion vehicles to the HL93 load model. As shown in that plot both models satisfy the objective of a uniform bias to the exclusion vehicles over the range of span lengths. The value of the bias is not important as it is simply incorporated into the load factors. The same bias as obtained for the AASHTO Legal Loads on simple spans under 200 FT must also be generated by the lane loads for table 6.4.4.2.3-1 in the Manual. In this way the actual vehicle configurations could still be used so that ratings and postings could be meaningful.

The 1989 AASHTO *Guide Specifications for Strength Evaluation of Steel and Concrete Bridges* includes a load case for longer span bridges that consists of 75% of the T3-3 axle weights with a superimposed uniform load of 0.2 KIP/FT. This loading was also adopted in the LRFR manual for simply supported span lengths between 200 FT and 300 FT. The LRFR load models for simple spans under 200 FT (AASHTO Family of T3, T3S2, and T3-3) provide a good fit for two span continuous bridges where each span is 50 FT or less. Beyond this range an additional load model must be considered. The load model adopted for longer span simply supported bridge, 75% of the T3-3 with a uniform distributed load of 0.2 KIP/FT, was modified by adding an additional 75% T3-3 in the lane. This model provided a good fit for the longer continuous span lengths when the distance from back axle of first truck to front axle of second truck was a minimum of 30 FT. Figure 4-3 shows the ratio of the negative moment caused by HL93 to the negative moment caused by the LRFR loads. The first data point is governed by the T3 vehicle and the second by the T3S2 vehicle. For spans with individual span lengths of 50 FT or more the lane type loading for negative moments governs. The negative moment lane load shown in Figure 4-3 uses a fixed spacing of 30 FT. For continuous spans with each span length less than 150 FT the fixed axle spacing provides a good relationship. For ease of application in ratings a fixed spacing of 30 FT was adopted in the Manual.

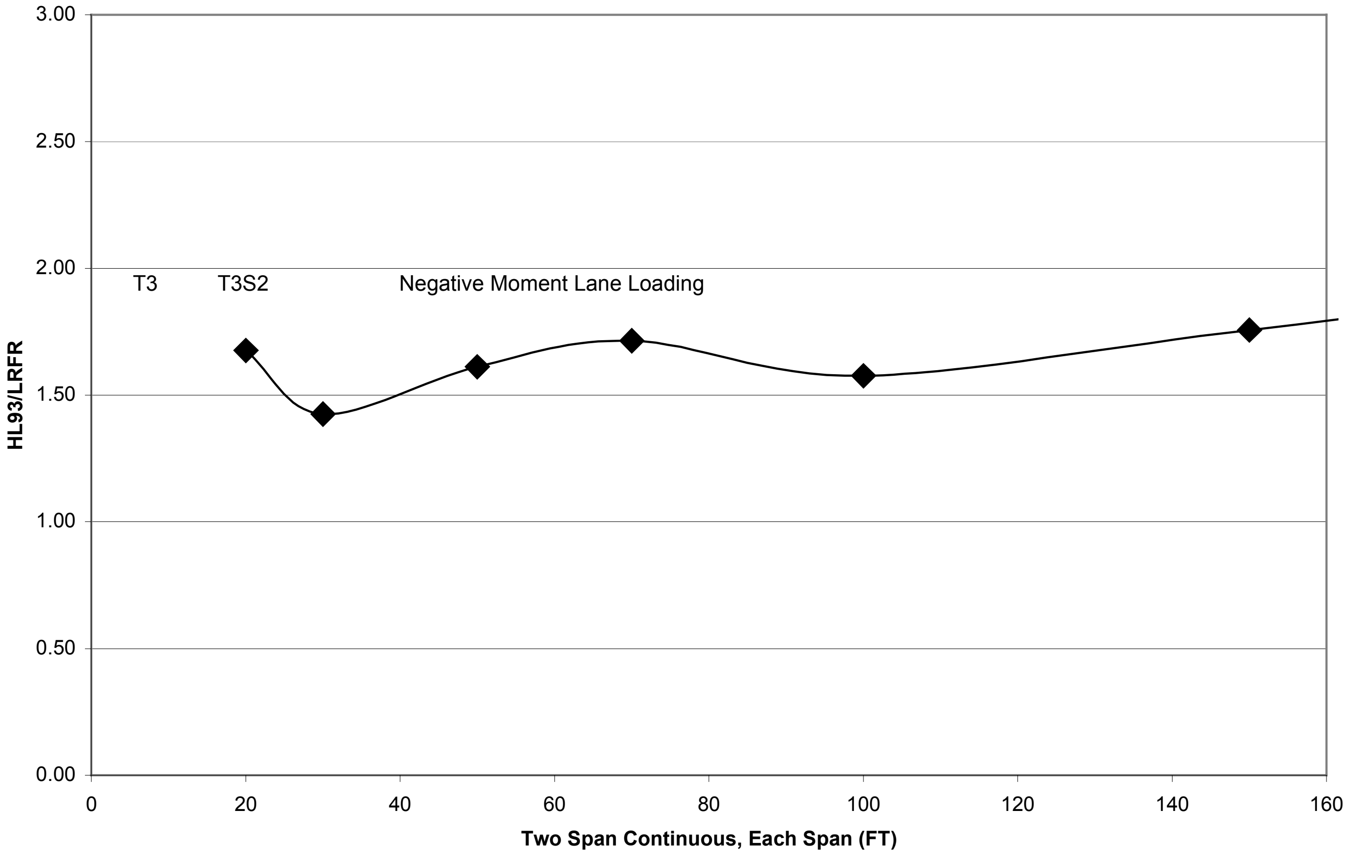

Figure 4-3 Ratios of Negative Moments for LRFR Legal Loads

4.5 SUMMARY OF MAJOR REVISIONS TO PRE-FINAL DRAFT MANUAL

Numerous revisions were made to Section 6 and the supporting Appendices of the Pre-Final Draft Manual in response to the comments of the participants in the testing phase. These revisions were then presented and discussed at the December 6, 7 meeting of 1999. Revisions are summarized individually with the article number and title underlined. One of the changes from the Pre-Final Draft Manual to the Final Draft Manual was a general reordering of Section 6 to make the rating system and procedures clearer. This section of the final report indicates substantial changes from the Pre-Final Draft to the Final Draft and does not indicate every instance of revision or reordering. The article numbers given first refer to the Draft Manual, the article number in bold following refers to the Final Draft Manual.

A6.2 General Load Rating Equation
A6.4.2

Multiplying one reduction factor by another (ϕ_s and ϕ_c) may be too severe for bridges where both ϕ_s and ϕ_c are 0.85 (a combined reduction of 28%). The lower limit of: $\phi_s\ \phi_c \geq 0.85$, was included in the Final Draft Manual.

A6.2.1.1 Rating in Tons
A6.1.7.1
A conversion of HL93 ratings to Tons is simplistic and is prone to serious misinterpretation, even though it is true in an average sense for bridges system wide. It was initially intended as a rough conversion to get a tonnage out of the HL93 Rating Factor for NBI reporting. FHWA currently collects the equivalent information from LFR in terms of metric tons in the NBI. The Final Draft Manual shows the conversion to Tons only under the section on legal load ratings. The best way to report HL93 Inventory and Operating ratings is simply as rating factors. The HL93 rating is not intended for use in determining a posting load.

A6.3.2.4 Load Factors for Permanent Loads
A6.2.2.3
γ_{DW} = 1.25 is provided for use when the wearing surface thickness is measured.

A6.2.5 Condition Factor ϕ_c
A6.4.2.3
NBI condition ratings are average ratings for bridge components. In some cases the condition of the member controlling the load rating may not match the average superstructure rating, a drawback inherent in using NBI component ratings. If element level inspection data is available, a better quantification of the condition factor is achieved. The wording has been changed to emphasize the condition of the member if that information is available. If not, the average component rating in NBI Item 59 should be used.

A6.2.6 System Factor ϕ_s
A6.4.2.4
The aim of ϕ_s is to add a reserve capacity such that the overall system reliability is the same for redundant and non-redundant systems. Applying a system factor of 0.85 increases the element reliability of a non-redundant element at the legal load level from approximately 2.5 to a more realistic target of 3.5. This results in the same system reliability for redundant and non-redundant bridges.

A more liberal system factor for non-redundant riveted sections and truss members with multiple eyebars has been added. The internal redundancy in these members makes a sudden failure far less likely. An increased system factor of 0.90 seems appropriate for such members.

It is not necessary to use system factors for shear, as shear failures tend to be brittle, so system reserve is not possible for shear. A constant value of $\phi_s = 1.0$ is suggested for shear evaluation.

Subsystems that have redundant members should not be penalized if the overall system is non-redundant. Thus, closely spaced parallel stringers would be redundant even in a two girder main system (or a truss bridge).

All bridges (irrespective of number of girders) with girder spacings less than 4 feet will get a 0.85 value for ϕ_s. For box girder bridges, consider each box as representing two distinct I-sections.

<u>A6.5.1 Design Load Check</u>

A6.4.3

Bridges that pass HL93 screening only at an Operating level reliability will not have adequate capacity for State legal loads significantly heavier than the AASHTO legal loads, which were the basis for our calibration. The text has been revised as follows to clarify the significance of the HL93 check in evaluation:

- Bridges that pass HL-93 screening at the Inventory level will have adequate capacity for all AASHTO legal loads and State legal loads that fall within the exclusion limits described in the LRFD Bridge Design Specifications.

- Bridges that pass HL93 screening at the Operating level will have adequate capacity for AASHTO legal loads, but may not rate (RF>1) for all state legal loads.

<u>A6.5.2 Load Rating for Legal Loads</u>

A6.4.4

Load rating by LRFR provides only a single safe load capacity for a given legal load (current practice provides an Inventory and Operating ratings). Usually, bridges are load rated for all three AASHTO legal loads, to determine the governing truck; the rating factor and/or safe load capacity in Tons may be computed for each vehicle type used in the rating. Posting signs used in some jurisdictions may indicate load limits for each legal truck type.

<u>A6.5.2.3.1 Live Loads for Load Rating</u>

A6.8.3

When the lane load governs legal load ratings (spans > 200 ft.) the equivalent truck weight for use in calculating a safe load capacity for the span shall be taken as 80 kips (weight of a Type 3-3 truck). This was clarified in the final draft.

A6.4.4.2

An additional load model is specified for checking negative moments and reactions at interior piers. A second truck (75% of type 3-3) with a fixed headway distance of 30 feet is added to the lane load model. This gives an acceptable bias when compared with HL93 negative moments.

A6.5.3.3 Permit Types

A6.4.5.3

The terms "Routine Permits" and "Special Permits" do not seem to adequately convey their purpose, as used in the context of the Manual. The definitions of these terms have been criticized as being confusing. The following change in terminology in the final draft should add to the meaning for some users of the Manual:

Routine (Annual) Permits - Valid for unlimited trips over a period of time, not to exceed one year, where the maximum gross weight of vehicles allowed by an agency under this permit category is usually not in excess of 150 KIPS. The permit vehicles are expected to mix with traffic and move at normal speeds.

Special (Limited Crossing) Permits - Valid for a single trip or for a limited number of trips, not exceeding 100 crossings. These permit vehicles are usually heavier than vehicles issued Annual Permits. The permit vehicles may be allowed to mix with traffic or single trip permits may be required to be escorted in a manner which controls speed and/or lane position, and the presence of other vehicles on the bridge.

A6.5.3.5.2 Permit Load Factors

C6.4.5.4.2.2

Live load factors for Special permits in the March 1999 draft were calibrated to an Operating level reliability and decrease with increasing loads when allowed to mix with traffic. This approach was perceived as leading to more liberal permit evaluation procedures. The decrease in load factor occurs because there is a smaller effect from vehicles in the other lanes as the weight of the Special permit increases. The factors have since been recalibrated to a higher reliability level and are not tied to the load level. An increased target safety (as there is higher risk of structural damage) for super-heavy trucks is appropriate. When load factors are made independent of the permit weights, it also avoids the variation in load factors depending on whether axle or gross loads govern.

A6.5.3.6 Dynamic Load Allowance

A6.4.5.5

The Final Draft Manual allows IM to be eliminated for slow moving ($\leq$10 MPH) permit vehicles.

A6.6.4.1 Design Load Check

Table 6.4.2.2-1 and **C6.5.4.1**

Service III need not be checked at the design Operating level. Most prestressed designs are designed for no cracking under full service loads. Fatigue is not a concern until cracking is initiated. Hence, p/s components need not be checked for fatigue.

C6.6.9 Evaluation for Shear (concrete structures)

C6.5.9

P/S concrete shear capacities are load dependant, which means computing the shear capacity involves an iterative process when using the current AASHTO MCFT. Multiple locations, preferably at 0.05 pts, need to be checked for shear. Location where shear is highest may not be critical because the corresponding moment may be quite low. Typically, locations near the 0.25 point are critical because of relatively high levels of both shear and moment. Also contributing to the need for checking multiple locations along the beam is the fact the stirrup spacings are typically not constant, but vary.

A6.7.2 Materials (Steel)

C6.6.2.1

LRFD did not include lower grade steels. These older steels generally have similar or better strain-hardening strains than their modern counterparts. The Manual specifies using the β factor of 0.9 which is specified for 36 ksi steel for 33 ksi steel also.

6.7.4.1 Design Load Check

A6.6.4.1 Design Load Ratings

Provides load factor for SERVICE II Operating:

Table 6.6.4.2.1-1
Evaluation Live Load Factors

Limit State	Load Type	Load Factor
SERVICE II (INV)	HL93	1.3
SERVICE II (OPR)	HL93	1.0

6.7.4.2.2 Service Limit States (Load Rating)

A6.6.4.2.2 and **Table 6.4.2.2-1**

SERVICE II check has been formulated into a LRFR rating factor format similar to the other limit states using the load factors noted below. This provision was misinterpreted and results of this check were often misapplied in the trial ratings. This check will be optional for permit review as indicated by shading in Table 6.4.2.2-1.

Table 6.6.4.2.2-2
Evaluation Live Load Factors

Limit State	Load Type	Load Factor
SERVICE II	Legal	1.3
SERVICE II	Permit	1.0

A6.7.8.1 Rating of Steel Compression Members with Eccentric Connections (Secant formula method)

C6.6.8 and **Appendix C6.3**

In compression members with unsymmetrical sections (such as truss chords) the gravity axis of the section may not coincide with the working lines, resulting in an eccentric connection. Compression members having equal end eccentricities are conveniently analyzed using the secant formula provided in the Appendix to the current MCE. The LRFD specification like most modern codes does not utilize the Secant formula but provides an interaction equation for the design of members with combined axial loads and concurrent moments. Rating compression members via an interaction equation is somewhat tedious as an iterative approach may be required to establish the governing rating. A rating approach using the interaction equation is given in Appendix C6.3 of the final draft Manual.

As an alternative to analyzing axial compression members with eccentric connections as combined compression-flexure members (LRFD 6.9.2.2) an axial load magnification factor may be applied to rate the member as a concentrically loaded members with an equivalent load. Secant formula is used to include the first and second order bending effects to produce a magnified axial load (dead and live) that would produce a constant stress over the cross section equal to the peak stress in an eccentric member. This approach is applicable to members assumed to be pinned at the ends and without lateral loads on the members. Pin connected compression chord members in truss bridges are a common example of this type. An advantage inherent in this method is that rating factors can be computed without having to first determine M_r which can be difficult to do for non-standard truss sections. An example using this approach is provided in Appendix C6.3 to Section 6.

A6.7.9.6 Riveted Members

A6.6.9.6

The following guidance was added for older riveted members: The moment capacity of riveted sections and sections with holes in the tension flange should be limited to My. LRFD C6.10.4.1.1: "At sections of

flexural members with holes in the tension flange, it has also not been fully documented that complete plastification of the cross section can be achieved prior to fracture of the net section of the flange". LRFD criteria could be used for older riveted sections if b/t ratios are satisfied. The evaluator needs to check the b/t between rivet lines, from the rivet line to the plate edge, and the spacing of the rivets. Net section failure should also be checked. This is dependent upon the yield to tensile ratio of the steel. Some older steels may not be so good, others are excellent. For riveted compression members LRFD curves would be conservative since the riveted members should have much lower residual compression stress.

SECTION 5.0 COMPARISON OF LRFR TO LFR

5.1 INTRODUCTION

Comparisons between the proposed LRFR and the current Load Factor Rating (LFR) systems for evaluating and rating existing bridges are important to enhance the understanding of engineers using the new rating system. Bridge engineers are familiar with the end result in terms of actual bridge performance of using the LFR. To instill confidence in the proposed LRFR it is important to demonstrate that LRFR will produce rating results that will be consistent with the expectations of how different bridge types behave.

There are a number of differences between the proposed LRFR and the current LFR. Like the LRFD, one of the primary objectives in the LRFR is to utilize load models that provide a uniform relationship in the load effects to the actual legal traffic loading in the US over all span lengths. Aside from differences arising from the loading models and evaluation factors, LRFR has fewer differences from the LFR than ratings by the LFR do from ratings by Allowable Stress. Some areas where differences exist between LRFR and LFR are summarized below. Other sections of this report also contain discussion of issues that highlight the differences between LFR and LRFR.

- Three load rating procedures targeted to specific needs
- Calibrated load and resistance factors
- Site-specific load factors for rating
- System factor
- Condition Factor
- Live load models for evaluation
- Live load distribution factors
- Impact factor (dynamic load allowance)
- Load factors for overweight permits
- Serviceability checks
- Member resistances

The first difference between the current LFR ratings and the LRFR ratings is the structure of the systems. The LFR method required a rating based on the controlling effect from either the HS20 truck or lane loading. This rating was reported to the National Bridge Inventory (NBI). Beyond that check the owner could determine rating factors for other legal vehicle configurations for posting. The LRFR has also implemented a tiered approach to load ratings. An initial check is performed based upon the HL93 loading in the same manner as was done for the HS20 loading and provides a value suitable for reporting to FHWA. The difference is that the HL93 loading provides a screening check for all of the AASHTO trucks and the State legal exclusion vehicles in the United States. If a bridge has a rating factor greater than 1.0 for the Inventory HL93 check then it is known that the bridge is satisfactory for all legal vehicles. This statement was not true for the HS20 check in the LFR system. After the screening check the LRFR manual gives guidance concerning the limit states and live load factors for legal loads that are applied if a bridge does not pass the initial HL93 check. These legal load checks are made using the AASHTO legal loads and individual state legal loads as was the practice of many states under LFR. Finally, the LRFR provides limit states and live load factors specific to overweight permit vehicles for bridges that pass the legal load checks. In LFR, provisions specific to the checking of permit loads are not included.

The differences in the evaluation factors involved in load ratings by LRFR and LFR can be grouped as shown in the following table.

Category	LRFR	LFR
Member Resistance	ϕR_n by LRFD	ϕR_n by LFD
Distribution Factors	LRFD formulas	"S over" formulas
Dead Load Factors	γ_{DC} and γ_{DW}	γ_D
Live Load Factor	Calibrated γ_L	γ_L
Condition and System Factors	ϕ_c ϕ_s	Not applicable
Dynamic Load Allowance	May be tied to riding surface conditions	Span length dependent

Table 5-1. Changes from LFR to LRFR

LRFR

$$RF = \frac{\phi_c \phi_s \phi R_n - \gamma_{DC} DC - \gamma_{DW} DW}{\gamma_L LL(1+IM)}$$

LFR

$$RF = \frac{\phi R_n - \gamma_D D}{\gamma_L LL(1+I)}$$

Changes to member resistance and load distributions result because the LRFR is a companion to the LRFD and the LFR is a companion to the LFD. These changes in LRFD were due to the reliability-based calibration of the ϕ factors and updating the specifications to meet the current state-of-the-art in member resistance predictions (R_n). Major changes were made in the live load distribution factors in the LRFD specifications that have resulted in more accurate though more complex distribution formulas.

The dead load factor, γ_D, was taken as 1.3 in the LFD specifications. This factor has been broken up into multiple categories in the LRFD. Each category is given a load factor based upon its variability statistics. The two main groups are the dead load factor for components, γ_{DC}, which has a maximum of 1.25 and the dead load factor for wearing surfaces, γ_{DW}, which has a maximum of 1.5. The LRFR allows the dead load factor for wearing surfaces to be reduced to 1.25 if the in-place thickness of wearing surfaces has been verified by field measurements.

The live load factor, γ_L, in LFR was fixed at 2.17 for Inventory ratings and 1.3 for Operating ratings for all vehicular loads and site traffic conditions. These two factors represented the design level for Inventory and the minimum safe level for Operating. The LRFR uses a fixed factor of 1.75 for the Inventory check with the HL93 and 1.35 for the Operating. For rating and posting calculations the LRFR has tied the legal load factors to the bridge ADTT and ranges from 1.8 to 1.4. These factors have been calibrated by reliability methods to provide a uniform safety level over varying traffic exposure conditions. Higher ADTT values correspond to a greater probability of side by side crossings of heavy vehicles and to a higher extreme gross vehicle weight itself. Live load factors have been provided to match these changes in traffic characteristics. Permit loads have a table of load factors that takes into account the permit type and the reduced chances of side-by-side crossings for heavier permits. Guidance on permit checking was not included in LFR.

The condition, ϕ_c, and system, ϕ_s, resistance factors have been incorporated into the LRFR based upon the findings of NCHRP report 301 and NCHRP report 406 respectively. The condition factor represents the change in member resistance variability (scatter), which increases in deterioration, and the probable future deterioration between inspection periods. The change in mean member resistance is a separate issue and is accounted for by using deteriorated dimensions and properties to calculate the nominal resistance. The system factor has been calibrated to address system failure (instead of member failure) which was not

addressed in the calibration of the LRFD and is especially important when considering older non-redundant bridge types. The system factor builds-in reserve member capacity (through lower ratings) in non-redundant bridges.

The impact factor, I, in the LFR is determined from a formula which calculates a decreasing impact with increasing span length. The dynamic load allowance, IM, in the LRFR for legal loads uses a constant factor (33%) with optional guidance for lower factors based on riding surface condition provided in the Manual commentary.

5.2 RATINGS OF STEEL AND CONCRETE BRIDGES: LFR vs. LRFR

The comparisons of the LRFR to the LFR results for the trial ratings are based on load ratings performed using the Pre-final Draft Manual (March 1999). Revisions have been made to the Draft manual after review of the ratings and the participant comments. However, the general comparisons presented herein do reflect the Final Draft Manual (March 2000). The trial ratings allow the differences between the two methods to be seen in an actual population of bridges of varied types and physical conditions. Comparisons are based on a population of 71 trial ratings. Appendix A of the Final Draft Manual also contains demonstration problems where the approach and results for the LRFR method are shown, LFR results are often presented for comparison.

The results from the trial ratings phase are presented for the common bridge types in tables and graphs of the tabulated data. The graphs show the results for individual bridges plotted with the LFR rating on the X axis and the LRFR rating on the Y axis. Each graph has a solid line indicated the boundary where the ratings are the same by both methods. The perpendicular distance of each bridge data point from the solid line indicates the amount of difference between the two methods. Data above the line indicates that the LRFR allows heavier traffic loads, and data below the line indicates that the LFR allows heavier traffic on a given bridge.

	Rating Summary				Ratios	
	LRFR (HL93)		LFR (HS20)		LRFR-Inv	LRFR-Opr
State	Inv	Opr	Inv	Opr	LFR-Inv	LFR-Opr
VT	1.35	1.75	1.77	2.96	0.76	0.59
VT	2.13	2.77	2.75	3.76	0.77	0.74
TN	1.11	1.44	1.11	1.85	1.00	0.78
TN	1.27	1.64	1.15	1.92	1.10	0.85
TN	1.13	1.46	1.23	2.05	0.92	0.71
IL	1.12	1.45	1.50	2.50	0.75	0.58
IL	1.35	1.75	1.52	2.53	0.89	0.69
IL	1.59	2.06	1.58	2.63	1.00	0.78
IL	0.70	0.90	1.07	1.78	0.65	0.51
ID	0.98	0.98	1.01	1.68	0.97	0.58
NY	0.52	0.98	0.57	0.96	0.91	1.02
NJ	0.21	0.28	0.20	0.34	1.05	0.82
NJ	0.95	1.23	1.25	2.09	0.76	0.59
IA	1.23	1.60	1.21	2.01	1.02	0.80
IA	0.88	1.14	0.85	1.41	1.04	0.81
TX	1.06	1.37	1.66	2.78	0.64	0.49
AL	0.85	0.85	0.77	1.28	1.10	0.66
				average:	0.90	0.71
				samples:	17	17

Table 5-2. Steel Multi-girder Bridges Design Loads (Inventory and Operating Rating Factors)

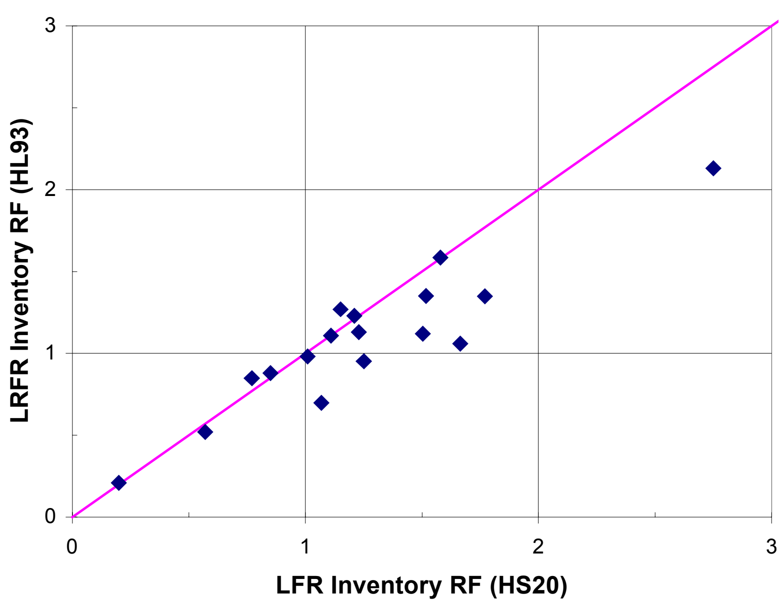

Figure 5-1. Steel Multi-girder Bridges Design Loads (Inventory)

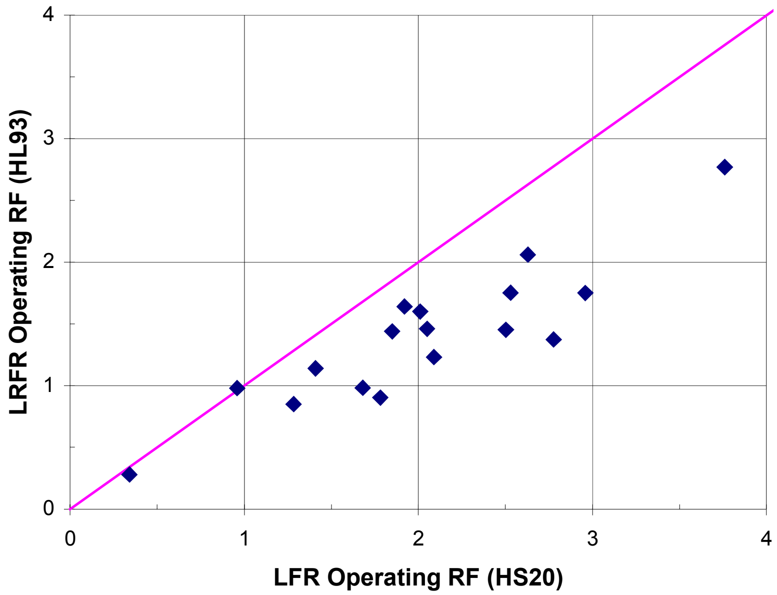

Figure 5-2. Steel Multi-girder Bridges Design Loads (Operating)

State	Rating Summary			Ratios	
	LRFR	LFR		LRFR / LFR-Inv	LRFR / LFR-Opr
		Inv	Opr		
VT	2.88	1.88	3.14	1.53	0.92
VT	5.66	2.87	4.79	1.97	1.18
IL	2.47	1.52	2.55	1.62	0.97
IL	3.29	1.57	2.62	2.09	1.25
IL	3.84	1.66	2.77	2.32	1.39
IL	1.40	1.13	1.89	1.24	0.74
ID	1.59	1.27	2.13	1.25	0.75
NY	1.49	0.73	1.21	2.04	1.23
NJ	0.41	0.26	0.44	1.58	0.93
NJ	1.95	1.13	1.89	1.73	1.03
			average:	1.74	1.04
			samples:	10	10

Table 5-3. Steel Multi-girder Bridges, Legal Loads

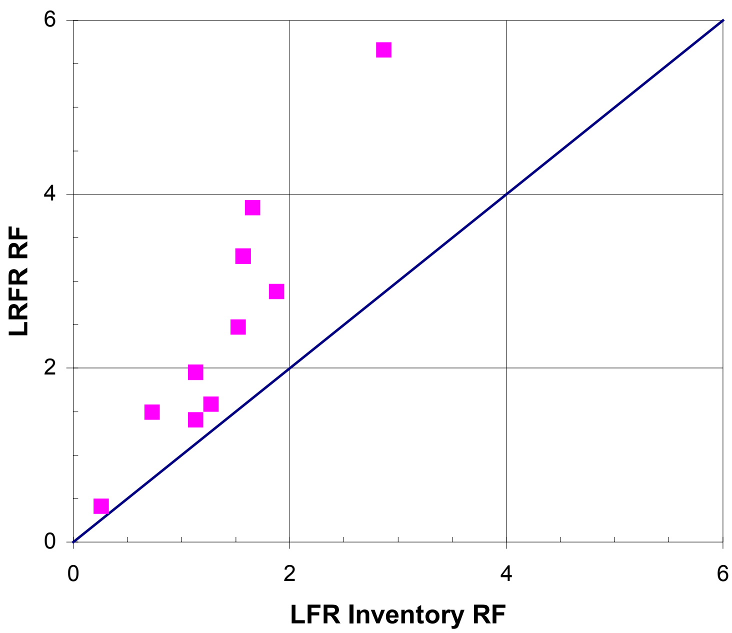

Figure 5-3. **Steel Multi-girder Bridges**
LRFR vs LFR Inventory for Legal Loads

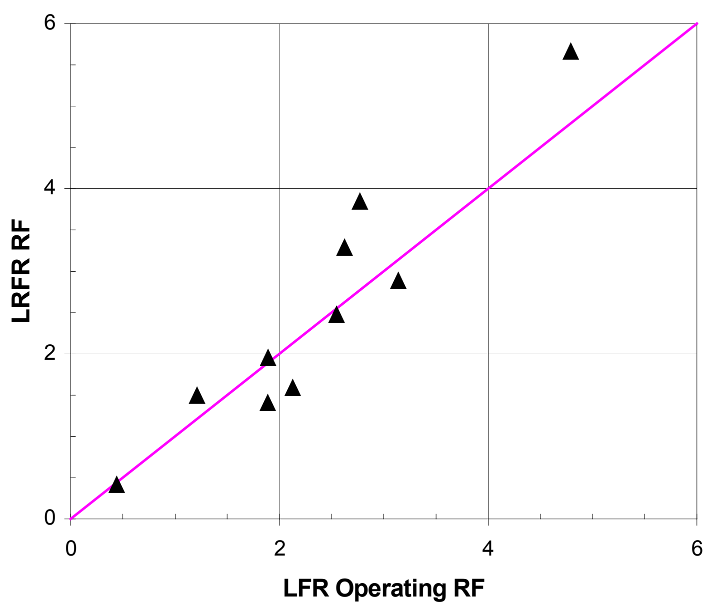

Figure 5-4. **Steel Multi-girder Bridges**
LRFR vs LFR Operating for Legal Loads

State	Rating Summary				Ratios	
	LRFR (HL93)		LFR (HS20)		LRFR / LFR - Inv	LRFR / LFR - Opr
	Inv	Opr	Inv	Opr		
TN	0.69	0.89	0.94	1.56	0.73	0.57
IL	1.08	1.39	1.50	2.50	0.72	0.56
IL	0.65	0.84	1.09	1.72	0.59	0.49
IL	0.77	1.00	1.29	2.04	0.60	0.49
ID	0.74	0.96	0.84	1.40	0.88	0.68
ID	0.56	0.73	0.54	0.90	1.04	0.81
MN	0.65	0.85	0.81	1.35	0.80	0.63
IA	1.15	1.49	1.20	2.00	0.96	0.75
FL	0.67	0.86	0.44	0.74	1.52	1.16
				average:	0.87	0.68
				samples:	9	9

Table 5-4. Reinforced Concrete T beam Bridges Design Load (Inventory and Operating Rating Factors)

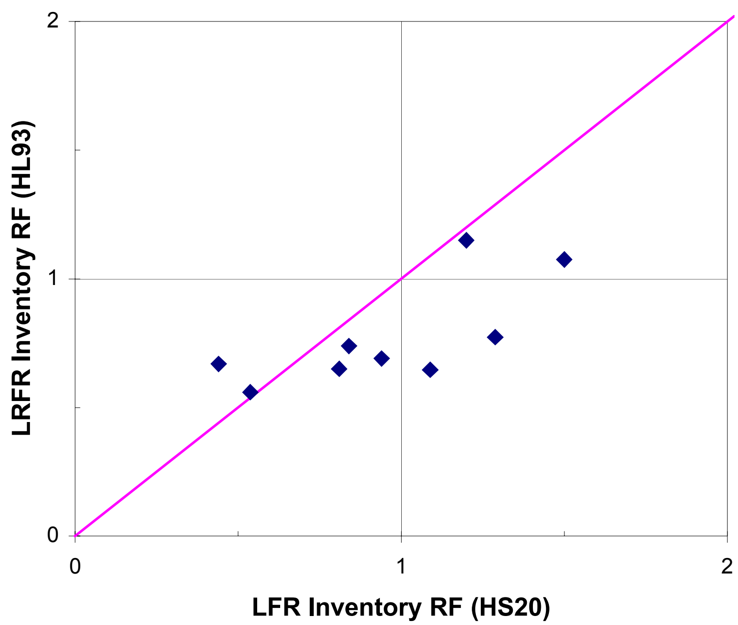

Figure 5-5. Reinforced Concrete T beam Bridges Design Load (Inventory)

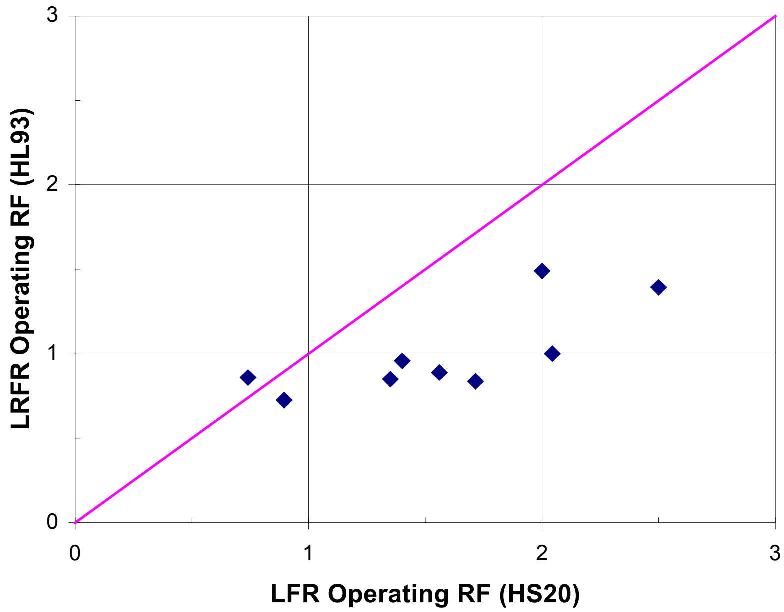

Figure 5-6. Reinforced Concrete T beam Bridges Design Load (Operating)

State	Rating Summary LRFR	LFR Inv	LFR Opr	Ratios LRFR / LFR - Inv	LRFR / LFR - Opr
TN	1.46	1.27	2.12	1.15	0.69
IL	2.25	1.67	2.78	1.35	0.81
IL	1.52	1.12	1.86	1.36	0.81
IL	1.81	1.33	2.22	1.36	0.82
ID	1.46	1.10	1.84	1.32	0.79
ID	1.01	0.73	1.22	1.38	0.83
MN	1.39	1.01	1.69	1.38	0.82
			average:	1.33	0.80
			samples:	7	7

Table 5-5. Reinforced Concrete T beam Bridges, Legal Loads

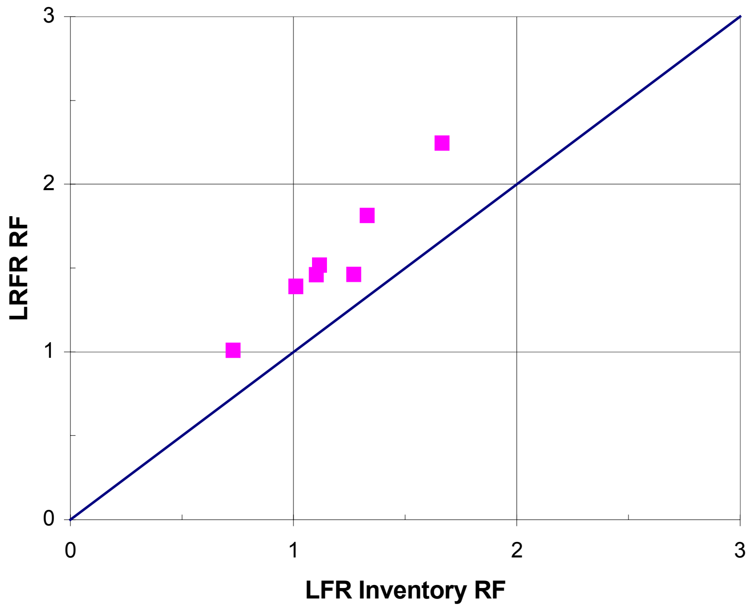

Figure 5-7. Reinforced Concrete T beam Bridges LRFR vs LFR Inventory for Legal Loads

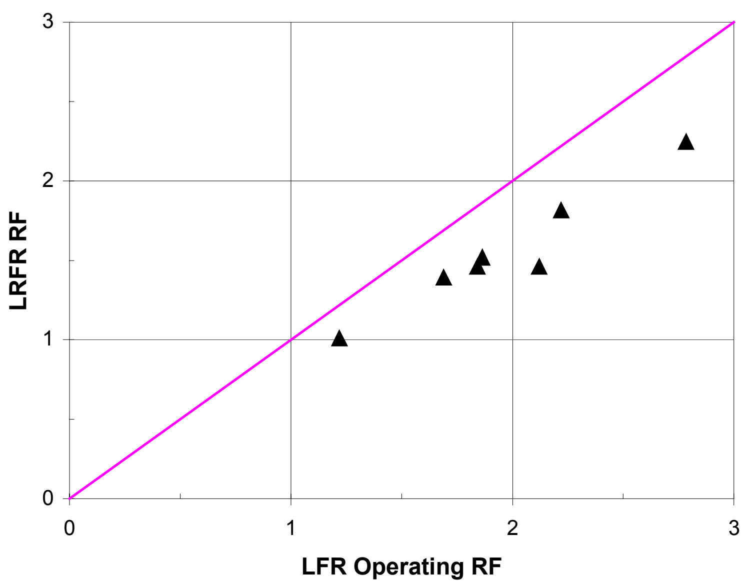

Figure 5-8. Reinforced Concrete T beam Bridges LRFR vs LFR Operating for Legal Loads

	Rating Summary				Ratios	
	LRFR (HL93)		LFR (HS20)		LRFR - Inv / LFR - Inv	LRFR - Opr / LFR - Opr
State	Inv	Opr	Inv	Opr		
TN	2.57	3.33	1.83	2.47	1.40	1.35
WA	1.09	1.41	1.24	2.07	0.88	0.68
WA	0.70	0.91	1.56	2.61	0.45	0.35
ID	0.54	0.54	1.09	1.33	0.50	0.41
ID	0.38	0.38	0.69	0.87	0.55	0.44
MN	1.04	1.35	1.04	1.49	1.00	0.91
MA	1.14	1.48	1.31	2.19	0.87	0.68
CA	0.61	0.79	0.79	1.32	0.77	0.60
IA	1.20	1.56	0.83	1.38	1.45	1.13
TX	0.24	0.31	0.76	1.27	0.31	0.24
FL	0.61	0.79	1.26	2.10	0.48	0.38
				average:	0.79	0.65
				samples:	11	11

Table 5-6. Prestressed Concrete I girder Bridges Design Load (Inventory and Operating Rating Factors)

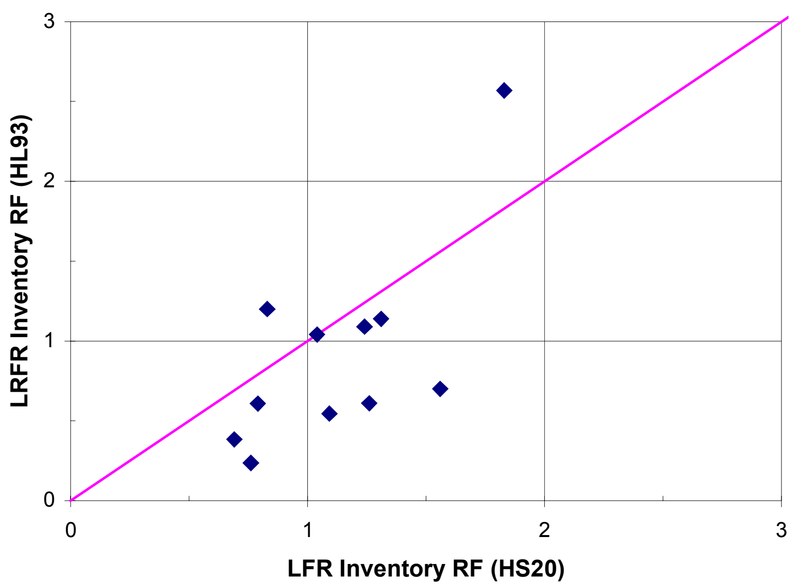

Figure 5-9. Prestressed Concrete I girder Bridges Design Load (Inventory)

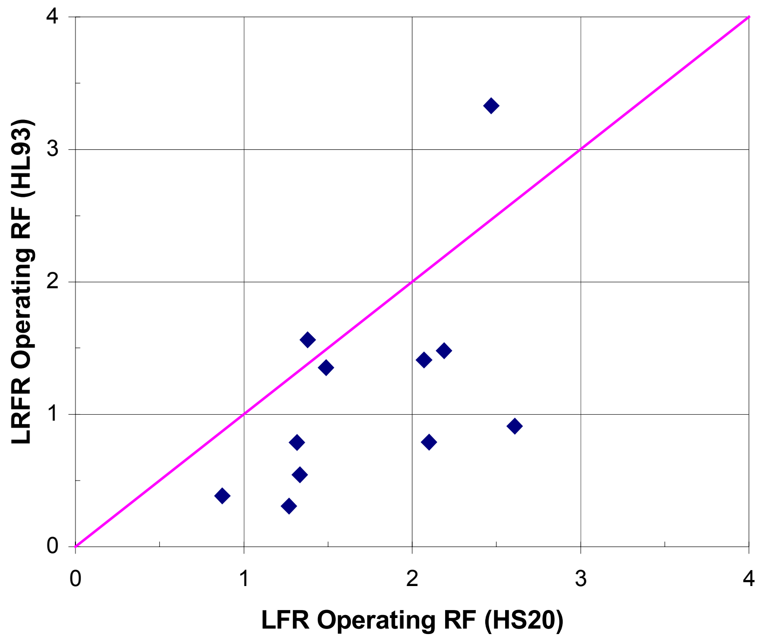

Figure 5-10. **Prestressed Concrete I girder Bridges Design Load (Operating)**

State	Rating Summary			Ratios	
	LRFR	LFR		LRFR / LFR - Inv	LRFR / LFR - Opr
		Inv	Opr		
WA	2.11	1.32	2.21	1.59	0.95
WA	1.20	1.20	2.01	1.00	0.60
ID	0.86	0.91	1.52	0.95	0.57
ID	0.62	0.64	1.07	0.96	0.58
CA	0.84	0.95	1.59	0.89	0.53
			average:	1.08	0.65
			samples:	5	5

Table 5-7. **Prestressed Concrete I girder Bridges, Legal Loads**

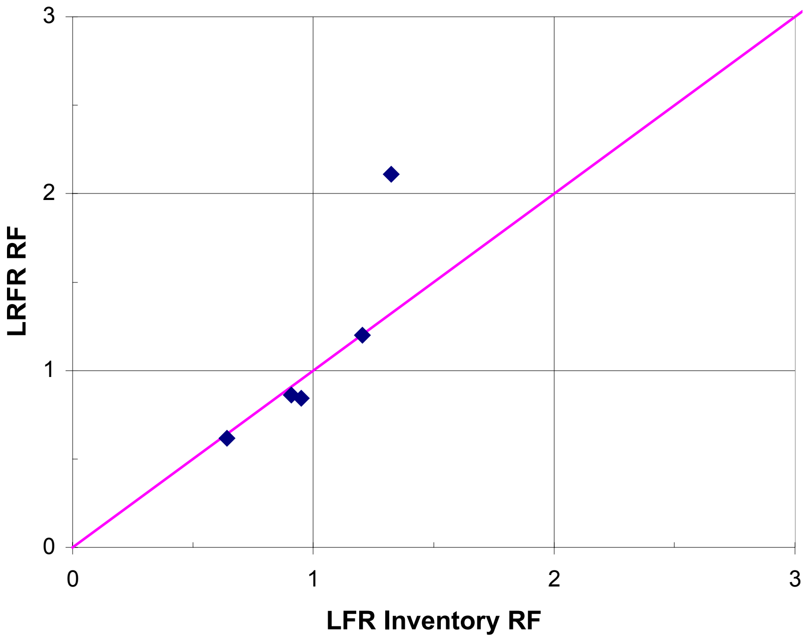

Figure 5-11. Prestressed Concrete I girder Bridges LRFR vs LFR Inventory for Legal Loads

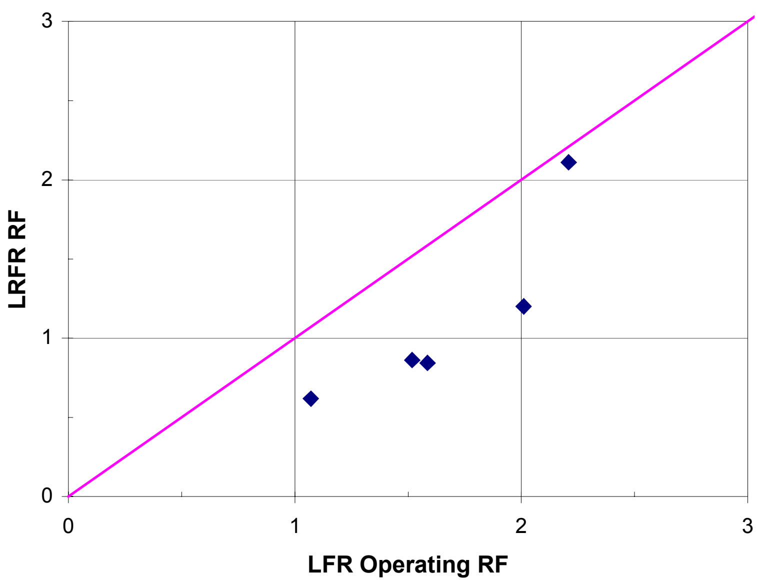

Figure 5-12. Prestressed Concrete I girder Bridges LRFR vs LFR Operating for Legal Loads

5.3 OVERALL COMPARISONS

The design Inventory (level of safety) for LRFD was calibrated to the average of the design Inventory for LFD, therefore those values are comparable. All of the design load Operating ratings (HL93 vs HS20) are lower for the LRFR than for the LFR. This is the expected result since the ratio of Inventory to Operating for LFR is 2.17/1.3 = 1.67, while the ratio of inventory to operating for LRFR is 1.75/1.35 = 1.30. The Operating for LRFR provides a second, lower safety level screening for states whose legal traffic follows the limits of the federal bridge formula.

Steel Multi-girder Bridges
The results for the steel multigirder bridges show a trend toward slightly lower design load Inventory ratings by LRFR than by LFR. The LRFR legal load ratings are much higher than the LFR Inventory ratings and approximately the same as the LFR Operating ratings.

Steel Nonredundant Bridges
The test population of this type of bridges was too small to make generalizations. The use of system factors on the resistance side to build-in reserve member capacity could result in reduced ratings under LRFR.

Reinforced Concrete T beam Bridges
Design load Inventory and Operating ratings are lower by LRFR than by LFR. Legal load ratings are slightly higher for LRFR than LFR Inventory but lower than LFR Operating. T-beam bridges are short span bridges with short beam spacings, a combination considered more vulnerable under LRFD criteria.

Prestressed Concrete I Girder Bridges
The prestressed concrete I girder bridges display a wider scatter in results than was present for the steel or reinforced concrete. Lower shear ratings under LRFR were obtained, and the majority of p/s concrete bridges were governed by shear rather than by flexure. Some reasons for this finding are discussed later in this section.

A comparison of the LRFR legal load results to the current ratings (by LFR and Allowable Stress) for the three main material types is given in Table 5-8 (not enough timber bridges were rated for legal loads to consider averages). The LRFR ratings are greater than the current Inventory ratings and less than the current Operating ratings on average.

Material	LRFR/LFR Inventory	LRFR/LFR Operating
Steel	1.59	0.88
Reinforced Concrete	1.30	0.78
Prestressed Concrete	1.21	0.70

Table 5-8. Overall LRFR/LFR Comparison for Legal Loads

A comparison of the design and legal load results for the LRFR to the LFR for multi-girder bridges is given in Table 5-9. The number of bridges for each comparison (#) and the average of the ratios for that group (μ) are given. The multi-girder bridges are redundant and therefore do not include modification due to the system resistance factor. Only comparisons to LFR results (flexural or shear) are made in Table 5-9. Since timber bridges ratings were all currently rated by the allowable stress approach there are no timber bridges shown in Table 5-9.

Material	Design (HL93/HS20)				AASHTO Legal Loads			
	LRFR Inv LFR Inv		**LRFR Opr** LFR Opr		**LRFR** LFR Inv		**LRFR** LFR Opr	
	μ	#	μ	#	μ	#	μ	#
Steel	0.9	17	0.71	17	1.74	10	1.04	10
Reinforced Concrete T beam	0.87	9	0.68	9	1.33	7	0.8	7
Prestressed Concrete I beam	0.79	11	0.65	11	1.08	5	0.65	5

Table 5-9. Ratios for Multi-Girder Bridges

Three figures are presented to show some of the changes from the LFR to the LRFR for simple span beam bridges. Using an approximation for dead load effects used in NCHRP report 301 the plots show the rating factor for moment on the vertical axis and the span length on the horizontal axis.

The figure 5-13 is based on bridges that have HS20 Inventory ratings of 1.0. A line at 1.0 indicates the LFR Inventory rating and the line at 1.67 indicates the LFR Operating Rating. LRFR HL93 Inventory and Operating ratings and their variation over length are plotted. The same distribution factor for LRFR and LFR has been assumed in the figure. On average the two LRFR plots would be shifted upward since the LRFR distribution factor is often lower than the LFR distribution factor, although it can be either higher or lower. The form of the plots is mostly due to the nature of the HL93 loading. The tandem vehicle produces larger force effects that the HS20 below 40 FT and the addition of the uniform load of 0.64 KIP/FT increases the force effects for the longer spans.

Figure 5-14 is based on the same HS20 RF (Inventory) = 1.0 bridges but shows the LRFR Legal load ratings for three ADTT values. Again the plots would be shifted upward by the difference in distribution factors. The form of the LRFR plots in 5-13 and 5-14 are similar in their rise and fall relative to the HS20. This is to be expected as both the HL93 and the LRFR Legal loads are intended to provide a uniform bias to the exclusion vehicle population.

Figure 5-15 shows the LRFR Legal load rating factors for bridges that are assumed to have a LFR Operating rating factor of 1.0 for the AASHTO legal loads. In this case the load models are the same for the LRFR and the LFR. This plot shows how the LRFR ratings will be between the old LFR ratings. Here the ADTT is used to obtain one safe rating factor for legal traffic instead of the upper and lower bounds obtained in the LFR. The comparisons from the trial ratings and from the components of each system show the trends of how ratings will change for the national bridge inventory from the current LFR to the LRFR.

The LRFR manual has implemented a systematic approach to bridge rating that yields uniform reliability indices where possible while providing a more realistic assessment of the safe load capacity of existing bridges. The different issues and philosophy for evaluation versus design are reflected in the target reliability index, dead load, live load, and resistance factors. The needs for bridge rating are accommodated through a system using an initial screening check followed by more detailed legal load checks with site specific data if required. Individual ratings showed that in some cases the LRFR rating factor can be greater than the current Operating rating (previously considered to be the upper bound). The LRFR ratings can also be less than the current Inventory rating (previously considered to be the lower bound) depending on bridge conditions and site traffic. The state trial ratings demonstrated that the

average ratings fall between the current Operating and Inventory ratings for legal traffic. The selection of where between the two previous bounds of Operating and Inventory is now dictated by the methodology which includes factors for the condition, system redundancy, and local traffic. These same considerations were used in the past in a more qualitative manner.

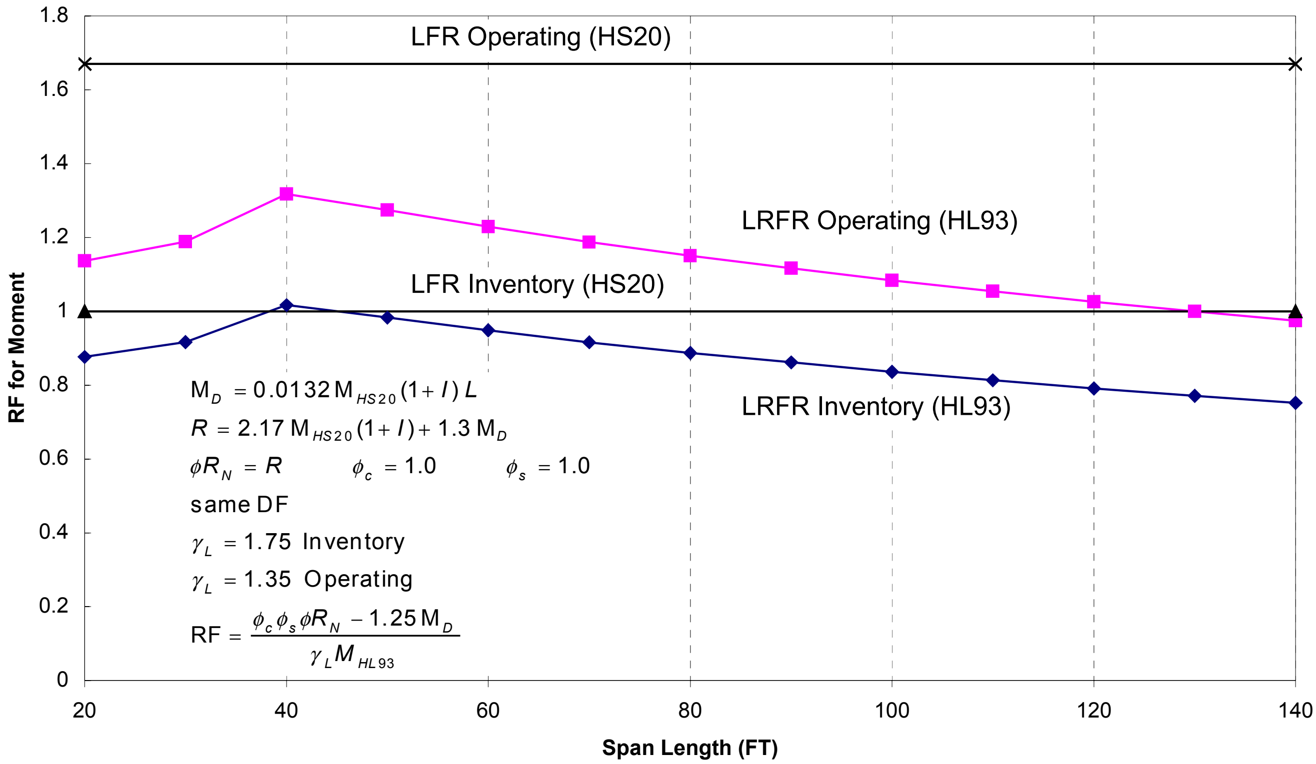

Figure 5-13 LFR (HS20) VS LRFR (HL93)
(Assuming same distribution of Live Loads)

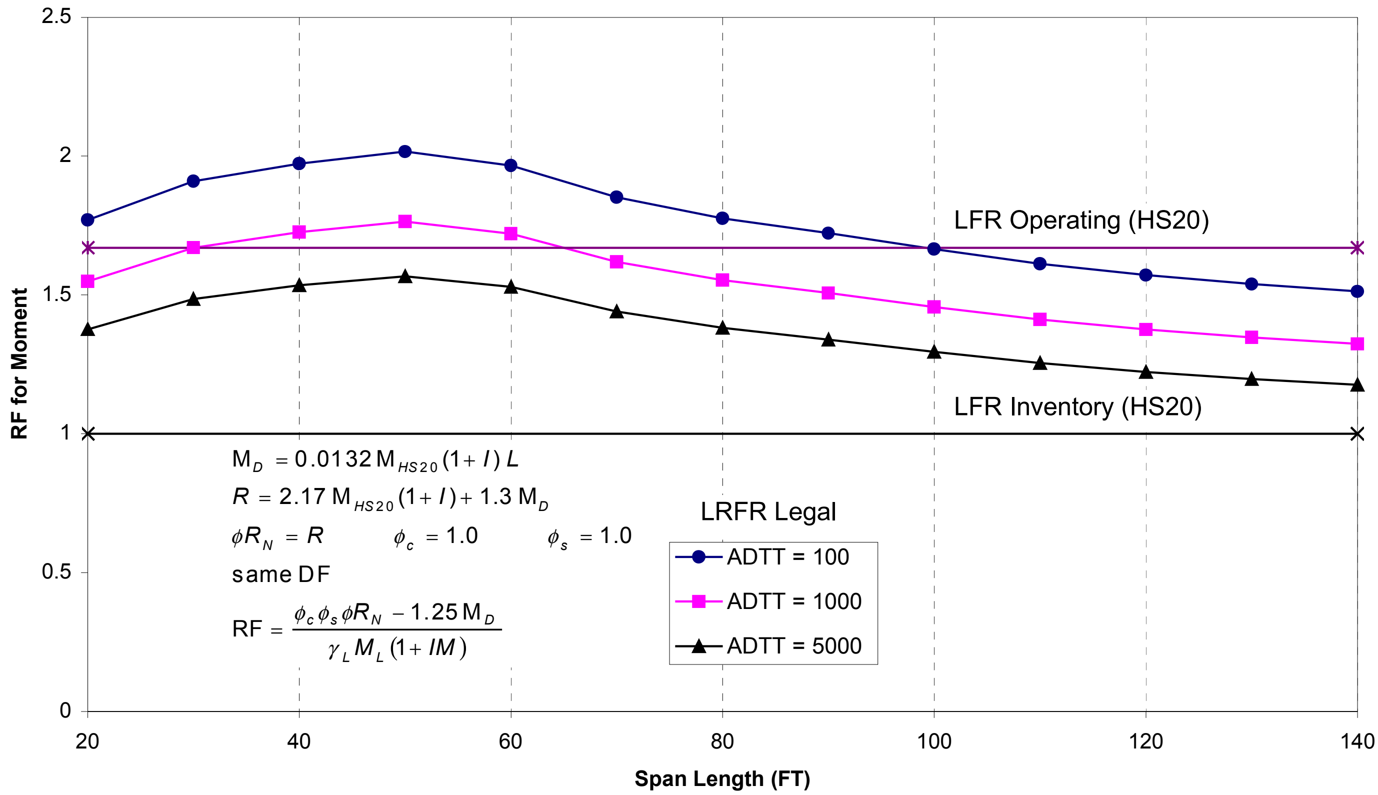

Figure 5-14 LFR (HS20) VS LRFR (Legal Loads)
(Assuming same distribution of Live Loads)

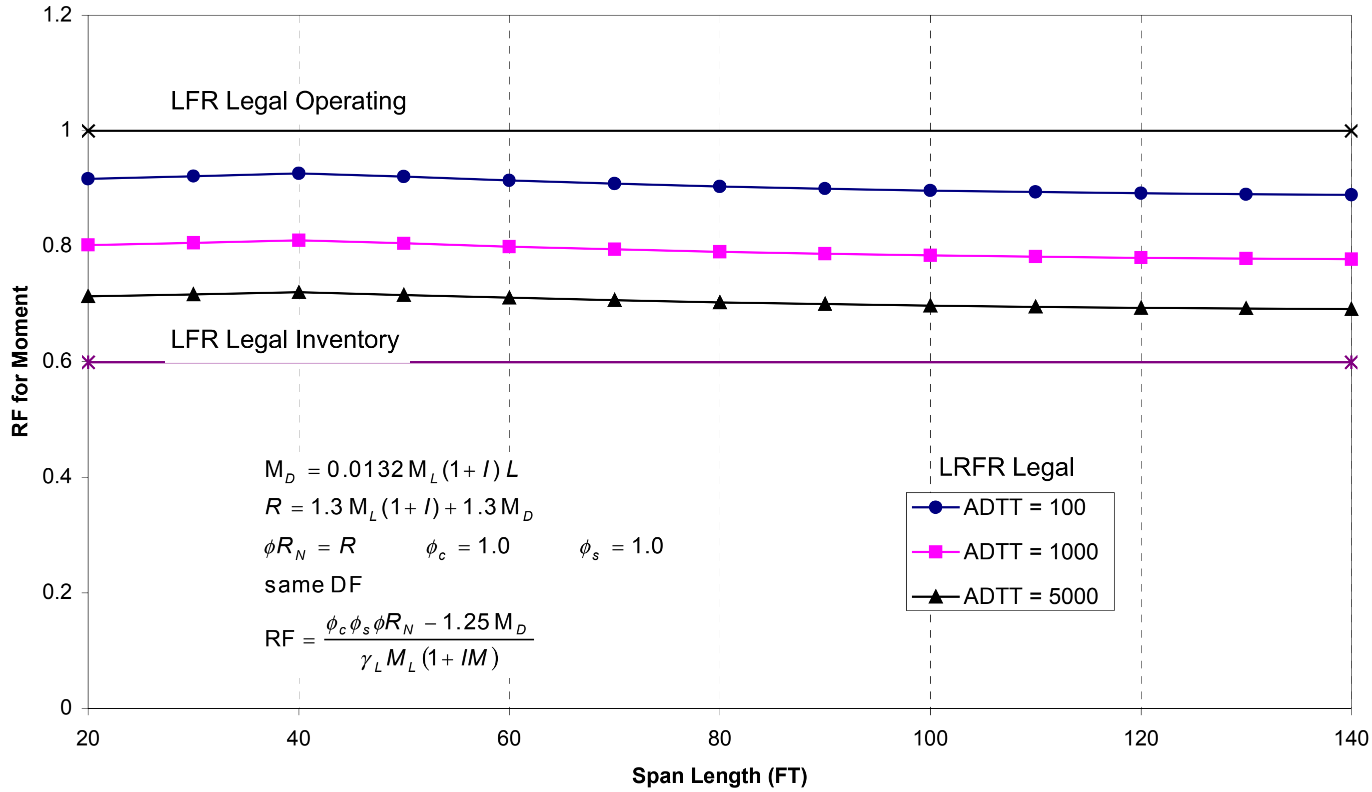

Figure 5-15 LFR (Legal Loads) VS LRFR (Legal Loads)
(Assuming same distribution of Live Loads)

5.4 GOVERNING LOAD EFFECTS

Typically, under the LFR, the flexural rating has governed over the shear rating. This is not always true in LRFR. Table 5-10 shows the number of bridges governed by each load effect in the STRENGTH limit state for the LRFR trial ratings for the HL93 (design) loading.

The results of Table 5-10 indicate that shear ratings could control more frequently with LRFR than with the current LFR procedures. This is due to a number of issues. For the design level the HL93 factored loading generally causes a higher shear force effect (relative to the moment) than the HS20 loading. This difference does not extend to the legal load level since the load models are then the same. The refined distribution factors in the LRFD give lower distributed moments for wider girder spacings. For the same bridge the distribution factors for in-span shear are much higher than the current S/over factors. The decrease in distributed moment and increase in distributed shear cause shear to govern more often under LRFR.

Table 5-10 shows an overall split of 75% of bridges being controlled by flexure and 25% being controlled by shear. Examining the prestressed concrete girders the split is 41% flexure and 59% shear. This is a radical change from the current ratings. In addition to the change in load effects mentioned previously there has also been a change in the shear design procedures for concrete girders in the LRFD. Modified Compression Field Theory (MCFT) is now used to calculate shear resistance instead of the previous semi-empirical formula. MCFT has similar results to the previous equations for reinforced concrete but can have very different results for prestressed concrete. Using MCFT results in resistance that depends upon the ratio of shear and moment at a section as well as the prestressing and stirrups. This means that the governing location cannot easily be determined and changing the loading model will result in changing resistance. Revisions to the MCFT specifications in the upcoming 2000 Interim Changes to the LRFD will provide some simplification to the shear resistance calculations and will generally result in higher shear resistance results.

Material	Limit	**Number of Bridges**	**Percentage**
Steel	Flexure	22	81%
	Shear	5	19%
Reinforced Concrete	Flexure	18	90%
	Shear	2	10%
Prestressed Concrete	Flexure	7	**41%**
	Shear	10	**59%**
Timber	Flexure	4	100 %
	Shear	0	0 %
Total	Flexure	51	**75 %**
	Shear	17	**25 %**

Table 5-10. Governing Load Effect: Flexure vs Shear (HL93)

5.5 RATINGS OF TIMBER BRIDGES

Timber bridges were not included in the tables and plots as the comparisons were to prior ratings done by the Allowable Stress method. Four timber bridges were rated by the states during the trial ratings. All had significantly lower design load ratings for LRFR. The average ratio of LRFR HL93 inventory rating

to LFR HS20 inventory rating was 0.62. The bridges were redundant and in good condition which resulted in no modification by the system and condition resistance factors. The lower design ratings are due to the combination of heavier loading for HL93 than HS20, higher live load distribution factors for the governing case (one-lane loaded) in LRFD than in the Standard Specifications, and a 16.5% dynamic load allowance in LRFD versus no impact factor in the Standard Specifications.

SECTION 6.0 IMPLEMENTATION OF LRFR

The key to implementation of the new Manual is acceptance by the bridge engineering community of the LRF evaluation concept and its benefits. We believe the general LRF philosophy is now more widely understood as use of the LRFD design specification is becoming more widespread. It is critical that the importance of extending these principles to evaluation be conveyed to bridge engineers. The Research Team's suggested Implementation Plan involves a multi-faceted approach to introducing the LRFR procedures as follows:

- Gain confidence of State Bridge Engineers and bridge owners in the LRFR procedures by actively involving this end user group, as was done in the Manual development phase.
- Educate the bridge engineering community in advance of the publication of the Manual on the benefits of moving to the LRFD philosophy for bridge evaluation.
- Train bridge rating engineers to use the Manual and appreciate its flexibility.
- Ensure that LRF bridge evaluation software is available when the new Manual is issued.
- Make LRFR the required method for reporting load ratings to the NBI, after a transition period.

The active participation of AASHTO Committee T18 throughout the Manual development process was beneficial in providing ongoing input and guidance from several State Bridge Engineers. Joint meetings attended by the Project Panel and Committee T18 served as an excellent forum for addressing and resolving many important implementation related issues during the preparation of the Manual. Added emphasis on well-documented and detailed load rating examples were done with an eye toward achieving a smoother transition to LRFR. The trial ratings phase also provided a valuable opportunity for the research team to interact with State Bridge Engineers and rating engineers from fifteen DOTs. The trial rating process served as a preview of the potential challenges and issues that would be encountered during the actual future implementation of the Manual. It also introduced the Manual to end users from some of the largest States in the nation. The numerous questions and comments that resulted from the testing phase helped in effecting improvements to the Manual content and organization from a user point-of-view. The research team believes that the input and feedback received on an ongoing basis from diverse sources has laid the important groundwork for a successful implementation of the Manual.

Education and training are critical steps in gaining acceptance of the new Manual. A valuable lesson learned by observing the successful transition to the LRFD bridge design code is the importance of educating the general bridge engineering community. The research team members have attended various bridge conferences over the course of this project to present papers that introduce and describe the LRFR concepts and promote the benefits of LRFR. In this way bridge engineers were introduced to the new Manual and its procedures as a logical extension of current bridge rating procedures. Once the Manual is adopted by AASHTO training seminars and workshops should be arranged --- could be offered as NHI courses or sponsored directly by the State DOTs -- to train rating engineers from the public and private sectors on the use of the Manual. These workshops could be conducted by the research team in conjunction with other highly knowledgeable engineers and industry experts. Software training is also an essential component of an effective implementation plan.

One major impediment to full and immediate implementation of the LRFD design code has been the lack of available design software. LRFD bridge design software, entitled OPIS, being developed by AASHTO is nearing completion. Some state DOT's and private firms have also developed independent bridge design programs using LRFD. Bridge rating programs have been in common use for a number of years. AASHTO is developing a load factor based bridge rating software, entitled VIRTIS, intended to replace the AASHTO BARS package. VIRTIS software is architected in a manner that will allow easy updating to accommodate the LRFR procedures when approved by AASHTO. The Research Team believes that

the availability of VIRTIS LRFR software will be a major step toward timely implementation of the new Manual. Without available software, bridge engineers would continue to use the Load Factor version of VIRTIS and other software until such time as LRFR software becomes available.

The issue of NBI reporting of LRFR load rating results is a key component of any implementation strategy for the Manual. Currently Load Factor is the required load rating methodology for NBI reporting. FHWA, AASHTO, and the States should coordinate efforts to bring about a timely and nationwide transition to LRFR.

In summary, the research team's suggested implementation plan for LRFR recommends taking active steps toward gaining the confidence and acceptance of bridge owners, educating bridge engineers in the concepts and benefits of LRFR, ensuring that software is available when the Manual is released, transitioning to the reporting of LRFR ratings to the FHWA/NBI, and training bridge rating engineers to use the Manual.