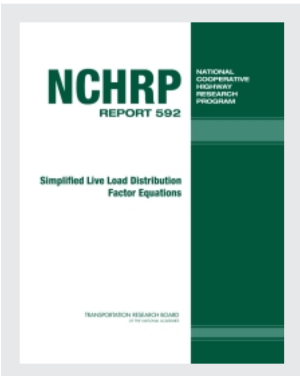

Simplified Live Load Distribution Factor Equations

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 592

Simplified Live Load Distribution Factor Equations

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Subject Areas
Bridges, Other Structures, and Hydraulics and Hydrology

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in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

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The Wyoming Department of Transportation provided BRASS-GIRDER(LRFD) and permitted programming of various simplified methods. Their help is greatly appreciated. AASHTOWare is recognized for providing the finite element engine and use of Virtis and Opis for computational work. These programs were an integral part of the effort.

FOREWORD

By David B. Beal
Staff Officer
Transportation Research Board

This report contains the findings of research performed to develop recommended LRFD live load distribution factor design equations for shear and moment. The report details the development of equations that are simpler to apply and have a wider range of applicability than current methods. The material in this report will be of immediate interest to bridge designers.

Simple "S-over" live load distribution factors for shear and moment have been used for bridge design since the 1930s. The traditional factors, which are included in the AASHTO Standard Specifications, are easy to apply, but can be overly conservative and even unconservative in some parameter ranges.

New, more accurate, and more complex, live load distribution factor equations were developed under NCHRP Project 12-26 and were included in the *AASHTO LRFD Bridge Design Specifications* (LRFD specifications). The "S-over" factors are not included in the LRFD specifications. The new distribution factor equations have limited ranges of applicability. When the ranges of applicability are exceeded, the LRFD specifications mandate that refined analysis is required.

Designers find the complexity of the current equations troubling. Simpler live load distribution factor equations would be welcomed by the design community. The objective of this research was to develop new LRFD live load distribution factor design equations for shear and moment that are simpler to apply and have a wider range of applicability than those in the current LRFD specifications and reduce the need for refined analysis.

This research was performed by BridgeTech, Inc., with contributions from Tennessee Technological University, HDR, Inc., and Dennis Mertz. The report fully documents the research leading to the recommended live load distribution factors.

CONTENTS

AUTHOR'S NOTE

This report was originally released for review by the bridge community in February 2006. During 2006, the Technical Committee on Loads and Load Distribution (T-05) of the AASHTO Subcommittee on Bridges and Structures continued to study the report, method, and proposed ballot items. From October to December 2006, several decisions were made by the technical committee with respect to implementation, and new ballot items were developed. At this writing, the following changes were made in the nomenclature, process, and details. Due to the significant rewriting required, this report is different than the final codified implementation in several places. The expected changes at this time are as follows:

1. The analysis factor, γ_a, was renamed the live load distribution simplification factor (DSF), γ_s. Both terms are functionally the same and may be used interchangeably.
2. This work provides an adjustment of the DSF of zero, one-half, and one standard deviation with respect to the rigorous results. This conservative adjustment is incorporated into the DSF. T-05 has agreed to base the DSF on a shift of one-half standard deviation.
3. The comparison plots contained within Appendix K are based on the changes listed in Item 2 above. This provides the reader with the results (as closely as possible) based on the implementation currently being considered by AASHTO.
4. The language in Appendix H (Recommended Specification Language) incorporates, as best possible, the most recent decisions by T-05. This language will be further modified by AASHTO during the specification balloting process.
5. The term d_e was defined in this work differently than in the 2005 specifications. This term will likely be renamed to avoid confusion in the ballot items.

SUMMARY

Literature Review and Synthesis

The goal of this project is to determine a simpler and possibly more accurate method to estimate live load effect on bridges. The literature on this and related topics is robust and comprehensive. It addresses many approximate methods using many different philosophies and technical approaches. If possible, the research team and panel wanted to use existing methods from the literature review or from existing bridge design specifications, including international sources, to establish a better approach. The research and design specification literature were reviewed in detail for possible simplified methods, relevant experimental results, and rigorous analysis methods. Approximately 150 references were reviewed, key information was categorized into areas important to the research, and results were placed in a searchable database and a comprehensive report. The papers were categorized into the following areas: current codes and related articles, international codes, simplified and/or more accurate approaches from other researchers, effect of parameters on live load distribution, modeling, nonlinear finite element analysis, field testing, bridge type, and miscellaneous items.

1. Current codes and related articles:
   - Several studies have been performed on the methods from the AASHTO Standard Specifications and the AASHTO LRFD Specifications. Results from these methods have been compared with analytical methods and field investigations. For most cases, the code-specified methods produce conservative results.
2. International codes:
   - The current bridge design practice in Japan does not consider the concept of lateral distribution factors. The Ontario Highway Bridge Design Codes follow a modified S-over method, in which a "D_d" factor is determined by considering several parameters. The Canadian Highway Bridge Design Code follows the concept of equal distribution as a "baseline," but applies modification factors in order to improve accuracy.
3. Simplified and/or more accurate approaches from other researchers:
   - The literature review investigated work by Bakht and Jaeger, which is based on the previous method and is the basis for the current Canadian Highway Bridge Design Code (CHBDC). Bakht and Jaeger's methods are semi-graphical, and several researchers report that they compare well with rigorous methods of analysis. The CHBDC is relatively simple to use.
   - The literature review investigated work by Sanders and Elleby in *NCHRP Report 83*, which used orthotropic plate theory.
   - The literature review investigated standard specification methods.
   - The literature review investigated lever rule and a calibrated version of the lever rule.

- The literature review investigated the equal (i.e., uniform) distribution factor (EDF) method, originally developed by Henry Derthick, a former bridge engineer at Tennessee DOT. This method has been used in Tennessee since 1963. This method assumes that all beams carry the same amount of live load and adjusts the uniform distribution upward by 10–15%. This method is referred to as either "Henry's method" or "the adjusted uniform distribution method" in this report.

4. Effect of parameters on live load distribution:
   - Beam spacing is an important parameter in determining the lateral distribution of live load. This finding is well known and is used in the present work.
   - Girder continuity over interior supports does not affect the moment distribution pattern; therefore, the effect of continuity can be taken into account by using the effective span length (i.e., the distance between contraflexure points) for flexural stiffness calculations. For the present work, this type of refinement was given minimal attention because the project goal was to simplify distribution factor calculations.
   - Skew angle is an important parameter but can typically be neglected for skew angles less than 30°. This finding was used in the present work.
   - Aspect ratio has an effect on load distribution at the ultimate limit state. Because of simplification, the various limit states were not considered per se; all analyses were linear elastic.
   - Consideration of secondary elements, such as diaphragms and barriers, has been shown to make a significant difference in lateral load distribution in some cases. However, the literature shows conflicting results with respect to their degree of effectiveness. The combination of skew and bracing is likely more important than bracing effects on straight bridges. This complexity was considered in detail in the present work.
5. Modeling
   - When using the finite element method, slab on girder bridges can effectively be modeled as beam/frame and shell elements.
   - The use of shell elements to model steel and concrete box girder bridges yields good results. Shell elements were used, in part, to validate grillage models.
   - The orthotropic plate theory compares well with the grillage analysis method, which is well accepted for all types of bridge superstructures. The grillage method compares well with finite element analysis, especially for global effects like live load distribution to the girders. This finding was used extensively in the present work.
   - For live load distribution, grillage methods compare well with three-dimensional finite element analyses. This finding was used extensively in the present work.
6. Nonlinear finite element analysis:
   - A nonlinear finite element model is required to accurately determine the ultimate load capacity of a bridge. Again, the present work was focused upon simplification, and nonlinear behavior was not pursued in detail.

Papers on field testing, bridge type, and miscellaneous items are not summarized here because they were not as extensively used or as important as the other papers. However, all of the papers are discussed in Appendix B.

In summary, the literature provides significant guidance on possible methods, previous parameter studies, modeling methods, and performance of simplified methods relative to refined analysis. These areas are addressed in several appendices that provide an overview of the research and practice in this area. Literature findings that supported simplification of the present specifications, economical and accurate modeling, and parametric studies were used. The comprehensive review of the literature is provided in Appendix B.

Basic Research Approach

Several candidates for the new approach were selected based upon the literature and present specifications used in the United States and Canada. These candidates offered several distinct approaches, including analytical procedures that incorporate the relative transverse, longitudinal, and torsional stiffness; pure empirical curve fits; and combinations of the two. The investigators hoped that a method with a well-founded analytical basis could be used, such as orthotropic plate theory (which was used by CHBDC and Sanders and Elleby) or a direct equilibrium approach (which was used in the lever rule). As outlined herein, a combination of approaches is recommended. The research team made a strong attempt to unify the recommended methods for all bridge types, thereby providing one method for a large number of bridges. Wooden bridges, stringer/floor beam bridges, and corrugated metal deck bridges were excluded, and their distribution methods remain unchanged.

Although filled with significant technical details, the basic approach for the research was straightforward:

1. The research team obtained a large number of descriptions of actual bridges that were representative of the state of current design. The research team used data from four independent sources: NCHRP Project 12-26 data (the basis for the present LRFD distribution factors) (809 bridges), a set of bridges from Tennessee Tech (24 bridges), bridges entered into AASHTO Virtis and obtained from several DOTs (653 bridges), and a set of bridges designed to push the limits of reasonable application (74 bridges).
2. The research team entered all the simple methods into a program that used all the data outlined above. This task provided the distribution factors. BRASS-GIRDER(LRFD) was used to compute the beam line actions (reactions, shears, and bending moments) at many points along the bridge and to determine the critical location for the truck position for all of the above. It was also used to program and compute several simplified methods.
3. BRASS-GIRDER(LRFD) generated a finite element grillage model. Actual properties and geometry were used to provide an accurate structural model. A finite element program was used to generate influence surfaces for every action at all nodes. These surfaces were passed to the live load program.
4. BRASS-GIRDER(LRFD) passed the critical beam line actions and the longitudinal truck position that produced those actions to the live load program.
5. The live load program placed the load at the critical longitudinal truck position and moved the truck(s) transversely across the influence surface. The rigorously determined actions were computed at each position, and critical values were determined.
6. The rigorous actions were divided by the beam line actions to determine distribution factors. All data were logged in the NCHRP 12-50 format for processing later.
7. For each bridge, girder location, action, and longitudinal location, the rigorous and simplified results were stored in a database. This form readily facilitates plotting, statistical analysis, and comparisons of rigorous, potential new methods, existing methods, and so forth. Herein, these comparisons are in the form of 1:1 plots, histograms, and parametric statistics.
8. This entire process was independently validated with separate engineers, SAP 2000 software, and load positioning. The Tennessee Tech bridges were used for this task. These bridges had been previously analyzed with yet another study using ANSYS, and the ANSYS results provided yet another validation. In addition, 22 bridges that were rigorously analyzed in a Caltrans study were compared with bridges in this study. These results are presented in Appendix G.
9. Because the research goal is to develop a "simple" method, additional new methods were readily added in spreadsheet cell formulas and/or Visual Basic for Application (VBA) code within Excel.
10. The most promising methods (uniform distribution method and calibrated lever rule) were pursued in detail to develop the recommended specification-based methods. Here, only the NCHRP 12-26 and the Tennessee DOT bridges were used.
11. Multiple presence factors were then incorporated into the results of the two selected simplified methods, and rigorous analysis was done for further comparison.

12. The Virtis database was held in reserve as a validation data source. These data were not used in the calibration, but were used to provide a check against rigorous results as well as regression against the present (2005) LRFD distribution factors.

Development of Proposed Specifications

Following the process outlined above, simple formulas and coefficients were developed and written into specification format. For most bridge types, the research team was successful in providing a unified approach. The proposed specifications are summarized as follows.

For one lane loaded for moment and one and multiple lanes loaded for shear:

$$mg = m\gamma_s \left[a(g_{lever\ rule}) + b \right] \geq m\left[\frac{N_{\text{lanes}}}{N_g} \right]$$

Where:

a and b = calibration constants,
m = multiple presence factor,
N_g = number of girders,
N_{lanes} = number of design lanes considered in the analysis (in this case, using the lever rule),
$g_{lever\ rule}$ = distribution factor computed by lever rule, and
g = distribution factor.

For multiple lanes loaded for moment:

$$mg_m = m\gamma_s \left[a_m \left(\frac{W_c}{10N_g} \right) + b_m \right] \geq m\left[\frac{N_L}{N_g} \right]$$

Where:

a_m and b_m = calibration constants,
γ_s = live load distribution simplification factor (DSF),
N_L = maximum number of design lanes for the bridges, and
Design lane width = 10 feet.

The multiple presence factor is then applied, i.e., $m = 1.2$ for one lane loaded and $m = 1.0$ for two lanes loaded, or as outlined in the specifications. The multiple presence factors are explicitly applied, thereby eliminating some confusion that is present in the current LRFD Specifications; errors can be significant in a misapplication. Formulas are provided to facilitate lever rule computations. These formulas are only for simplification and convenience. The engineer (or software) may compute the lever rule distribution factors in the usual manner and then adjust the result by the calibration constants a and b as necessary. The equation for multiple lanes loaded for moment is based upon the uniform method, which starts with a uniform distribution (same for all girders) and then adjusts the result upward, typically 10–15%. Note that the calibration constants are typically provided in this work *without* rounding. The research team expects the specification committee to round these values at their discretion.

The proposed method works well for all bridges investigated, including those parametrically generated to test the limits of applicability. Based on these results, few limits of applicability have been recommended. This addresses a significant constraint in the current specification approach. Most limitations in the present work are associated with the skew adjustment factors.

The skew adjustment factors were kept fundamentally the same as in the current LRFD specifications, with the exception of simplification to include only the following parameters: girder spacing, span length, and girder depth. These parameters are readily available or easily estimated. Limited basis exists within the present work to make significant specification changes for skew adjustment.

Finally, the proposed methods perform well, though some cases (e.g., one-lane loaded, interior girder, and moment) have more variability than others. To account for this, the DSF is applied to the distribution factors. The distribution factor coefficients *a* and *b* were calibrated to the mean of the rigorous results. Therefore, approximately one-half of the values will be below the rigorous results. To adjust the values systematically, the DSFs were determined on the basis of the means of the ratios (simple/rigorous methods) and the coefficient of variation of this distribution. In short, the more variable the data, the larger the DSF required to move the simplified results reasonably above the mean of the rigorous results. *The shift is a matter of judgment; results for one-half standard deviations are presented herein.* Additional safety is provided via load and resistance factors in the usual manner. Other shifts can be readily computed using the data presented herein. In most cases, the accuracy is good, the variability is small, and the DSFs are small as well. The exception (i.e., poor) case is one lane loaded for moment.

To address the high variability of the simplified method, specifically in the one lane loaded for moment, an alterative method was developed. This method uses a parametric equation that is slightly more complex and takes the following form:

$$g_{PF} = \left(\frac{S}{D}\right)^{Exp1}\left(\frac{S}{L}\right)^{Exp2}\left(\frac{1}{N_g}\right)^{Exp3}$$

$$mg_m = \gamma_s m\left[a_m(LR, Uniform, or\ PF) + b_m\right]$$

The simple method (whether lever rule, uniform, or parametric) is then adjusted. This increased complexity yields a relatively simple method with lower variability and improved accuracy. The proposed specifications include this method as an optional method outlined in an appendix. This significantly improves the one-lane load effects for moment that could be of significant concern if these design distribution factors are used for rating. Additionally, it also improves the accuracy for cast-in-place concrete box girders.

As an aside, data are now available to support a recalibration of the specification load factors, including analysis methods and their variability. In short, including these effects could change the live load factors in the future and/or provide a basis for the possible benefits associated with more rigorous analysis.

Regression Testing

One of the recommendations of the NCHRP Project 12-50 report was to test proposed specifications by comparing them with the current specifications. The Virtis data, which was not used in the development of the research, was used to compare the new specifications for slab-on-girder bridges with the existing LRFD methods. This task provides a basis for understanding how the new provisions will affect practice. Note that in some cases deviations exist, and in these cases it is particularly important to review the rigorous results (i.e., assess the accuracy of both methods).

Conclusion

This research has provided live load distribution methods that are not only simpler than present LRFD methods, but, in most cases, exceed their performance in terms of lower variability and greater accuracy when comparing with rigorous analysis. Hundreds of bridges were analyzed with finite element analysis and simplified methods. The results for the recommended method are outlined in the body of the report. Many more data on other methods (CHBDC, AASHTO

Standard Specifications, AASHTO LRFD Specifications, the Sanders and Elleby method, etc.) are available to provide information of significant value to researchers and agencies who use these methods. Several parametric studies were conducted, and these studies are also presented in both the report and the appendices. These studies address transverse truck spacing, the effect of lane positioning, the effect of end and intermediate diaphragms (with and without skew), skew formula simplification, and more. All studies were integral in gaining insight into the key elements of the simplified methods. The literature was helpful as well.

CHAPTER 1

Introduction and Research Approach

Introduction

Distribution factors have been used in bridge design for decades as a simple method to estimate live load effects on individual girders. Live load distribution is important for the design of new bridges, as well as for the evaluation of existing bridges, and has been the basis for design in the United States for over seven decades. The AASHTO Standard Specifications and AASHTO LRFD Specifications contain simplified methods currently used to compute live load effects. The LRFD equations were developed under NCHRP Project 12-26 and reflected a wide variation in modern bridge design. These equations include limited ranges of applicability that, when exceeded, require a refined analysis to be used.

The ranges of applicability and complexity of the equations have been viewed by some as weaknesses since their adoption into the LRFD specifications. The objective of this research was to develop even *simpler* live load distribution factor equations for moment and shear to replace those in the current LRFD specifications. These equations should be straightforward to apply and easily understood and yield results comparable to rigorous analysis results. Rigorous analysis was used as the basis for establishing the target distribution factors for this research; it helped the research team to better delineate the effects (i.e., contributions) of multiple-vehicle presence, of variability associated with the simplified analysis, and of the calibration (tuning the simple method to better match the rigorous results).

The development of this methodology is outlined in this report. First, the research method is outlined in detail. This description includes the sample of bridges used for calibration, computational processes that provide the basis for rigorous results, validation of these computational processes, development of the design/analysis approach, and comparisons with many rigorous analyses of real bridges from state DOT inventories. Proposed specifications were developed in an iterative manner during the research. The approach, findings, and application are presented in separate chapters.

Research Approach

Bridge Data Sets

Three sources of data were used for the parametric study and regression testing that formed the basis for this research: the NCHRP 12-26 bridge set (*1*), the Tennessee Technological University set (*2*), and a set of bridges from AASHTO Virtis/Opis used to compare the load factor design (LFD) and load and resistance factor design (LRFR) rating procedures (*3*). Table 1 presents the details of these databases, including the total number of bridges and specific information about the bridge types and parametric limits. The total sample includes 1,560 bridges. Due to lack of readily available data combined with time and budget constraints, open steel box bridges were not investigated in the initial work. A small follow-up study was conducted (see Appendix Q).

Figure 1 illustrates the collection of data into an NCHRP 12-50 database (*4*) that was used for both bridge definitions and results. This database was then used to create BRASS-GIRDER(LRFD) input files. BRASS-GIRDER(LRFD) performed computations for simplified methods and generated files necessary for a rigorous analysis. BRASS-GIRDER(LRFD) placed simplified results back into the NCHRP 12-50 database. The rigorous analyses were run, and distribution factors were computed. These factors were placed back into the database, as shown in Figure 2. Finally, the database was used to compare the simple and rigorous approaches, simplified methods were adjusted as necessary, and the database was updated with the latest results, as shown in Figure 3.

Final results from the simple methods from BRASS-GIRDER(LRFD) and from rigorous analyses were put back into the 12-50 database for comparison and analysis. Variations of the simplified methods were programmed into the database in order to view revised results quickly. Because of the simplicity of the methods being considered, many modifications were performed in the database without significant computational effort.

Table 1. Detailed characteristics of bridge data sources.

Data Source	Reference	Total No. Bridges	Bridge Types	Number of Bridges	Parameter Ranges										
					Number of Spans	Span Length (ft)		Girder Spacing (ft)		Slab Thickness (in)		Skew Angle (deg)		Aspect Ratio (L/W)	
						min.	max	min	max	min	max	min	max	min	max
NCHRP 12-26	1	809	Conc. T-Beam	71	n/a	12	93	2.42	16	5	11	0	52.98	0.32	3.26
			Steel I-Beam	163	n/a	12	205	2	15.5	4.42	12	0	66.1	0.4	4.53
			Prestressed I-Beam	94	n/a	18.75	136.2	3.21	10.5	5	90	0	47.7	0.31	3.12
			Prestressed Conc. Box	112	n/a	43.3	243	6	20.75	n/a	n/a	n/a	n/a	0.52	8.13
			R/C Box	121	n/a	35.2	147	6.58	10.67	n/a	n/a	n/a	n/a	0.53	5.5
			Slab	127	n/a	14.2	68	n/a	n/a	9.8	36	0	70	0.21	2.56
			Multi-Box	66	n/a	21	112.7	n/a	n/a	0	11	0	55.8	0.22	5.96
			Conc. Spread Box	35	n/a	29.3	136.5	6.42	11.75	6	8.5	0	52.8	0.54	3.11
			Steel Spread Box	20	n/a	58	281.7	8.67	24	5	9.5	0	60.5	0.75	8.02
TN Tech Set 1	2	24	Precast Conc. Spread Box	4	1 - 6	44.38	81.49	5.67	13.75	7.75	8.75	0.00	48.49	1.68	2.03
			Precast Conc. Bulb-Tee	4	2 - 6	115.49	159.00	8.33	10.29	8.25	8.27	0.00	26.70	1.43	4.97
			Precast Conc. I-Beam	3	3 - 5	67.42	74.33	9.00	10.58	8.25	8.75	0.00	33.50	1.45	1.53
			CIP Conc. T-Beam	3	4 - 5	66.00	88.50	8.17	12.58	7.00	9.00	0.00	31.56	1.91	2.74
			CIP Conc. Multicell	4	2 - 3	98.75	140.00	9.00	10.33	8.00	9.25	0.00	26.23	2.24	3.05
			Steel I-Beam	4	2 - 4	140.00	182.00	9.33	11.50	8.00	9.00	0.00	50.16	1.60	5.11
			Steel Open Box	2	1 - 3	170.67	252.00	9.00	9.38	8.50	8.50	4.50	31.95	3.28	7.00
LRFR	3	653	Slab on RC, Prest., and Steel Girders	653	1 - 7	18.00	243.00	2.33	18.00	0.00	8.00	N/A	N/A	0.38	5.22
Parametric Bridges	N/A	74	Spread Box Beams	27	1	100.00	190.00	5.00	20.00	6.00	12.00	N/A	N/A	1.40	8.00
			Adjacent Box Beams	23	1	100.00	210.00	3.00	5.83	5.00	6.00	N/A	N/A	1.13	9.60
			Slab on Steel I-Beam	24	1	160.00	300.00	12.00	20.00	9.00	12.00	N/A	N/A	2.76	6.82
			Summary:	1560	1 - 7	12.00	300.00	2.00	24.00	0.00	36.00	0.00	70.00	0.21	9.60

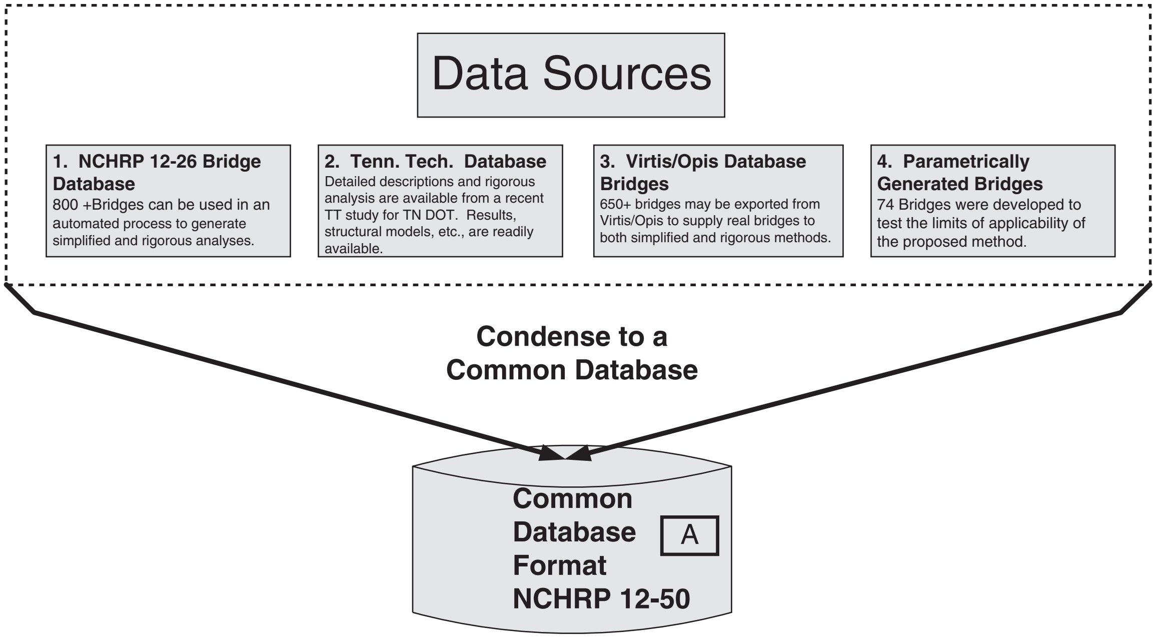


Figure 1. Data sources.

The initial review and calibration of the results was performed using the results from the NCHRP 12-26 bridge set. The methods and calibrations were then compared to the results from the LRFR study bridge data set and additional parametrically generated bridges to verify that the procedure was valid for a wide range of application.

Skew, diaphragms, and lane load location (as required for fatigue) were studied separately from the overall parameter study to establish whether each parameter needed to be considered in the recommended simplified approach (see Appendix L). The effects of such elements were quantified and prescribed independently of the simplified method ultimately

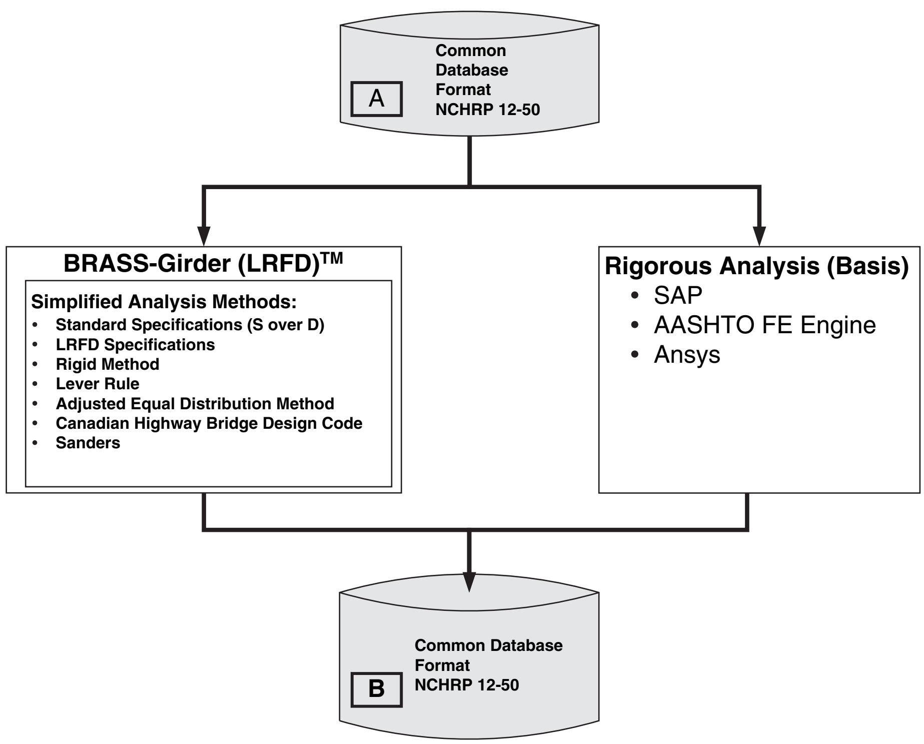


Figure 2. Computational methods.

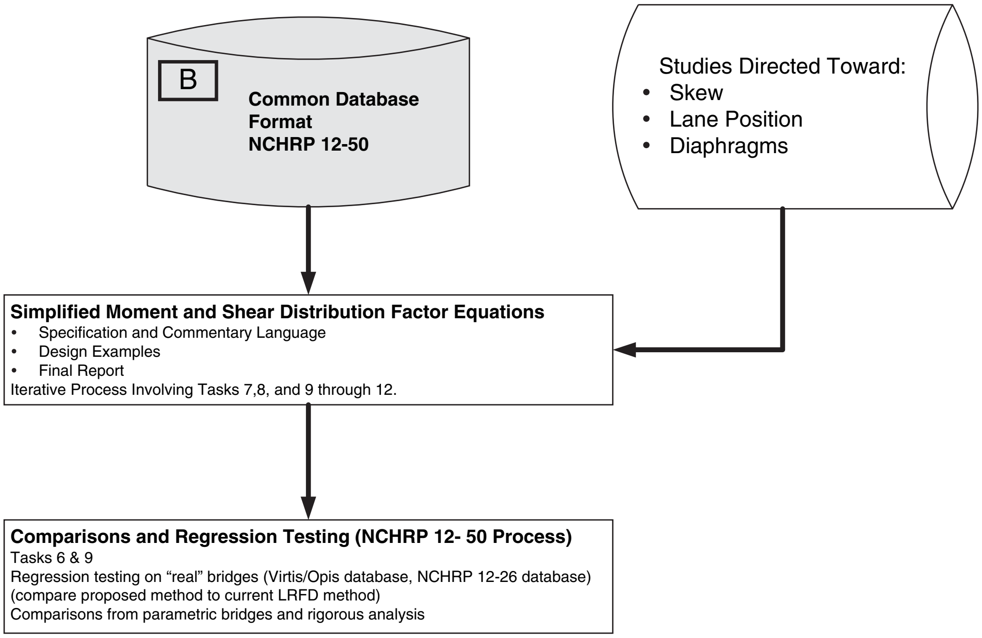


Figure 3. Comparison research and iteration.

used. The current AASHTO LRFD skew adjustments were modified slightly and applied to the proposed method to estimate the effect of skew. No modification was included for the other parameters. These conclusions were based on the results of this study and the literature review (Appendix B).

Rigorous Distribution Factor Calculation

BTLiveLoader, a program developed at BridgeTech, was responsible for returning a calculated distribution factor. The program transferred the requisite input information via a script file. After the script was interpreted and the distribution factor was calculated, all relevant information to the analysis was appended to a pair of database files. The information stored in these files contained data describing the results, each being identified by NCHRP 12-50 data description tags. These components are explained in detail below.

BRASS-GIRDER(LRFD) was responsible for generating three distinct sets of data: the input structural model of the bridge, the live load information, and the single-lane action used in the distribution factor calculation. BRASS-GIRDER(LRFD) generated this information and passed it on to the live load program. See Appendix F for the assumptions used in developing the various grillage models.

The structural analysis model was used for generating influence surface results. The model is a three-dimensional linear frame type that describes nodes, elements, material properties, and so forth (akin to a STAAD or ANSYS input file). The format of this file is an XML schema. The engine (hereafter referred to as the "FE Engine") was developed by BridgeTech for AASHTO and was used with permission from AASHTO within the NCHRP 12-62 project for structural analysis.

The loading was specified as "influence surface" type, which the FE Engine interpreted as a series of load cases, each with a single-unit load placed on each individual node. Thus, the number of load cases was the same as the number of nodes in the model. This loading scheme resulted in influence surfaces for each of the effect types (shear, moment, and reaction), as well as displacements, if desired. Influence surfaces were passed on to BTLiveLoader directly in memory, but it could optionally be saved in text files. A typical model and influence surface are shown in Figure 4 and Figure 5, respectively.

BTLiveLoader first parsed the input live load data. These data specified the type of live load and its placement. The live load was specified as a type of truck. Currently, the truck type

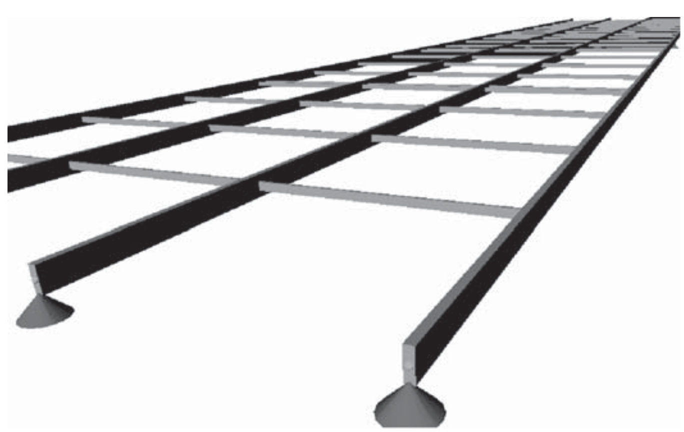


Figure 4. Grillage model.

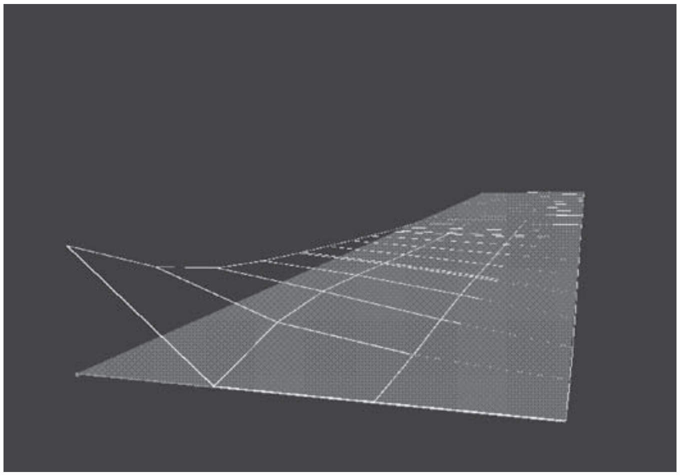


Figure 5. Influence surface.

is always an LRFD design truck (AASHTO HS20) with 14-foot axle spacings and a 6-foot gage.

Truck placement was handled by a transverse positioning algorithm. A longitudinal location was specified along with the truck type. The truck was moved transversely across the entire width of the travel way at a given small interval (for example, at a 0.5-foot interval). At each placement, the truck's wheel locations and corresponding wheel loads were "placed" on an influence surface. This was, in effect, multiplying each wheel times the influence surface and summing the results.

Wheels were considered to be point loads acting on a bridge. In most cases, wheel placement was not directly on a structural node. In such cases, BTLiveLoader interpolated the forces between the nearest bounding nodes. These four nodal loads, which were equivalent to a single wheel load, were then used to calculate the resultant effect.

After the truck had been moved transversely across the bridge, the resultant effects from each placement were compared. The most critical value for the desired action (shear, moment, or reaction) was calculated. For a particular placement, any effect type or combination could be calculated.

The choice of influence surfaces used for distribution factor calculations was determined by BRASS-GIRDER(LRFD). For each distribution factor to be calculated, a longitudinal location was specified along with a load effect type or types. BRASS-GIRDER(LRFD) calculated the actions for a single lane. The single-lane action was divided into the critical three-dimensional (full-bridge) result to determine the distribution factor.

After the distribution factor was calculated, the resultant information was saved (i.e., appended to) a database file. The file contained results from numerous bridges. Each distribution factor was stored on a separate line in the file. NCHRP 12-50 process ID tags were saved with the distribution factor to uniquely identify the relevant information (longitudinal location, effect type, etc.).

Finally, the whole process was run in batch mode. BRASS-GIRDER(LRFD) is capable of generating and running numerous bridges in a loop fashion. The influence generation and live loading algorithms were run from a script list, which listed a series of individual bridges (i.e., scripts) to be run. The script list may contain hundreds of bridges to be analyzed. This allowed for a set of problems to be set up and run over night.

Each bridge analysis was accompanied by a log output file that detailed the steps of the analysis and live loading, including any problems that may have arisen. This file was particularly effective in determining if any calculation problems arose during execution of the script. The verification of the process that was used to automatically compute distribution factors is detailed in Appendix G.

Evaluation of Simplified Methods—An Example

This example illustrates the concepts involved in the comparison and calibration of two simple methods: calibrated lever rule and the AASHTO Standard Specifications (S/D). Figure 6 shows the distribution factors for bending moment in an exterior girder subjected to one lane loaded. For this case, the correlation coefficient (R^2) and the slope are 0.38 and 0.99, respectively. A slope of unity means that this method could be adjusted downward by approximately 0.3 (from the equation shown in Figure 6) and the regression line would align well with the 1:1 baseline with no modification

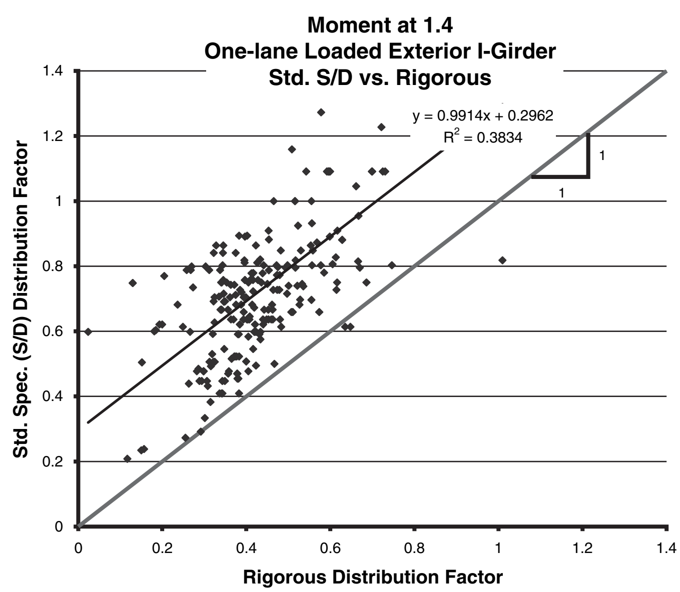


Figure 6. Standard specifications versus rigorous example.

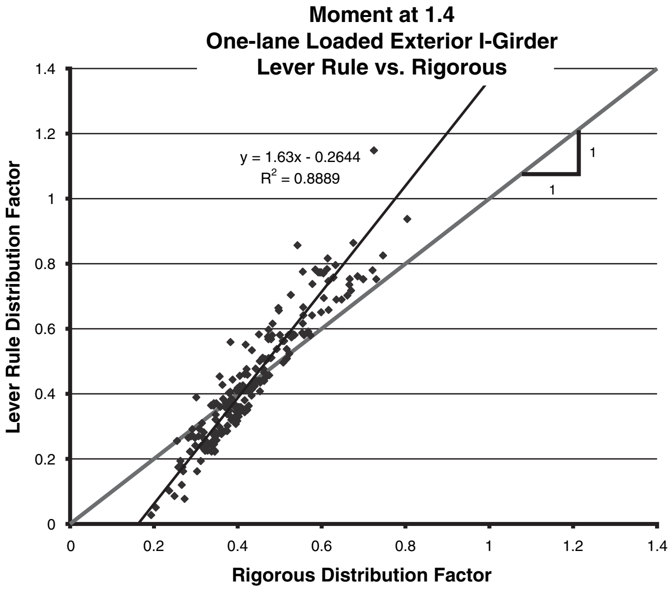


Figure 7. Lever rule (without calibration) versus rigorous example.

to the slope. However, the large variability (small R^2 value) and the associated errors cannot be eliminated by transformation. In short, this method is simple but does not work well. Adjustment of the calibration constants will not improve the results because of this inherent variability.

Figure 7 illustrates the same bridges and rigorous results plotted against the lever rule. In this case, the slope of the trend line is 1.63, and the method gives nonconservative results for small girder spacings (i.e., low distribution factors). However, the correlation coefficient is approximately 0.9, which indicates that this method shows promise; an affine transformation may be used to significantly improve the results. A brief summary of affine transformation is provided by Wolfram Research (*5*). To illustrate, consider the regression line equation in Figure 7:

$$y_1 = 1.63x - 0.2644 \qquad (1\text{-}1)$$

The slope can be set to unity by multiplication of 1/1.63, giving:

$$y_2 = \frac{y_1}{1.63} = \frac{1.63x}{1.63} - \frac{0.2644}{1.63} = x - 0.1622 \qquad (1\text{-}2)$$

The data can be shifted upward by adding 0.1622, giving:

$$\begin{aligned} y_3 &= y_2 + 0.1622 = \frac{y_1}{1.63} + 0.1622 \\ &= x - 0.1622 + 0.1622 = x \end{aligned} \qquad (1\text{-}3)$$

which provides a unit slope and zero y-intercept, i.e., $y = x$.

The transformation (known as an "affine" transformation) is summarized as follows:

$$g_{calibrated\ lever\ rule} = a_m g_{lever\ rule} + b_m \qquad (1\text{-}4)$$

Where:

$$a_m = \frac{1}{1.63} = 0.61,$$

$$b_m = 0.1622,$$

$g_{calibrated\ lever\ rule}$ = adjusted distribution factor, and

$g_{lever\ rule}$ = lever rule distribution factor computed with the typical manual approach.

The post-transformation results are illustrated in Figure 8.

The subscript m denotes an adjustment for bending moment (v is used for shear and reactions). As is elaborated later, the values used for this bridge type in the draft specifications for a_m and b_m are 0.61 and 0.16, respectively.

To further adjust for multiple presence and the inherent variability, the factors m and γ_s are applied next:

$$mg_g = m\gamma_s \left[a_m g_{lever\ rule} + b_m \right] \qquad (1\text{-}5)$$

Where:

mg = a factor used to estimate the live load effects = the product of the multiple presence factor and the distribution factor,

m = multiple presence factor, and

γ_s = DSF that accounts for the variability of the method.

Throughout this research, similar transformations were made. The assessment of the quality of the simple method was made on the basis of variability, *not* the initial "accuracy" with respect to rigorous analysis. In cases where variability was high, these simplified methods were not recommended for further study. In cases where variability was low, affine transformations were applied to improve the alignment with rigorous results. This process was used for the uniform distribution method (i.e., Henry's method) as well.

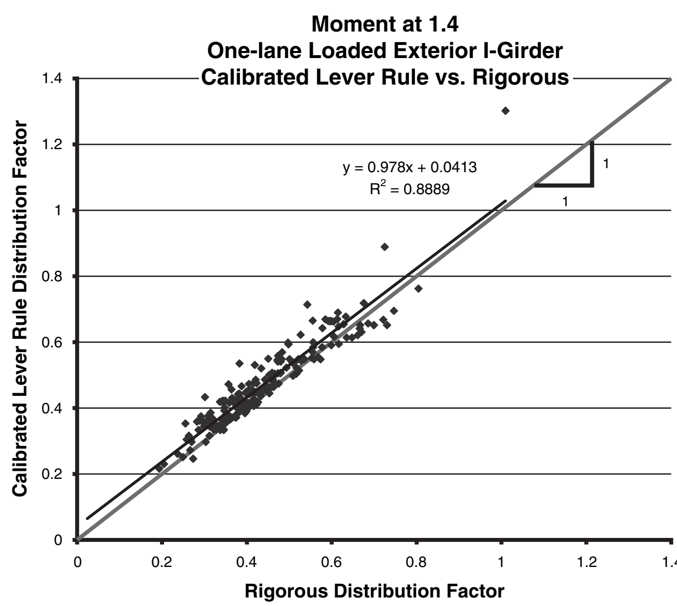


Figure 8. Lever rule (with calibration) versus rigorous example.

CHAPTER 2

Findings

Introduction

This chapter discusses the development of the simplified live load distribution factor equations to be proposed for adoption into the AASHTO LRFD Specifications. Based upon the analysis of several simplified methods, two were further developed for the proposed equations. The uniform distribution method (i.e., Henry's method) was used for moment for two or more lanes loaded, and the calibrated lever rule was used for moment for one lane loaded and for all shear loading cases. An alternative method (parametric) was developed to improve accuracy of some one-lane loaded cases, and this alternative method was codified into an appendix for LRFD Section 4.

This chapter first addresses studies for skew effect, vehicle position, and barrier stiffness. Next, it details the simplified methods. The implementation details and proposed specifications are reserved for Chapter 3.

Preliminary Findings

Parameter Studies

The effect that skew angle, support and intermediate diaphragms, and vehicle loading position have on lateral live load distribution was investigated for precast concrete I-beam bridges and steel I-beam bridges. Skew angles of 0°, 30°, and 60° were used for both bridge types. The effect of the support diaphragm was determined by modeling the same bridge with and without the support diaphragm. Intermediate diaphragm cases for the precast concrete I-beam bridges included diaphragms at quarter points along each span, including midspan. For the steel I-beam bridges, intermediate diaphragms were spaced similar to what was shown on the original structural drawings. For both bridge types, vehicles were placed within 2 feet of the barrier or curb and moved transversely across the bridge at intervals of 1 foot. These different variations were used to gain a better understanding of the effect of each parameter in question. The following conclusions were made:

- **Skew.** The skew angle of a bridge was shown to affect both live load moment and shear distribution factors. Generally, skew angles below 30° had a small effect on live load distribution. As the skew angle increased from 30° to 60°, the live load moment distribution factor decreased while the live load shear distribution factor increased. The behavior observed was expected and is consistent with the literature. Table 2 contains sample results. Complete results are presented in Appendix L.
- **Diaphragms.** Diaphragms were also shown to affect live load distribution. Both support and intermediate diaphragms decreased the controlling moment distribution factor to some extent for both exterior and interior girders. The decrease in moment distribution factor due to the support diaphragms was generally small; however, in some cases, the decrease was significant for intermediate diaphragms. Both support and intermediate diaphragms caused an increase in the shear distribution factor. The increase in the shear distribution factor due to *support* diaphragms was generally small. The increase due to the presence of *intermediate* diaphragms is a function of diaphragm stiffness. For diaphragm configurations commonly used in practice, these effects were found to be relatively small. This is consistent with what was found in the literature. Figure 9, Table 3, and Table 4 contain sample results. The diaphragm stiffness was varied to "infinite" stiffness to determine the upper bound (see Appendix L).
- **Vehicle transverse position.** The vehicle location with respect to the barrier or curb was shown to have a similar effect for both moment and shear distribution. As the vehicle was positioned away from the barrier or curb, both the live load moment and shear distribution factors decreased in a linear trend. The amount of skew and the presence of support or intermediate diaphragms did not have an effect on this linear relationship. See Figure 10.
- **Barrier stiffness.** Barrier stiffness and associated loads carried by the barriers were neglected in this study. The continuity of the barrier is difficult to ensure, and if the stiffness

Table 2. Effect of skew on Beam 6.

		With Support Diaphragm						Without Support Diaphragm					
	Skew	0		30		60		03		06		0	
Location from Barrier	Load	Moment	DF	Moment	DF	Moment	DF	Moment	DF	Moment	DF	Moment	DF
2	MOVE1	267.10	0.314	253.76	0.298	203.39	0.239	267.18	0.314	254.65	0.299	220.42	0.259
3	MOVE2	298.32	0.350	284.05	0.333	227.83	0.267	299.84	0.352	285.65	0.335	317.66	0.373
4	MOVE3	329.33	0.387	314.05	0.369	253.00	0.297	332.15	0.390	316.30	0.371	342.64	0.402
5	MOVE4	359.00	0.421	342.69	0.402	280.76	0.330	362.99	0.426	345.51	0.406	348.72	0.409
6	MOVE5	386.24	0.453	368.89	0.433	306.03	0.359	391.25	0.459	373.39	0.438	354.76	0.417
7	MOVE6	409.95	0.481	392.25	0.461	327.49	0.384	415.83	0.488	400.96	0.471	359.63	0.422
8	MOVE7	429.02	0.504	412.11	0.484	344.71	0.405	435.61	0.511	423.53	0.497	372.70	0.438
9	MOVE8	442.35	0.519	427.65	0.502	359.97	0.423	449.49	0.528	439.97	0.517	392.85	0.461

DF = distribution factor.

is used to attract the live load then the barrier strength should be designed accordingly. These two issues, combined with the need to simplify the specifications with respect to live load distribution, guided the panel and the research team to neglect the effect of the barriers on live load distribution. To do so is conservative.

Detailed results from this study are available in Appendix L.

Preliminary Simplified Method Investigation

Six sets of bridges were used for comparing simplified method results to rigorous analysis results. Bridge Set 1 included steel I-beam bridges, and Bridge Set 2 included precast concrete I-beam and precast concrete bulb-tee beam bridges. Bridge Set 3 included the cast-in-place concrete tee beam bridges. Bridge Set 4 included the precast concrete spread box beam bridges. Bridge Set 5 included cast-in-place multicell box beam bridges, and Bridge Set 6 included adjacent box beams. See Table 5.

The results were presented in plots of the distribution factors computed by various simplified methods against those generated by the grillage analysis. A study was conducted using the National Bridge Inventory database to estimate the number of bridges of each type built in the last 10 years. The results are presented in Appendix C. The timeframe of 10 years was used to represent "new" design rather than the old inventory bridges. The number of bridges may be an indicator of relative importance.

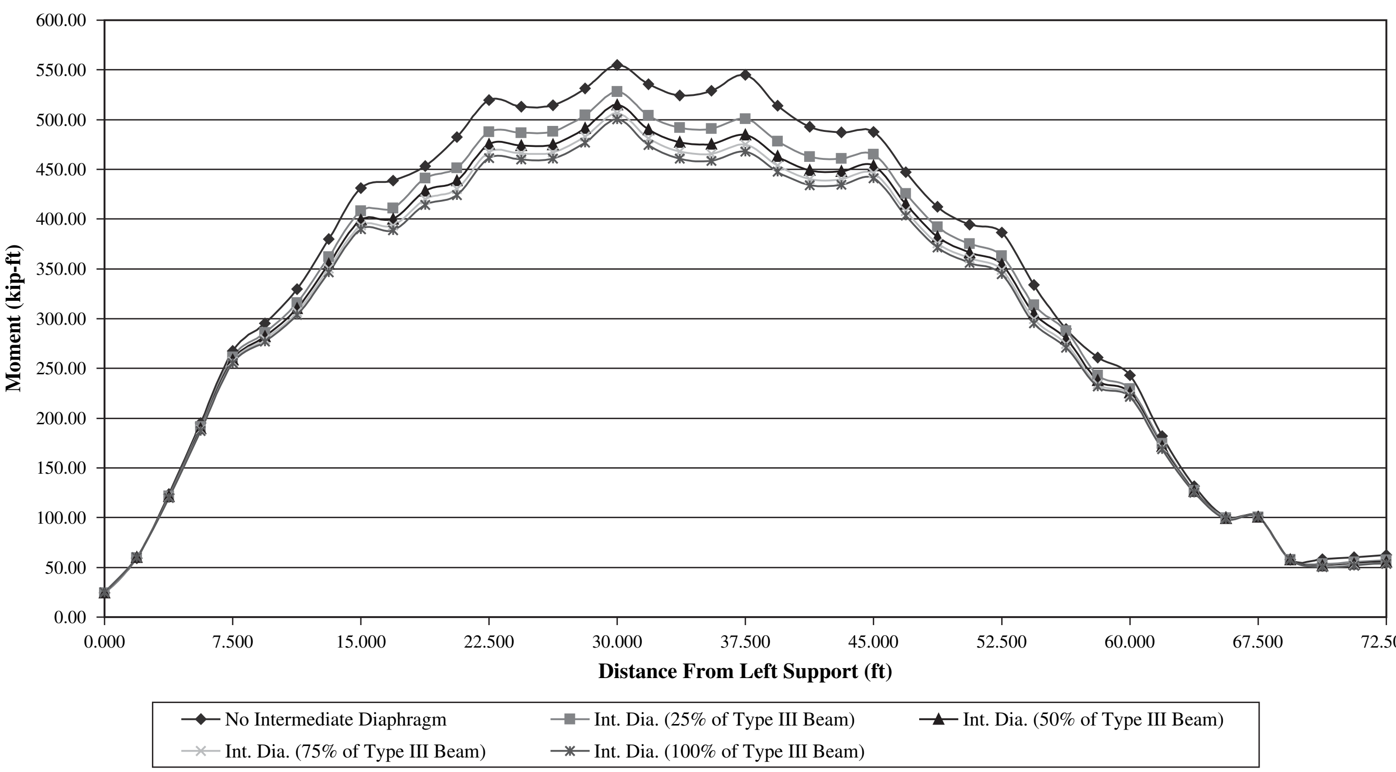


Figure 9. Intermediate diaphragms at quarter points, Beam 1, 0° skew.

Table 3. Shear at obtuse corner, Beam 1, with no intermediate diaphragms.

		With Rigid Support Diaphragms						Without Support Diaphragms					
Skew Angle (deg)		0		30		60		0		30		60	
Distance From Barrier (ft)	Load	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF
2	MOVE1	52.70	0.761	54.54	0.788	54.73	0.791	52.10	0.753	54.19	0.783	54.86	0.792
3	MOVE2	47.16	0.681	49.17	0.710	49.86	0.720	46.42	0.670	48.65	0.703	50.02	0.722
4	MOVE3	41.46	0.599	43.59	0.630	44.92	0.649	40.65	0.587	42.99	0.621	45.11	0.651
5	MOVE4	35.73	0.516	37.95	0.548	39.97	0.577	34.91	0.504	37.32	0.539	40.20	0.581
6	MOVE5	30.08	0.434	32.37	0.468	35.10	0.507	29.32	0.423	31.76	0.459	35.38	0.511
7	MOVE6	25.13	0.363	27.70	0.400	31.11	0.449	24.89	0.359	27.68	0.400	31.49	0.455
8	MOVE7	22.24	0.321	24.71	0.357	27.96	0.404	22.05	0.318	24.70	0.357	28.37	0.410
9	MOVE8	19.91	0.288	22.17	0.320	25.23	0.364	19.72	0.285	22.17	0.320	25.65	0.371
10	MOVE9	17.88	0.258	19.96	0.288	22.76	0.329	17.70	0.256	19.93	0.288	23.17	0.335

DF = distribution factor.

Table 4. Shear at obtuse corner, Beam 1, with rigid intermediate diaphragms.

		With Rigid Support Diaphragms						Without Support Diaphragms					
Skew Angle (deg)		0		30		60		0		30		60	
Distance From Barrier (ft)	Load	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF	Shear (kips)	DF
2	MOVE1	47.82	0.691	53.66	0.775	56.12	0.811	47.70	0.689	52.72	0.761	51.00	0.737
3	MOVE2	44.71	0.646	50.13	0.724	52.78	0.762	44.56	0.644	49.27	0.712	47.84	0.691
4	MOVE3	41.37	0.598	46.35	0.669	49.29	0.712	41.21	0.595	45.57	0.658	44.53	0.643
5	MOVE4	37.88	0.547	42.41	0.613	46.21	0.667	37.75	0.545	41.71	0.602	41.13	0.594
6	MOVE5	34.59	0.500	39.13	0.565	44.10	0.637	34.62	0.500	38.27	0.553	38.10	0.550
7	MOVE6	32.35	0.467	36.74	0.531	42.13	0.608	32.37	0.468	35.98	0.520	36.23	0.523
8	MOVE7	30.14	0.435	34.44	0.497	40.23	0.581	30.17	0.436	33.75	0.488	34.38	0.497
9	MOVE8	38.44	0.411	32.22	0.465	38.40	0.555	28.47	0.411	31.61	0.457	32.61	0.471
10	MOVE9	26.85	0.388	30.20	0.436	36.68	0.530	26.88	0.388	29.65	0.428	30.88	0.446

DF = distribution factor.

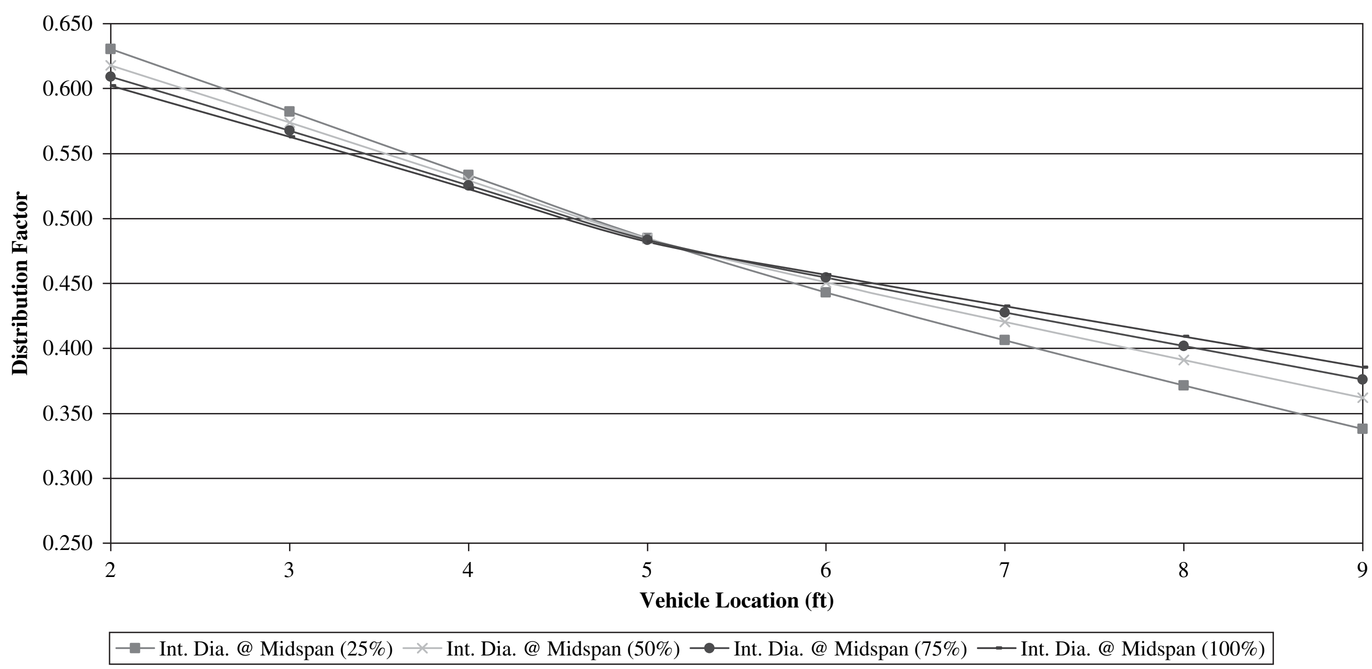
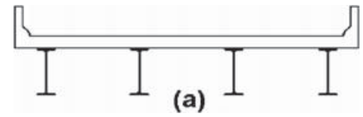
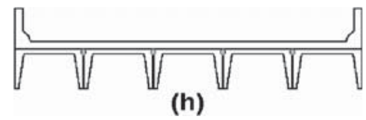
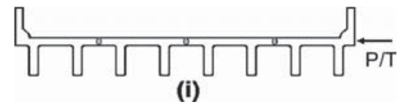
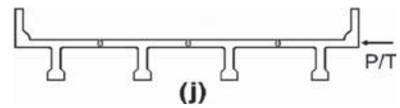
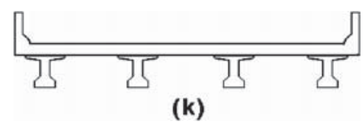
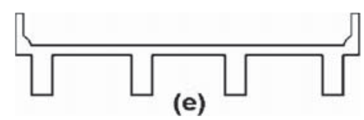
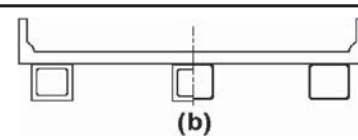
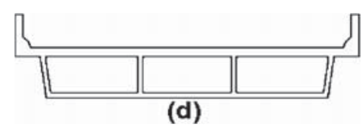
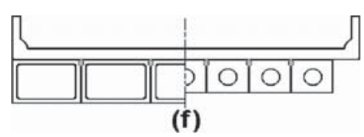
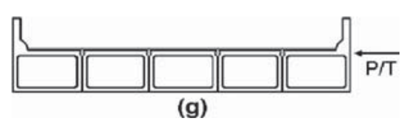


Figure 10. Moment distribution with vehicle location and diaphragm stiffness, Beam 1, 0° skew.

Table 5. Bridge set definitions.

DATA SET	AASHTO LETTER DESIGNATION	SUPPORTING COMPONENTS	TYPE OF DECK	TYPICAL CROSS-SECTION
Set 1	a	Steel Beam	Cast-in-place concrete slab, precast concrete slab, steel grid, glued/spiked panels, stressed wood	
Set 2	h	Precast Concrete Channel Sections with Shear Keys	Cast-in-place concrete overlay	
	i	Precast Concrete Double Tee Section with Shear Keys and with or without Transverse Post-Tensioning	Integral concrete	
	j	Precast Concrete Tee Section with Shear Keys and with or without Transverse Post-Tensioning	Integral concrete	
	k	Precast Concrete I or Bulb-Tee Sections	Cast-in-place concrete, precast concrete	
Set 3	e	Cast-in-Place Concrete Tee Beam	Monolithic concrete	
Set 4	b	Closed Steel or Precast Concrete Boxes	Cast-in-place concrete slab	
Set 5	d	Cast-in-Place Concrete Multicell Box	Monolithic concrete	
Set 6	f	Precast Solid, Voided or Cellular Concrete Boxes with Shear Keys	Cast-in-place concrete overlay	
	g	Precast Solid, Voided, or Cellular Concrete Box with Shear Keys and with or without Transverse Post-Tensioning	Integral concrete	

Initially, the simplified methods included the AASHTO LRFD Specifications, the *Canadian Highway Bridge Design Code* (*6*), a method by Sanders and Elleby (*7*), and two variations of Henry's method. Detailed descriptions of these methods are presented in Appendix D, and examples of their use are presented in Appendix E. Upon comparison to rigorous analysis, the *Canadian Highway Bridge Design Code* method, the method by Sanders and Elleby, and one of the Henry's method variations were discarded. Table 6 contains performance measures regarding how each method performed for each bridge type, action, loading condition, and girder location. The ratings are based on the comparison of the correlation coefficient (R^2) relating the distribution factors computed by each simplified method to those computed by rigorous analysis. A correlation coefficient approaching 1 indicates a tight banding of the data. In other words, a higher

Table 6. Rating of simplified methods based on correlation with rigorous analysis.

	excellent ≥ 0.9		0.90 > good ≥ 0.80	0.80 > acceptable ≥ 0.70		0.70 > poor ≥ 0.50		bad < 0.5				
				Method								
Bridge Set	**Action**	**Girder Locations**	**Lanes Loaded**	Sanders and Elleby	AASHTO Standard Specification	CHBDC	LRFD	Alternate for Moment	Uniform Distribution	Lever Rule	**Best Method**	
1	Shear	Exterior	1	bad	bad	bad	good	NA	bad	excellent	**Lever**	Slab On Steel I
			2 or more	bad	bad	bad	good		bad	excellent	**Lever**	
		Interior	1	good	good	good	good		acceptable	good	**Lever**	
			2 or more	good	good	good	acceptable		good	excellent	**Lever**	
	Moment	Exterior	1	bad	bad	bad	acceptable	bad	poor	good	**Lever**	
			2 or more	bad	bad	bad	good	bad	poor	good	**Lever**	
		Interior	1	bad	bad	bad	bad	poor	bad	bad	**Alternate**	
			2 or more	acceptable	poor	acceptable	acceptable	acceptable	good	acceptable	**Uniform**	
2	Shear	Exterior	1	bad	bad	bad	excellent	NA	poor	excellent	**Lever**	Slab on Concrete I
			2 or more	bad	bad	bad	acceptable		poor	excellent	**Lever**	
		Interior	1	good	good	good	excellent		acceptable	excellent	**Lever**	
			2 or more	good	good	good	good		excellent	good	**Uniform**	
	Moment	Exterior	1	bad	bad	bad	good	bad	poor	excellent	**Lever**	
			2 or more	bad	bad	bad	good	bad	poor	excellent	**Lever**	
		Interior	1	bad	poor	acceptable	good	good	bad	poor	**Alternate**	
			2 or more	good	good	good	good	good	excellent	good	**Uniform**	
3	Shear	Exterior	1	poor	poor	poor	good	NA	good	excellent	**Lever**	CIP Tees
			2 or more	poor	poor	poor	excellent		excellent	excellent	**Uniform**	
		Interior	1	good	good	excellent	excellent		acceptable	excellent	**Lever**	
			2 or more	acceptable	good	excellent	good		excellent	good	**Uniform**	
	Moment	Exterior	1	poor	poor	poor	good	bad	acceptable	excellent	**Lever**	
			2 or more	poor	poor	poor	excellent	bad	excellent	excellent	**Uniform**	
		Interior	1	poor	acceptable	good	excellent	poor	poor	acceptable	**Lever**	
			2 or more	good	acceptable	good	excellent	poor	excellent	poor	**Lever**	
4	Shear	Exterior	1	acceptable	good	acceptable	excellent	NA	good	excellent	**Lever**	Spread Boxes
			2 or more	good	good	good	excellent		excellent	excellent	**Lever**	
		Interior	1	good	excellent	good	good		acceptable	excellent	**Lever**	
			2 or more	excellent	excellent	excellent	excellent		poor	excellent	**Lever**	
	Moment	Exterior	1	poor	poor	acceptable	poor	bad	poor	poor	**CHBDC**	
			2 or more	good	good	good	good	bad	poor	good	**CHBDC**	
		Interior	1	bad	poor	bad	poor	poor	bad	poor	**Lever**	
			2 or more	bad	poor	poor	poor	poor	excellent	poor	**Uniform**	
5	Shear	Exterior	1	bad	bad	bad	good	NA	acceptable	good	**Lever**	Cast-In-Place Boxes
			2 or more	bad	bad	bad	acceptable		acceptable	excellent	**Lever**	
		Interior	1	bad	good	good	acceptable		poor	good	**CHBDC**	
			2 or more	bad	good	good	good		poor	acceptable	**LRFD**	
	Moment	Exterior	1	bad	bad	bad	bad	poor	poor	bad	**Alternate**	
			2 or more	bad	bad	bad	bad	poor	poor	bad	**Alternate**	
		Interior	1	bad	bad	bad	bad	good	bad	bad	**Alternate**	
			2 or more	bad	bad	bad	poor	good	bad	bad	**Alternate**	
6	Shear	Exterior	1	good	good	good	excellent	NA	good	excellent	**Lever**	Adjacent Boxes
			2 or more	good	good	good	excellent		excellent	excellent	**Lever**	
		Interior	1	acceptable	acceptable	acceptable	good		acceptable	excellent	**Lever**	
			2 or more	good	good	good	excellent		excellent	excellent	**Lever**	
	Moment	Exterior	1	poor	poor	poor	acceptable	acceptable	poor	acceptable	**Alternate**	
			2 or more	poor	poor	poor	good	acceptable	excellent	acceptable	**Uniform**	
		Interior	1	bad	bad	bad	bad	excellent	bad	bad	**Alternate**	
			2 or more	poor	poor	poor	poor	good	excellent	poor	**Uniform**	

CIP = cast-in-place.
CHBDC = *Canadian Highway Bridge Design Code*.

value of R^2 means a more predictable result compared to rigorous analysis. These results are presented in Appendix N. Note that *agreement* with the rigorous results is not necessary at this point; a tight/low variability is the most important characteristic. The simplified method can be (and was) shifted and rotated with an affine transformation process (described earlier).

Final Simplified Method Investigation

Based on the results summarized in Table 6, two primary methods were chosen for further investigation: the uniform distribution method (Henry's method) and the lever rule. Both methods are based on fundamental concepts, are easy to use, and provide the best results when compared to rigorous analyses.

The lever rule was calibrated to better compare with rigorous analysis. Hereafter, this method is referred to as the *calibrated lever rule* and is computed as follows:

$$mg_v = \gamma_s m\left[a(g_{lever\,rule}) + b\right] \geq m\left[\frac{N_{lanes}}{N_g}\right] \tag{2-1}$$

Where:

a and b = calibration constants,
m = multiple presence factor,
N_g = number of girders,
N_{lanes} = number of lanes considered in the lever rule analysis,
$g_{lever\,rule}$ = distribution factor computed by the lever rule, and
g = distribution factor.

The term mg is used to clearly delineate that the multiple presence factor is included. γ_s (the DSF) accounts for the variability associated with the simple method; this variability is outlined in a later section.

The uniform method is initially based on equal distribution of live load effects. In determining the distribution factor using this method, the bridge is considered to be fully loaded, and each girder is to carry approximately the same amount of load. Calibration factors are then applied because some girders attract more loads.

The procedure for the calculation of live load moment distribution factors by use of the uniform distribution method is as follows. For both exterior and interior girders with multiple lanes loaded:

$$mg_m = m\gamma_s\left[a_m\left(\frac{W_c}{10N_g}\right) + b_m\right] \geq m\left[\frac{N_L}{N_g}\right] \tag{2-2}$$

Where:

W_c = clear roadway width (feet),
a_m and b_m = calibration constants,
γ_s = DSF,
N_L = maximum number of design lanes for the bridges, and
Design lane width = 10 feet.

Initially, the constants were based on Huo et al. (*2*), and then the more general affine transformation method was applied to the uniform distribution method. This approach is general, improves accuracy, and is consistent with the adjustments used for the lever rule method. In order to simplify the specifications, a span length factor (F_L) was placed in the commentary as an optional factor to account for lower distribution factors in spans over 100 feet long.

Comparisons of simplified methods to rigorous analysis for all the bridge types studied, without limits of applicability, resulted in several primary conclusions:

- For live load moment distribution, the adjusted uniform method performed well for both the exterior and interior girder with two or more lanes loaded.
- For one lane loaded, the calibrated uniform method performed better for the exterior girder than for the interior girder. The reason for the better performance was that the calibration was based on the exterior girder results.
- For the interior girder with one lane loaded, the calibrated lever rule performed better than the calibrated uniform method for moment. However, for one-lane moment, the results illustrate significant variability. This is the only significant "problem" case for the primary methods. To address the one lane loaded for moment, an alternative approach was developed and is codified within an appendix for LRFD Section 4.
- The calibrated lever rule produces excellent results for shear. In the few cases where another method outperformed it, the calibrated lever rule still produced good results. In the interest of simplicity, the calibrated lever rule was used for all cases for shear.
- In general, the calibrated uniform distribution method for moment in both exterior and interior girders with two or more lanes loaded and the calibrated lever rule for all other cases performed better than the AASHTO Standard Specifications and the AASHTO LRFD Specifications.
- In general, the AASHTO Standard Specifications perform poorly in many cases.

Summaries of the performance of the calibrated uniform distribution, the calibrated lever rule, and the alternative methods for moment and shear are shown in Table 7 and Table 8, respectively.

The live load distribution for moment with one lane loaded for the exterior girder and, in particular, the interior girder, was difficult to accurately predict with any simplified method.

Table 7. Simplification of Table 6 for moment distribution.

Girder Location	Moment		Method			
	Bridge Set	Lanes Loaded	Alternate for Moment	Uniform Distribution	Lever Rule	Best Method
Exterior	1	1	bad	poor	good	**Lever**
		2 or more	bad	poor	good	**Lever**
	2	1	bad	poor	excellent	**Lever**
		2 or more	bad	poor	excellent	**Lever**
	3	1	bad	acceptable	excellent	**Lever**
		2 or more	bad	excellent	excellent	**Uniform**
	4	1	poor	poor	poor	**CHBDC**
		2 or more	bad	poor	good	**CHBDC**
	5	1	poor	bad	bad	**Alternate**
		2 or more	poor	poor	bad	**Alternate**
	6	1	acceptable	poor	acceptable	**Alternate**
		2 or more	acceptable	excellent	acceptable	**Uniform**
Interior	1	1	poor	bad	bad	**Alternate**
		2 or more	acceptable	good	acceptable	**Uniform**
	2	1	good	bad	poor	**Alternate**
		2 or more	good	excellent	good	**Uniform**
	3	1	poor	poor	acceptable	**Lever**
		2 or more	poor	excellent	poor	**Lever**
	4	1	poor	bad	poor	**Lever**
		2 or more	poor	excellent	poor	**Uniform**
	5	1	good	bad	bad	**Alternate**
		2 or more	good	bad	bad	**Alternate**
	6	1	excellent	bad	bad	**Alternate**
		2 or more	good	excellent	poor	**Uniform**

CHBDC = *Canadian Highway Bridge Design Code*.

Table 8. Simplification of Table 6 for shear distribution.

Girder Location	Shear		Method		
	Bridge Set	Lanes Loaded	Uniform Distribution	Lever Rule	Best Method
Exterior	1	1	bad	excellent	**Lever**
		2 or more	bad	excellent	**Lever**
	2	1	poor	excellent	**Lever**
		2 or more	poor	excellent	**Lever**
	3	1	good	excellent	**Lever**
		2 or more	excellent	excellent	**Uniform**
	4	1	good	excellent	**Lever**
		2 or more	excellent	excellent	**Lever**
	5	1	acceptable	good	**Lever**
		2 or more	acceptable	excellent	**Lever**
	6	1	good	excellent	**Lever**
		2 or more	excellent	excellent	**Lever**
Interior	1	1	acceptable	good	**Lever**
		2 or more	good	excellent	**Lever**
	2	1	acceptable	excellent	**Lever**
		2 or more	excellent	good	**Uniform**
	3	1	acceptable	excellent	**Lever**
		2 or more	excellent	good	**Uniform**
	4	1	acceptable	excellent	**Lever**
		2 or more	poor	excellent	**Lever**
	5	1	poor	good	**CHBDC**
		2 or more	poor	acceptable	**LRFD**
	6	1	acceptable	excellent	**Lever**
		2 or more	excellent	excellent	**Lever**

CHBDC = *Canadian Highway Bridge Design Code*.

The calibrated lever rule was selected for the one-lane loaded condition because it produced only one R^2 value less than 0.5, and for that case, all other methods performed worse or only slightly better. This primary method is codified within the body of the proposed specifications. Improvement of this performance is certainly a concern here. However, the one-lane loaded case is typically used for fatigue and will likely not control the design. This design characteristic does not excuse the poor performance. This issue could be quite important should these methods be considered for rating.

To address this problem, an alternative method was developed under NCHRP Project 12-26 based upon a parametric approach similar to that of the present LRFD specifications. The equation takes the form of:

$$g = \left(\frac{S}{D}\right)^{Exp1} \left(\frac{S}{L}\right)^{Exp2} \left(\frac{1}{N_g}\right)^{Exp3} \geq \frac{N_{lanes}}{N_g} \qquad (2\text{-}3)$$

Where:

Exp1, *Exp2*, *Exp3*, and *D* = constants that vary with bridge type;

S = girder spacing in feet;

L = span length in feet; and

N_g = number of girders or number of cells +1 for the bridge.

This parametric equation was developed by combining terms for the one-lane loaded, interior girder moment distribution factor equations for I-section and cast-in-place box girder bridges. The terms that depended on the stiffness of the section were dropped. By varying the values of the three exponents and the *D* constant, this equation form produced reasonable results for the various bridge types. In cases where one of the exponents was determined to be near zero, the term was dropped (i.e., the exponent was set equal to zero) in order to simplify the application of this equation as much as possible. Specific coefficient values are present in the appendix of the draft specifications contained within Appendix H.

The researchers sought methods that did not include the span length because of the complexities of outlining which span to use. However, for the one-lane loading, the transverse deflections (and curvatures) are much more localized than the multiple-lane loading case. Therefore, a parameter that represents the longitudinal to transverse stiffness is necessary for better accuracy. The quantification of this was achieved by the geometric ratio S/L.

Based on the summary above, the primary simplified distribution factor equations for moment are described in Table 9. These equations are applicable for all bridge types investigated. The moment calibration factors are shown in Table 10.

The live load shear distribution factor equation is

$$mg_v = \gamma_s m[a_v(g_{lever\ rule}) + b_v] \geq m\left[\frac{N_{lanes}}{N_g}\right] \qquad (2\text{-}4)$$

Where:

mg_v = distribution factor including multiple presence,
$g_{lever\ rule}$ = distribution factor based upon the lever rule,
a_v, b_v = calibration constants for shear and reactions defined in Table 11,
m = multiple presence factor,
N_{lanes} = number of lanes used in the lever rule analysis, and
γ_s = live load DSF described later.

The last term represents the theoretical lower bound of a uniform distribution of live load.

Lever Rule Review and Formulas

The lever rule is defined as an approximate distribution factor method that assumes no transverse deck moment continuity at interior beams, which renders the transverse deck cross section statically determinate. The method uses direct equilibrium to determine the load distribution to a beam of interest. Equations were derived in order to further simplify the lever rule. These equations were derived assuming constant 4-foot spacing between multiple vehicles. The lever rule equations are shown in Table 12 and Table 13 for exterior and interior girders, respectively, where:

d_e = distance from the center of the exterior girder to the location of the centroid of the outermost wheel group (feet) and
S = girder spacing; if splayed, use the largest spacing within the span (feet).

A wheel positioned outside of the fascia girder gives a positive d_e. These equations are applicable for the ranges of application shown in the table. If d_e is less than zero, the interior girder distribution factor must be determined by manually placing the load on the bridge for critical effect. Manual placement and lever formula are functionally the same. Therefore, a standard hand approach and/or existing computer-based algorithms can be used for the calibrated lever rule method. These formulas are provided only for convenience.

The derivations of two lever rule equations are illustrated as examples. All equations were derived by using direct equilibrium. For example, for an exterior girder with two or more lanes loaded and two wheels contributing to the beam reaction (see Figure 11), the equation is derived as follows:

$$\sum M_A : \frac{1}{2}(d_e + S) + \frac{1}{2}(d_e + S - 6) - RS = 0 \qquad (2\text{-}5)$$

Table 9. Live load moment distribution factor equations.

Number of Loaded Lanes	Girder	Distribution Factor	Multiple Presence Factor
One	Interior and Exterior	$mg_m = m\gamma_s\left[a_m\left(g_{lever\ rule}\right) + b_m\right] \geq m\left[\frac{N_{lanes}}{N_g}\right]$	$m = 1.2$
Two or more	Interior and Exterior	$mg_m = m\gamma_s\left[a_m\left(\frac{W_c}{10N_g}\right) + b_m\right] \geq m\left[\frac{N_L}{N_g}\right]$	Use integer part of $\frac{W_c}{12}$ to determine number of loaded lanes for multiple presence. m shall be greater than or equal to 0.85.

Table 10. Live load moment adjustment factors.

Structure Type	AASHTO LRFD Cross Section Type	Moment							
		Exterior				Interior			
		One Loaded Lane		Two or More Lanes		One Loaded Lane		Two or More Lanes	
		a_m	b_m	a_m	b_m	a_m	b_m	a_m	b_m
		Lever Rule		Uniform		Lever Rule		Uniform	
Steel I-Beam	a	0.53	0.19	1.14	-0.12	0.97	-0.24	1.17	-0.08
Precast Concrete I-Beam,Precast Concrete Bulb-Tee Beam, Precast Concrete Tee Section with Shear Keys and with or without Transverse Post-Tensioning, Precast Concrete Double Tee with Shear Keys with or without Post-Tensioning, Precast Concrete Channel with Shear Keys	h, i, j, k	0.68	0.14	1.25	-0.20	1.33	-0.41	1.39	-0.19
Cast-in-Place Concrete Tee Beam	e	0.65	0.15	1.11	-0.14	1.40	-0.41	1.14	-0.04
Cast-in-Place Concrete Multicell Box Beam	d	0.54	-0.09	0.65	-0.07	1.71	-0.82	0.93	-0.10
Adjacent Box Beam with Cast-in-Place Concrete Overlay	f	0.26	0.02	0.53	-0.01	0.59	-0.15	0.64	0.05
Adjacent Box Beam with Integral Concrete	g								
Precast Concrete Spread Box Beam	b	0.62	-0.08	1.00	-0.06	0.77	-0.17	0.90	0.00
Open Steel Box Beam	c	Use Article 4.6.2.2.3							

Table 11. Live load shear adjustment factors.

Structure Type	AASHTO LRFD Cross Section Type	Shear							
		Exterior				Interior			
		One Loaded Lane		Two or More Lanes		One Loaded Lane		Two or More Lanes	
		a_v	b_v	a_v	b_v	a_v	b_v	a_v	b_v
		Lever Rule							
Steel I-Beam	a	0.70	0.13	0.83	0.11	1.04	-0.12	0.99	0.01
Precast Concrete I-Beam, Precast Concrete Bulb-Tee Beam, Precast Concrete Tee Section with Shear Keys and with or without Transverse Post-Tensioning, Precast Concrete Double Tee with Shear Keys with or without Post-Tensioning, Precast Concrete Channel with Shear Keys	h, i, j, k	0.83	0.07	0.92	0.06	1.08	-0.13	0.94	0.03
Cast-in-Place Concrete Tee Beam	e	0.79	0.09	0.94	0.05	1.24	-0.22	1.21	-0.17
Cast-in-Place Concrete Multicell Box Beam	d	0.85	0.00	0.82	0.04	1.19	-0.20	0.71	0.23
Adjacent Box Beam with Cast-in-Place Concrete Overlay	f	0.87	0.03	0.91	0.03	1.05	-0.10	1.00	-0.05
Adjacent Box Beam with Integral Concrete	g								
Precast Concrete Spread Box Beam	b	0.61	0.15	0.78	0.12	1.00	-0.11	0.83	0.07
Open Steel Box Beam	c	Use Article 4.6.2.2.3							

Table 12. Lever rule equations for exterior girders.

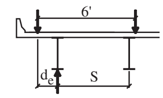
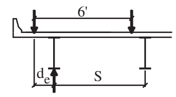
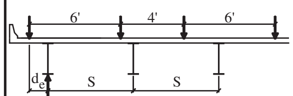
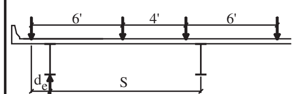
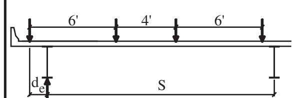
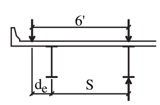
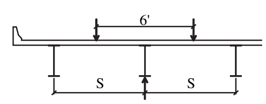
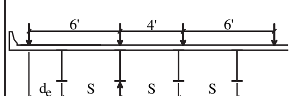
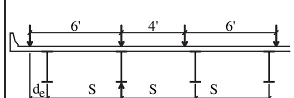
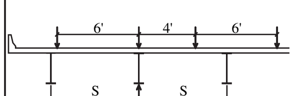
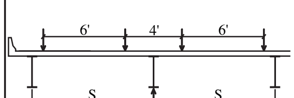
Number of Loaded Lanes	Distribution Factor	Range of Application	Loading Diagram	Number of Wheels to Beam
1	$\frac{1}{2}+\frac{d_e}{2S}$	$(d_e+S)\le 6\,ft$ $\lvert d_e\rvert < S$		1
	$1+\frac{d_e}{S}-\frac{3}{S}$	$(d_e+S)>6\,ft$		2
2 or more	$1+\frac{d_e}{S}-\frac{3}{S}$	$(d_e+S)\le 10\,ft$		2
	$\frac{3}{2}+\frac{3d_e}{2S}-\frac{8}{S}$	$10<(d_e+S)\le 16\,ft$		3
	$2+\frac{2d_e}{S}-\frac{16}{S}$	$16<(d_e+S)\le 20\,ft$		4

Table 13. Lever rule equations for interior girders.

Number of Loaded Lanes	Distribution Factor	Range of Application	Loading Diagram	Number of Wheels to Beam
1	$\frac{1}{2}$	$S\le 6\,ft$ $d_e\ge 0$		1
	$1-\frac{3}{S}$	$S>6\,ft$ $d_e\ge 0$		2
2 or more	$\frac{1}{2}$	$S\le 4\,ft$ $d_e\ge 0$		1
	$1-\frac{2}{S}$	$4<S\le 6\,ft$ $d_e\ge 0$		2
	$\frac{3}{2}-\frac{5}{S}$	$6<S\le 10\,ft$ $d_e\ge 0$		3
	$2-\frac{10}{S}$	$10<S\le 16\,ft$ $d_e\ge 0$		4

Note: If $d_e<0$, use lever rule and manually place the vehicle for critical effect on the first interior beam.

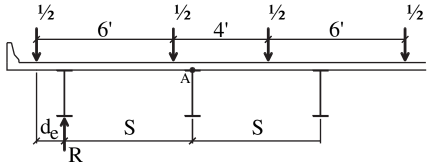


Figure 11. Loading diagram for exterior girder with two lanes loaded and two wheels to beam.

$$R=\frac{\frac{1}{2}d_e+\frac{1}{2}S+\frac{1}{2}d_e+\frac{1}{2}S-3}{S} \quad (2\text{-}6)$$

$$R=\frac{d_e+S-3}{S} \quad (2\text{-}7)$$

$$R=1+\frac{d_e}{S}-\frac{3}{S} \quad (2\text{-}8)$$

For an interior girder with two or more lanes loaded and three wheels contributing to the beam reaction (see Figure 12), the equation is derived as follows:

The total interior girder reaction is divided into four parts, associated with each wheel load:

$$R=\sum wheel\,reactions=R_1+R_2+R_3+R_4$$

Where:
R_1, R_2, R_3, and R_4 = reactions due to the four wheels, from left to right.

Wheel 1 reaction:

$$\sum M_A=0=\frac{1}{2}(S-6)-SR_1 \quad (2\text{-}9)$$

$$R_1=\frac{1}{2}-\frac{3}{S} \quad (2\text{-}10)$$

Wheel 2 reaction:

$$R_2=\frac{1}{2} \quad (2\text{-}11)$$

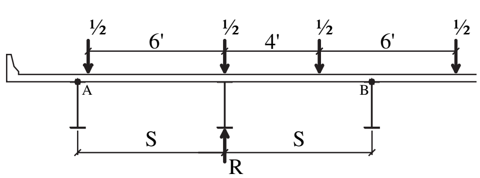


Figure 12. Loading diagram for interior girder with two lanes loaded and three wheels to beam.

Wheel 3 reaction:

$$\sum M_B=0=\frac{1}{2}(S-4)-SR_3 \quad (2\text{-}12)$$

$$R_3=\frac{1}{2}-\frac{2}{S} \quad (2\text{-}13)$$

Wheel 4 reaction:

$$R_4=0 \quad (2\text{-}14)$$

Total reaction:

$$R=\frac{1}{2}-\frac{3}{S}+\frac{1}{2}+\frac{1}{2}-\frac{2}{S} \quad (2\text{-}15)$$

$$R=\frac{3}{2}-\frac{5}{S} \quad (2\text{-}16)$$

Culmination of Research

Specification Language

The recommended specification language describing this method is presented in Appendix H. The alternative method is outlined in the appendix to the proposed specifications in Section 4, Appendix 4C.

Example Problems

Example problems using the recommended method are presented in Appendix I, where several bridges are illustrated with the computations performed within MathCAD. The MathCAD computations are self-documenting and are similar to those typically done by hand.

Comprehensive Comparisons with Rigorous Results

Comparisons of the recommended method with rigorous analyses are presented in Appendix J. Note that rigorous grillage models were used as the basis for the analysis and development of the simplified approaches.

Comparison of the Present LRFD Specifications with the Proposed Work

Appendix K contains regression plots of the recommended method against the current LRFD specifications distribution factor method. Implementation details are presented in Chapter 3. Again, note that the basis for correctness is rigorous analysis. Computational details and performance are elaborated next.

Details of Calibration and Computational Performance

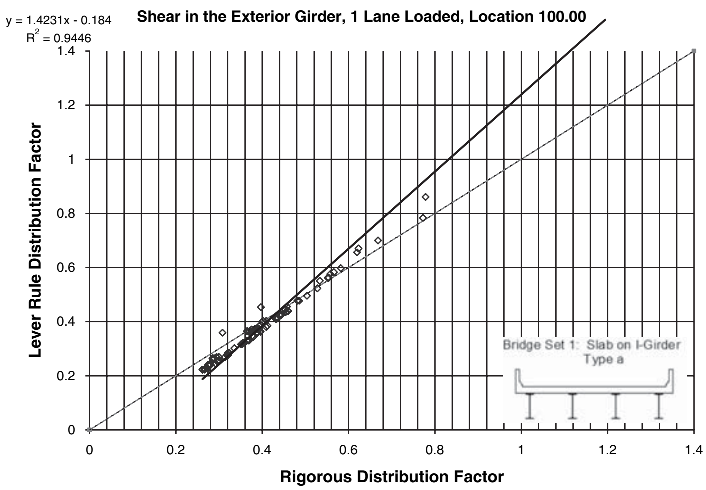
Calibration of the Lever Rule

The calibration was performed so that the method would closely approximate the mean of the rigorous values. The adjustment of the data was accomplished by multiplying the lever rule results by a constant, *a*, which had the effect of rotating the trend line. Once the results formed a trend line roughly parallel to a 1:1 trend line, the line was moved up or down by adding a second constant, *b*. This process is the affine transformation outlined earlier. Figures 13 through 84 show affine transformations. Within each of these figures, the first part ("a") shows the results for shear distribution factors for before the calibration constants have been applied, the second part ("b") shows the results after the calibration constants have been applied, and the third part ("c") shows the comparative statistics. Note that an affine transformation does not affect the variability, or scatter. The R^2 value is invariant under an affine transformation.

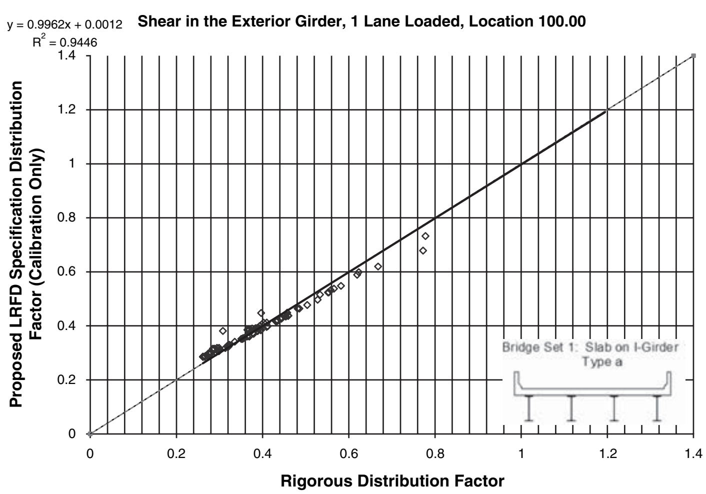
Calibration of the Uniform Distribution Method

The calibration of the uniform distribution method involves an affine transformation, as outlined for the lever rule. Huo et al. (*2*) originally calibrated the method with a single parameter that changed the slope (called a structure factor, which was analogous to the factor a_m used in this report). Huo et al. calibrated the method so that the results were above the mean in order to be conservative. The amount of the calibration was based on judgment. Huo et al.'s initial work was recalibrated in the present work with the affine transformations and calibrated to the mean. Application of the DSF then accounts for the variability in a manner consistent with the calibrated lever rule and the parametric formula. The DSFs are based on setting simplified method results above the rigorous by one-half standard deviation.

Text continues on page 97.



a.



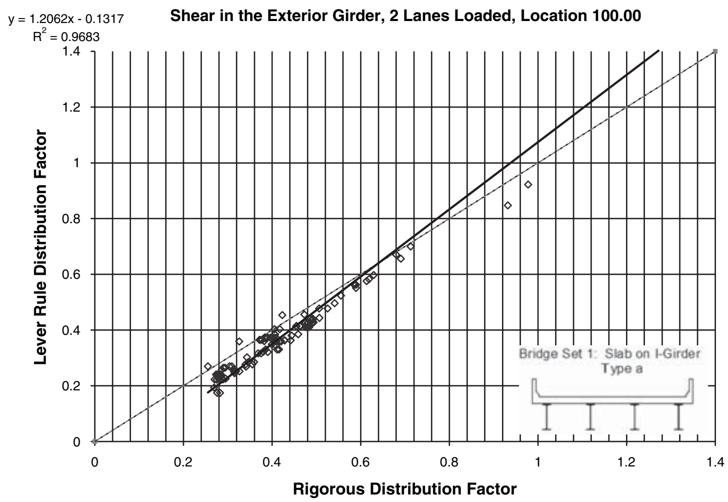
b.

Bridge Set 1 - Concrete Deck on Steel I Sections, Type a

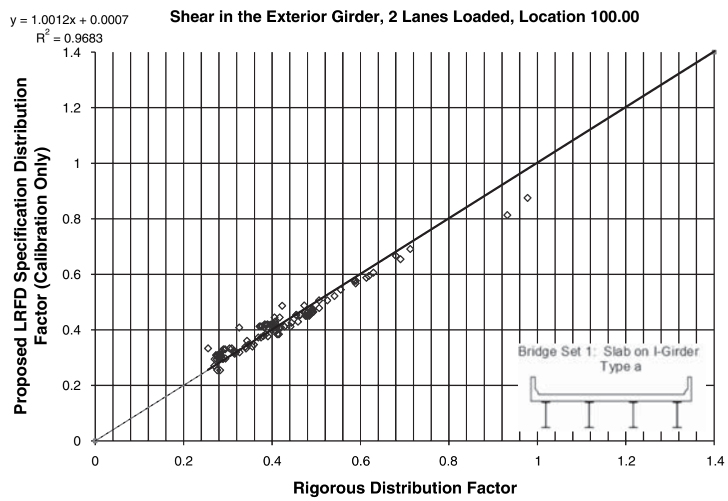
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.703	1.358	1.008	1.006
Standard Deviation	0.471	0.180	0.401	0.056
Coefficient of Variation	0.276	0.132	0.397	0.056
Count	97	99	99	99

c.

Figure 13. Shear, one lane, exterior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

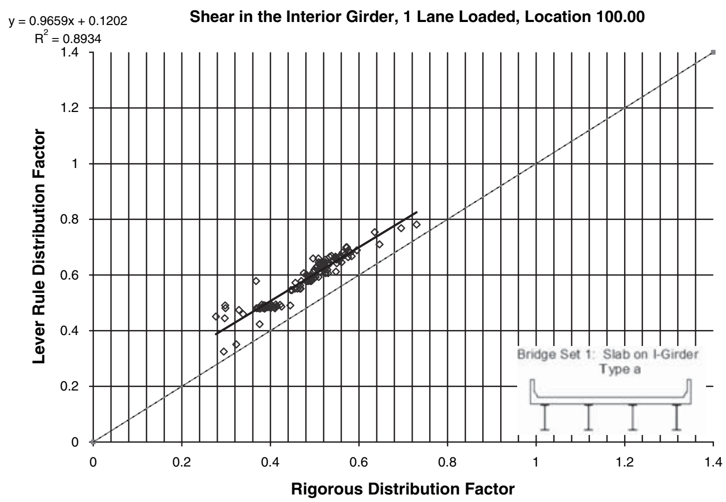


b.

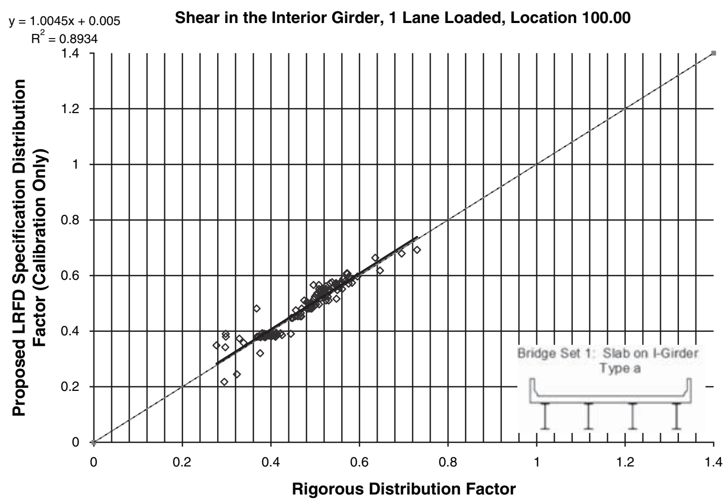
Bridge Set 1 - Concrete Deck on Steel I Sections, Type a				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.645	1.436	0.999	1.011
Standard Deviation	0.497	0.283	0.404	0.073
Coefficient of Variation	0.302	0.197	0.404	0.072
Count	102	103	40	103

c.

Figure 14. Shear, multiple lanes, exterior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



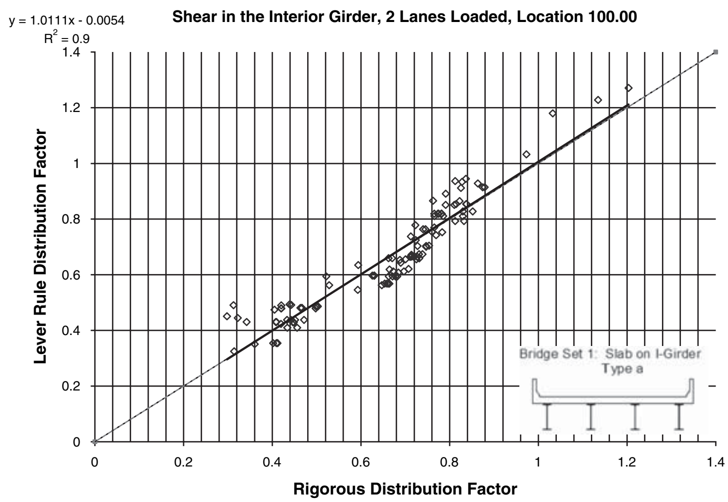
b.

Bridge Set 1 - Concrete Deck on Steel I Sections, Type a

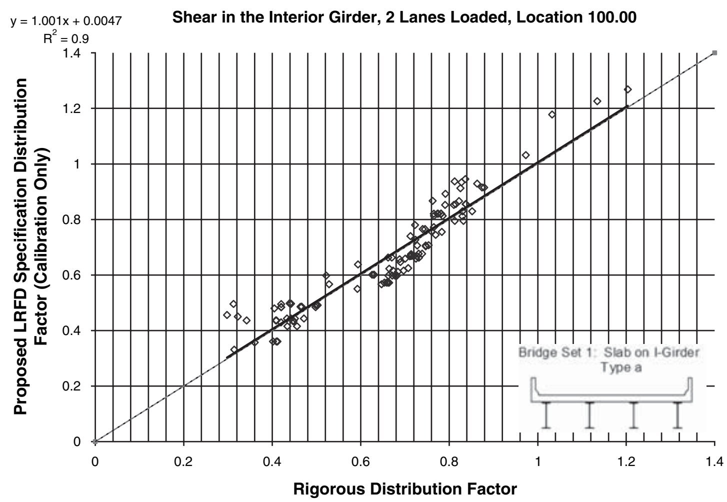
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.352	1.388	1.016	1.016
Standard Deviation	0.180	0.159	0.097	0.079
Coefficient of Variation	0.133	0.115	0.096	0.078
Count	115	115	115	115

c.

Figure 15. Shear, one lane, interior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



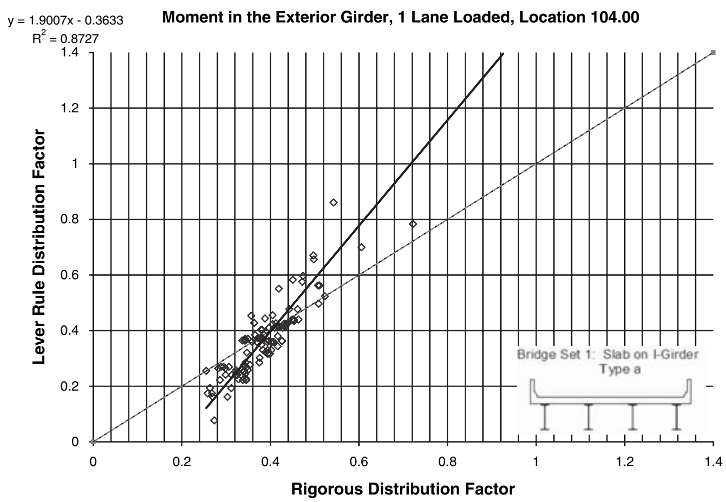
b.

Bridge Set 1 - Concrete Deck on Steel I Sections, Type a

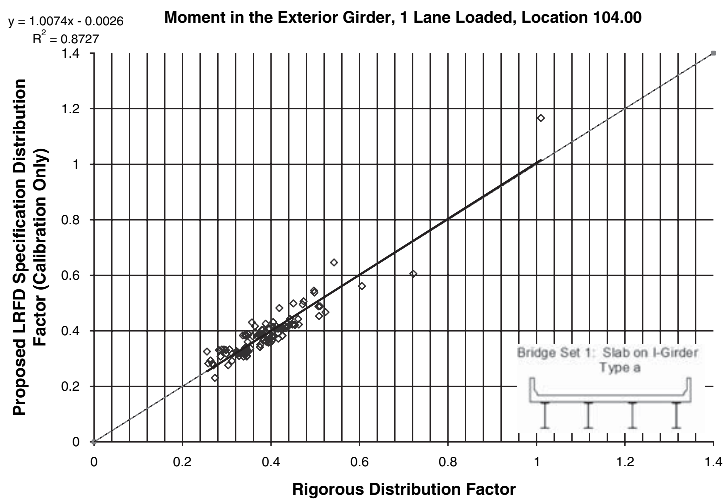
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.017	1.216	0.997	1.015
Standard Deviation	0.132	0.197	0.149	0.118
Coefficient of Variation	0.130	0.162	0.149	0.116
Count	115	114	44	114

c.

Figure 16. Shear, multiple lanes, interior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



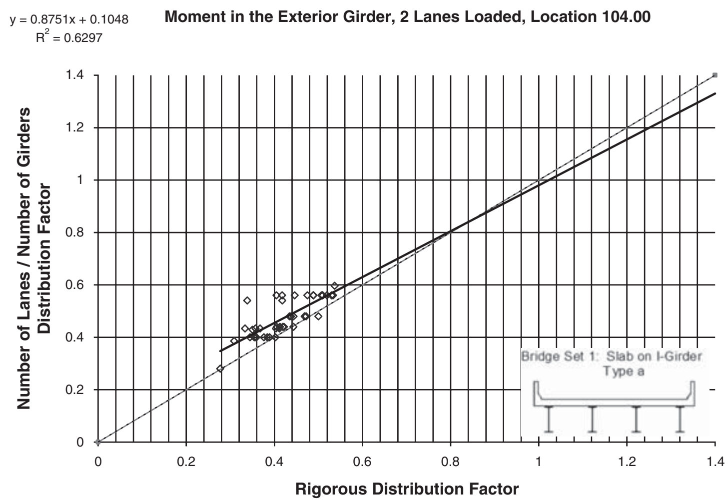
b.

Bridge Set 1 - Concrete Deck on Steel I Sections, Type a

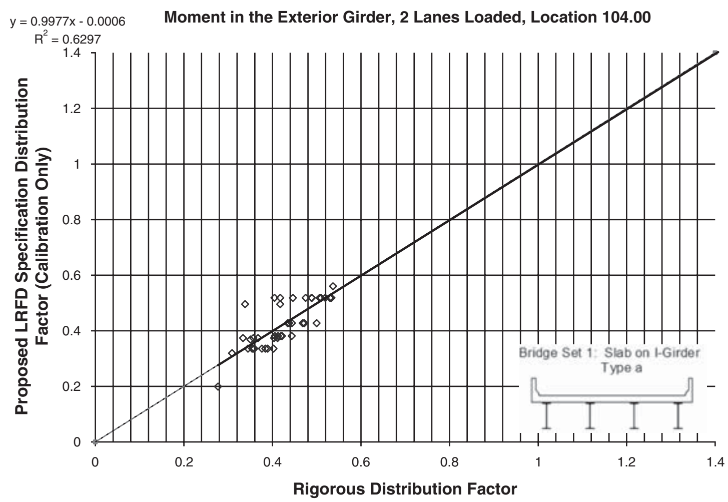
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.740	1.369	1.008	1.004	0.965
Standard Deviation	0.412	0.179	0.248	0.086	0.568
Coefficient of Variation	0.237	0.131	0.246	0.086	0.588
Count	107	108	108	108	107

c.

Figure 17. Moment, one lane, exterior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

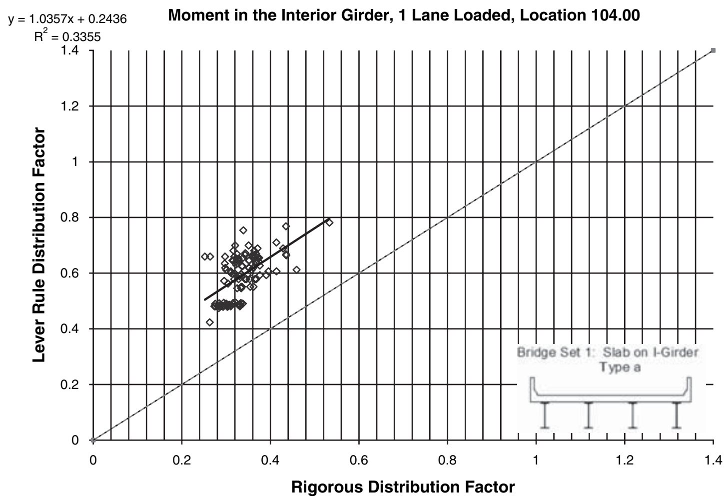


b.

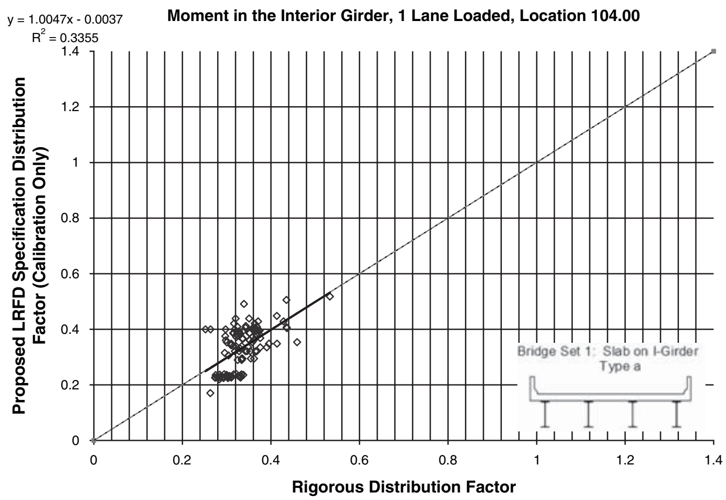
Bridge Set 1 - Concrete Deck on Steel I Sections, Type a					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.370	1.191	0.996	1.008	0.903
Standard Deviation	0.309	0.142	0.132	0.130	0.796
Coefficient of Variation	0.225	0.119	0.133	0.129	0.881
Count	109	109	42	109	106

c.

Figure 18. Moment, multiple lanes, exterior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



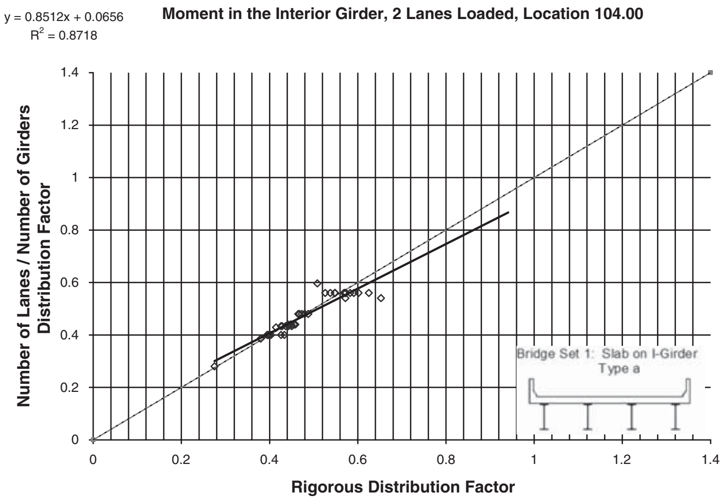
b.

Bridge Set 1 - Concrete Deck on Steel I Sections, Type a

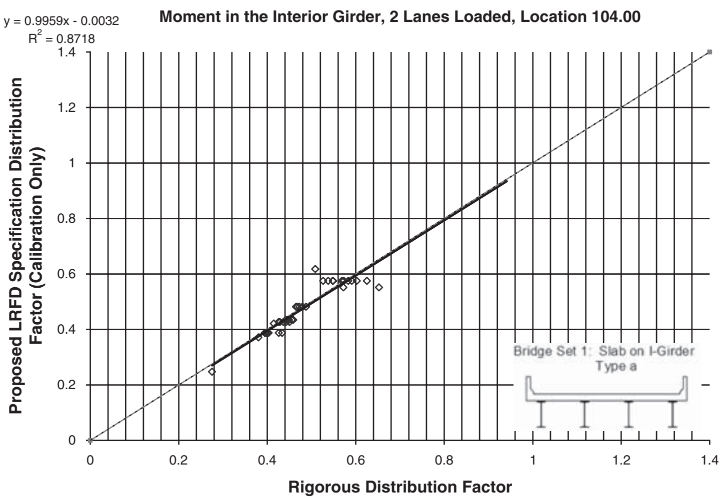
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.977	1.294	1.008	0.993	1.008
Standard Deviation	0.353	0.094	0.198	0.197	0.099
Coefficient of Variation	0.179	0.072	0.196	0.198	0.099
Count	107	107	109	109	109

c.

Figure 19. Moment, one lane, interior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

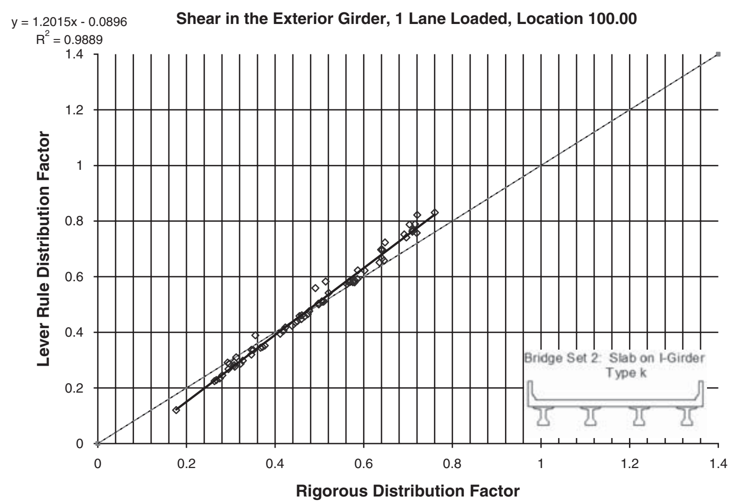


b.

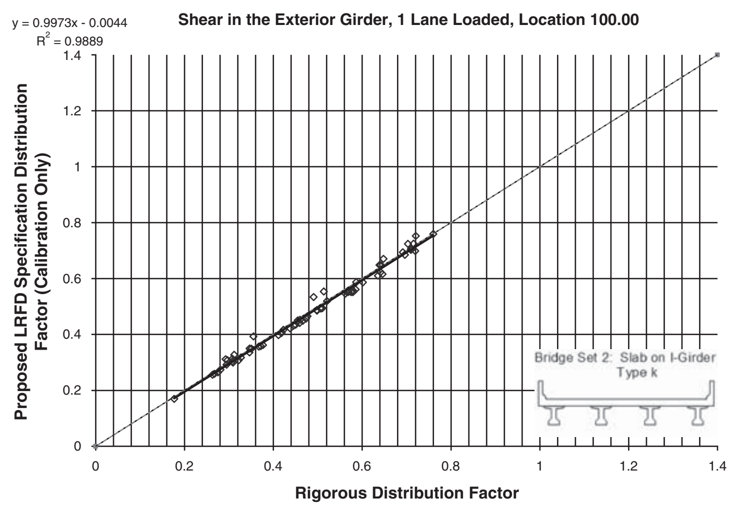
Bridge Set 1 - Concrete Deck on Steel I Sections, Type a					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.232	1.113	0.988	1.011	1.010
Standard Deviation	0.177	0.128	0.059	0.123	0.123
Coefficient of Variation	0.144	0.115	0.059	0.122	0.121
Count	112	112	42	112	112

c.

Figure 20. Moment, multiple lanes, interior, slab-on-steel I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

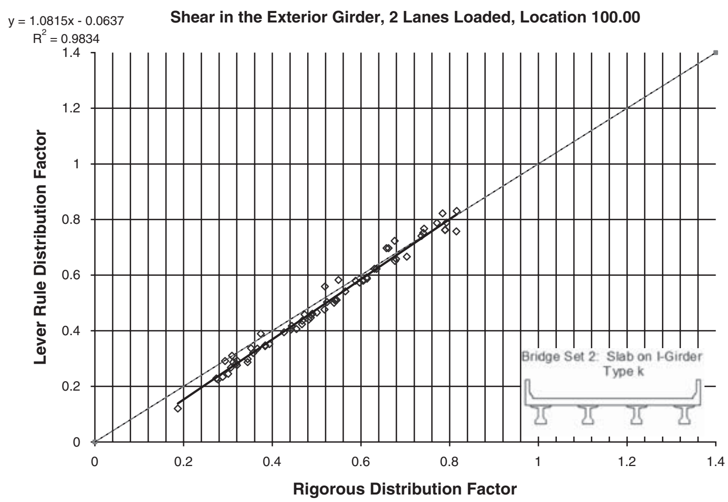


b.

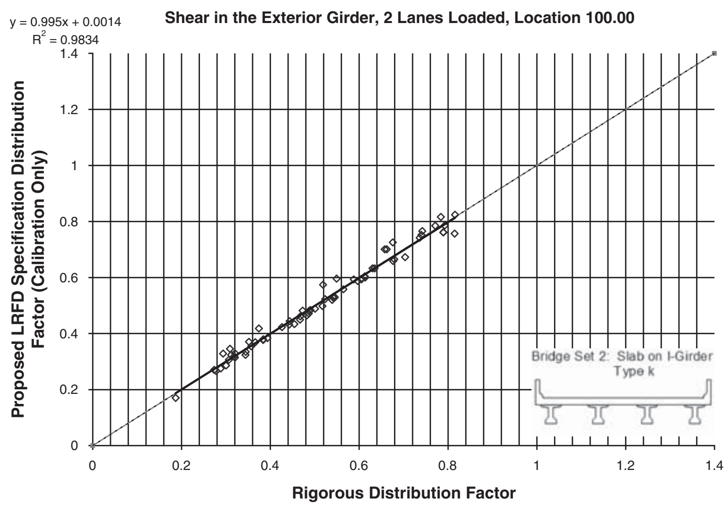
Bridge Set 2 - Slab on Concrete I-Girders, Type k				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.455	1.305	0.959	0.988
Standard Deviation	0.414	0.172	0.394	0.033
Coefficient of Variation	0.285	0.132	0.411	0.033
Count	67	69	69	69

c.

Figure 21. Shear, one lane, exterior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

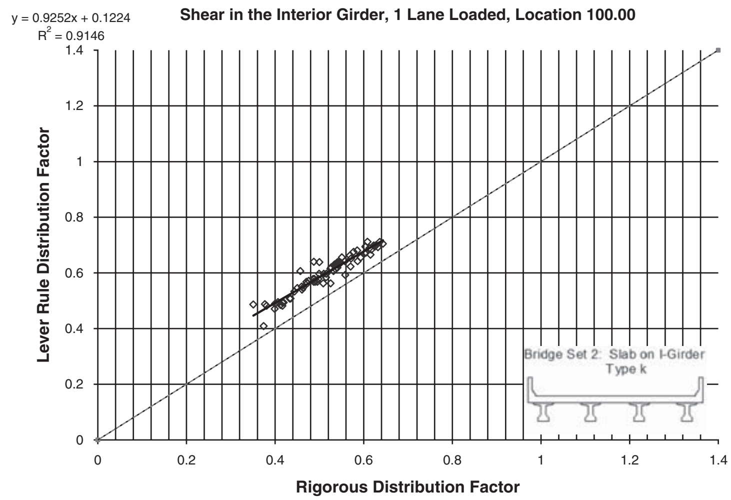


b.

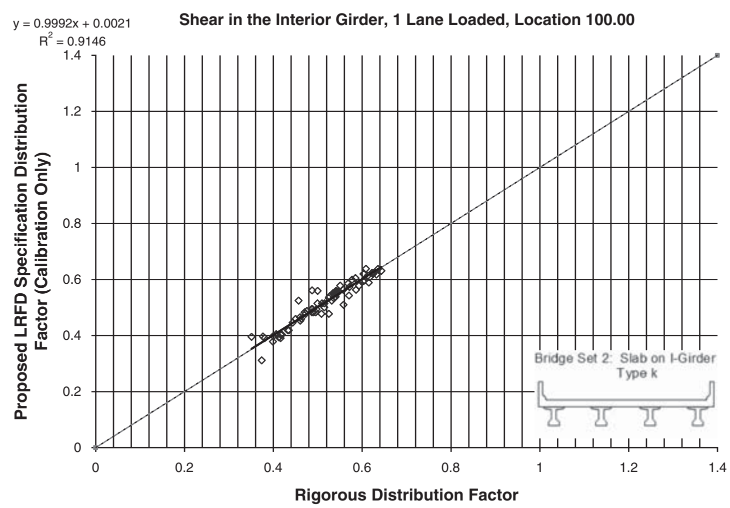
Bridge Set 2 - Slab on Concrete I-Girders, Type k				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.378	1.307	0.999	0.998
Standard Deviation	0.403	0.312	0.293	0.043
Coefficient of Variation	0.292	0.239	0.293	0.043
Count	67	69	15	69

c.

Figure 22. Shear, multiple lanes, exterior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

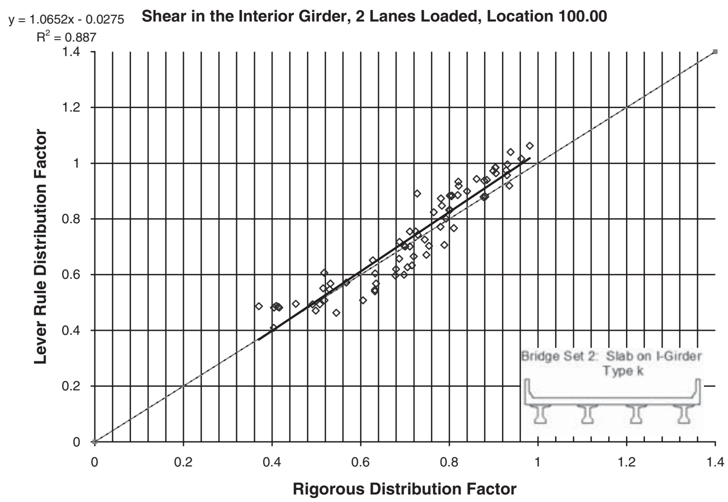


b.

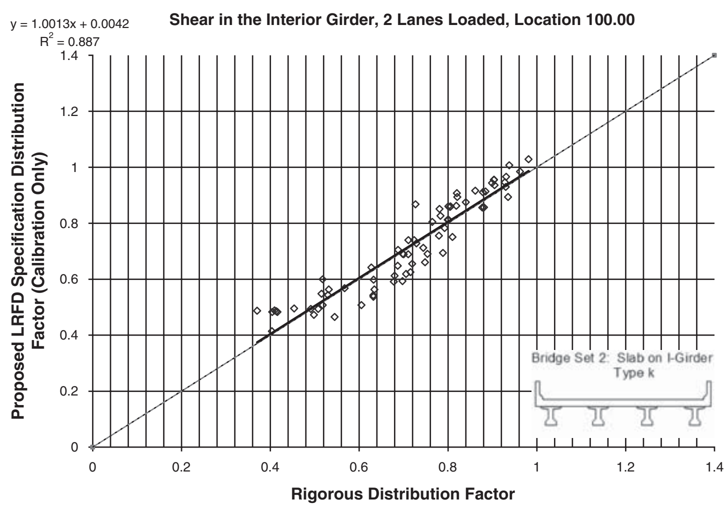
Bridge Set 2 - Slab on Concrete I-Girders, Type k				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.314	1.296	0.999	1.003
Standard Deviation	0.135	0.094	0.085	0.048
Coefficient of Variation	0.103	0.072	0.085	0.048
Count	73	73	73	73

c.

Figure 23. Shear, one lane, interior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

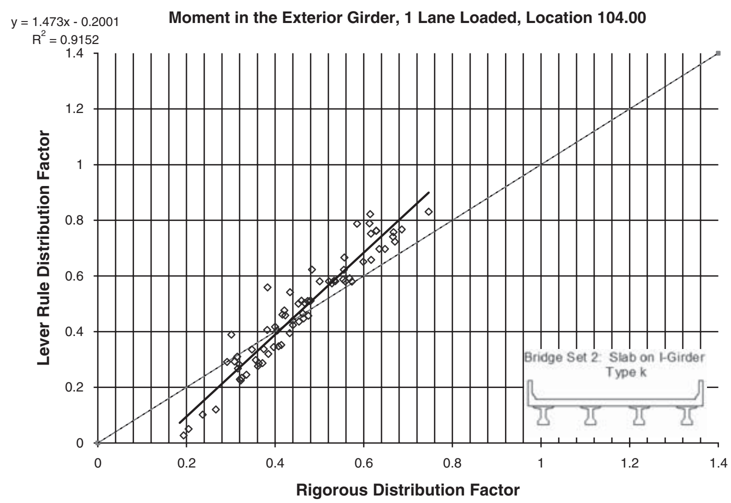


b.

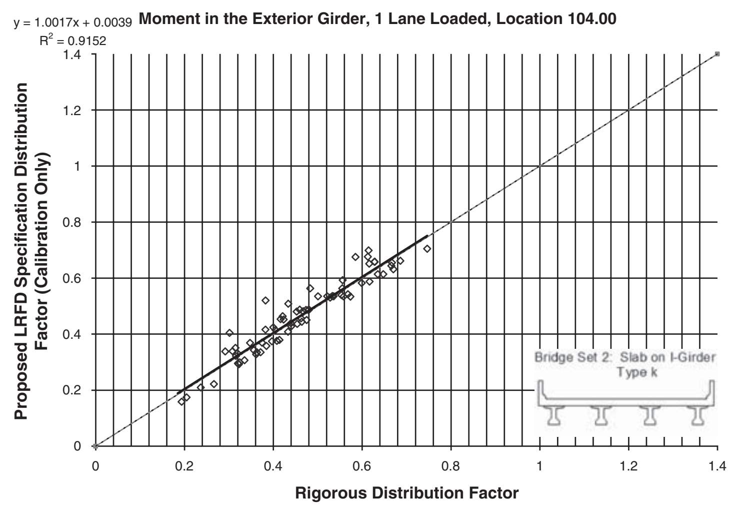
Bridge Set 2 - Slab on Concrete I-Girders, Type k				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	0.968	1.134	1.004	1.011
Standard Deviation	0.111	0.154	0.092	0.094
Coefficient of Variation	0.115	0.136	0.092	0.093
Count	73	73	15	73

c.

Figure 24. Shear, multiple lanes, interior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

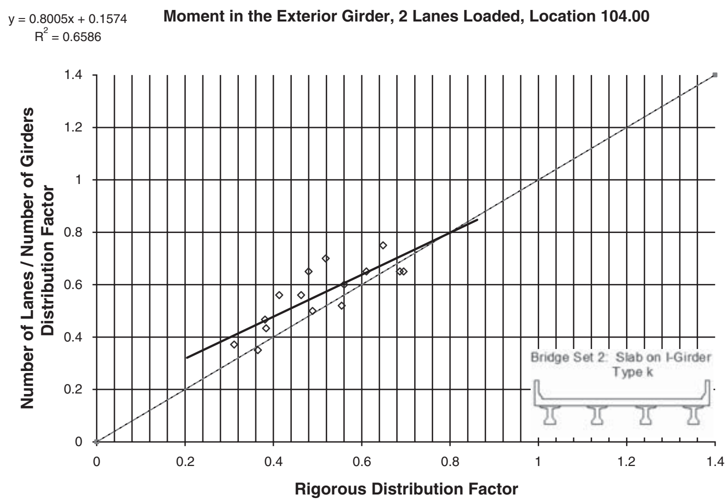


b.

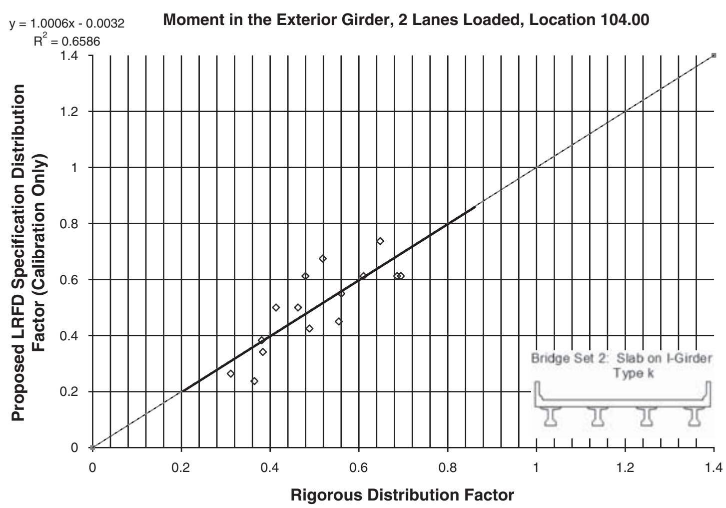
Bridge Set 2 - Slab on Concrete I-Girders, Type k					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.515	1.348	1.014	1.008	1.004
Standard Deviation	0.367	0.178	0.271	0.098	0.509
Coefficient of Variation	0.242	0.132	0.268	0.097	0.507
Count	70	73	73	72	73

c.

Figure 25. Moment, one lane, exterior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

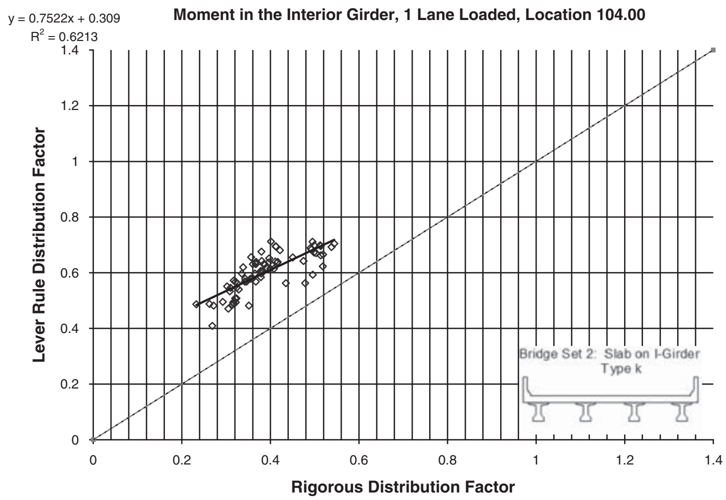


b.

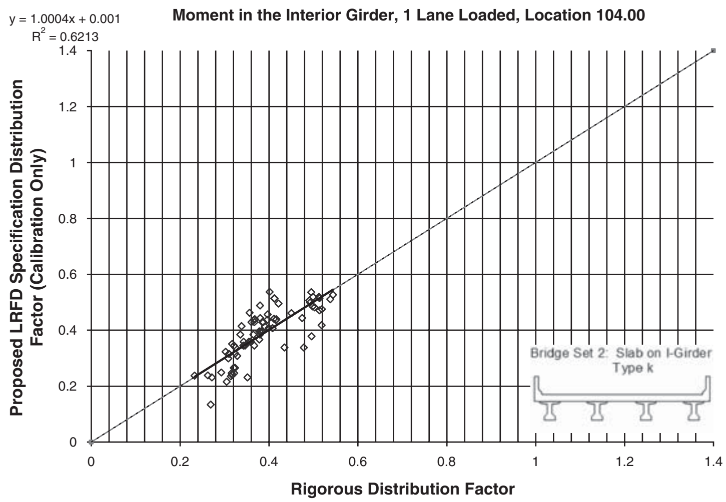
Bridge Set 2 - Slab on Concrete I-Girders, Type k					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.283	1.208	0.990	1.000	1.027
Standard Deviation	0.380	0.267	0.183	0.098	0.721
Coefficient of Variation	0.296	0.221	0.185	0.098	0.702
Count	71	73	15	72	73

c.

Figure 26. Moment, multiple lanes, exterior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

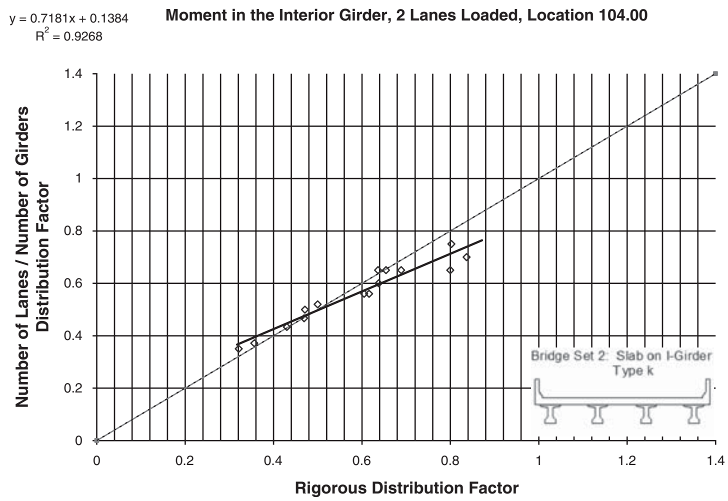


b.

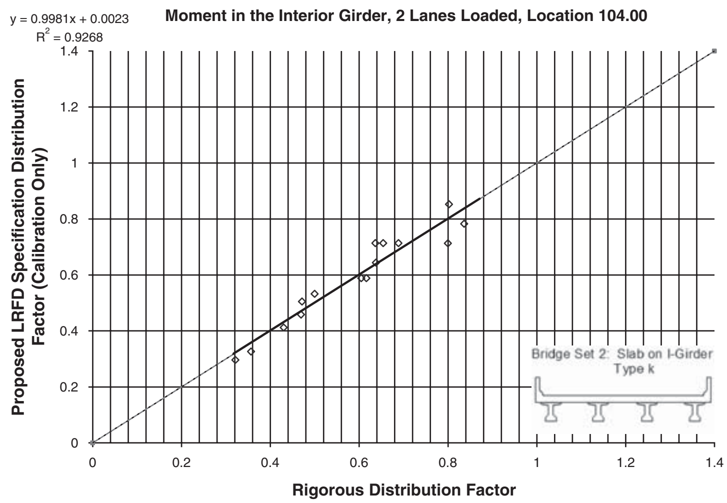
Bridge Set 2 - Slab on Concrete I-Girders, Type k					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.773	1.292	0.990	1.000	0.993
Standard Deviation	0.245	0.108	0.206	0.160	0.071
Coefficient of Variation	0.138	0.083	0.208	0.160	0.071
Count	73	73	73	73	73

c.

Figure 27. Moment, one lane, interior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



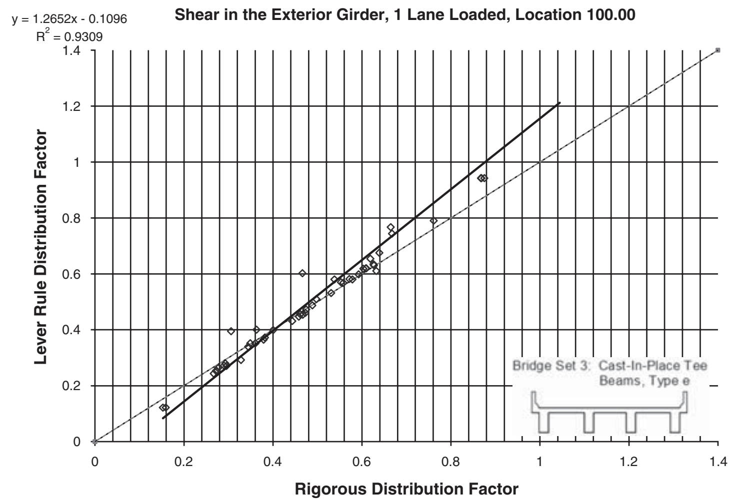
b.

Bridge Set 2 - Slab on Concrete I-Girders, Type k

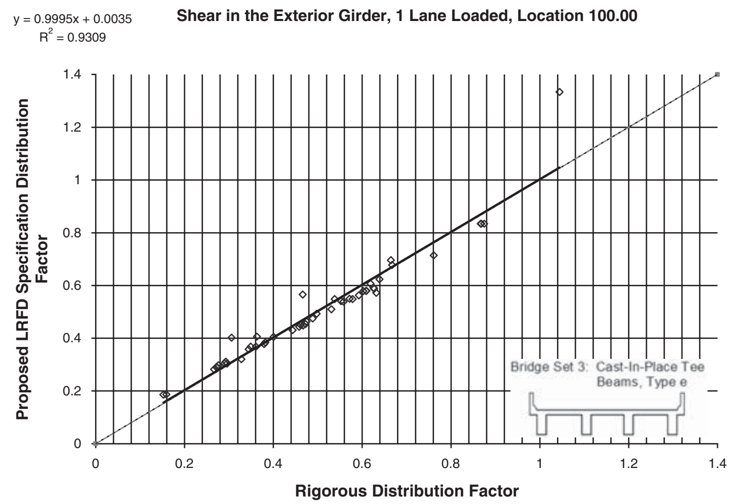
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.115	1.109	0.999	1.001	1.000
Standard Deviation	0.119	0.115	0.072	0.110	0.132
Coefficient of Variation	0.107	0.104	0.072	0.110	0.132
Count	73	73	15	73	73

c.

Figure 28. Moment, multiple lanes, interior, slab-on-concrete I-girder. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

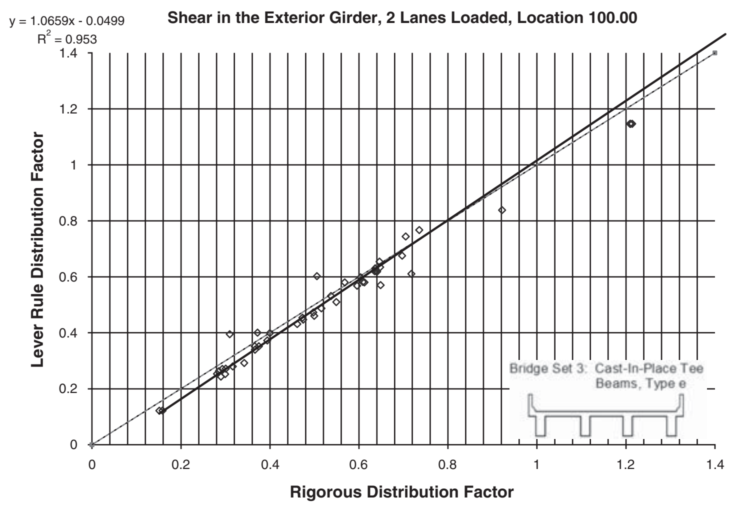


b.

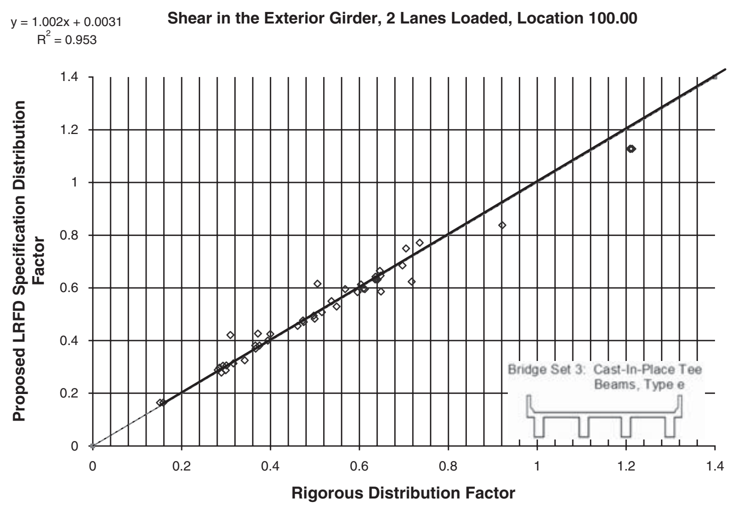
Bridge Set 3 - Cast-in-Place Tee Beams, Type e				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.191	1.415	1.021	1.018
Standard Deviation	0.362	0.289	0.206	0.089
Coefficient of Variation	0.304	0.204	0.202	0.087
Count	49	49	49	49

c.

Figure 29. Shear, one lane, exterior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

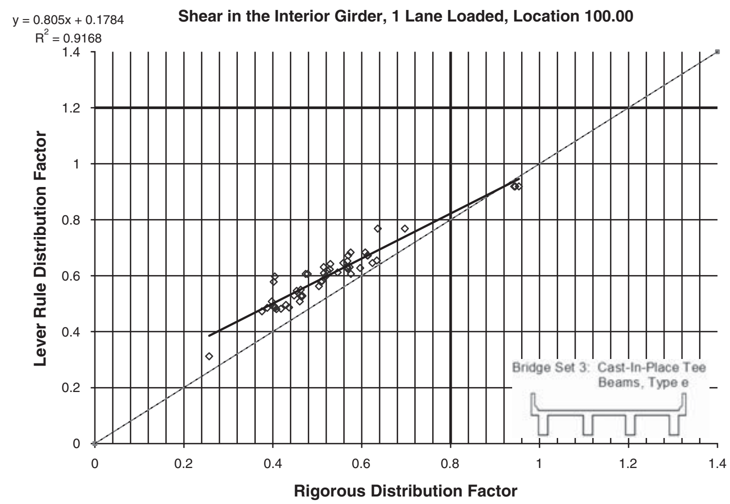


b.

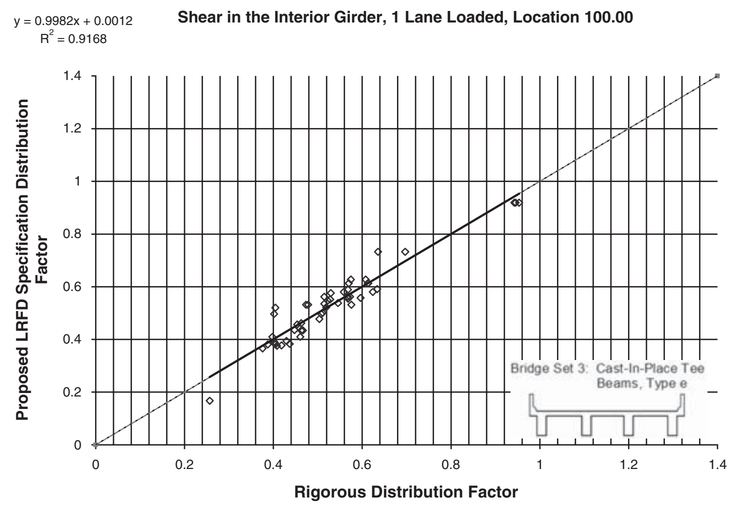
Bridge Set 3 - Cast-in-Place Tee Beams, Type e				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.396	1.337	1.007	1.015
Standard Deviation	0.415	0.334	0.162	0.084
Coefficient of Variation	0.297	0.250	0.161	0.083
Count	46	47	20	47

c.

Figure 30. Shear, multiple lanes, exterior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

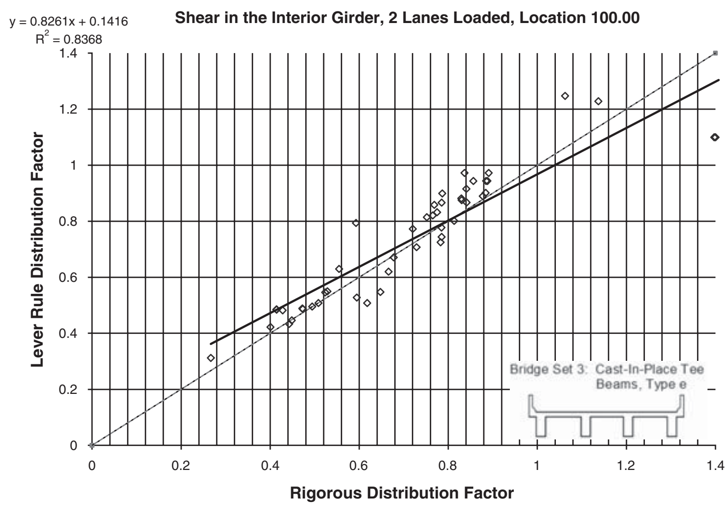


b.

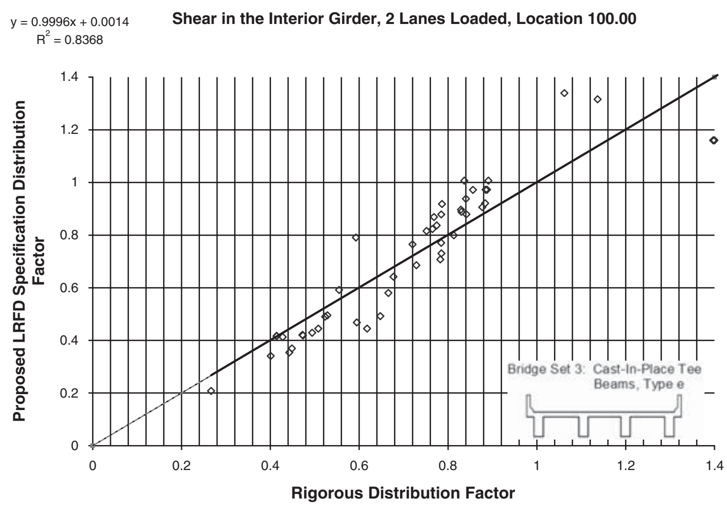
Bridge Set 3 - Cast-in-Place Tee Beams, Type e				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.013	1.312	0.991	0.998
Standard Deviation	0.106	0.119	0.148	0.096
Coefficient of Variation	0.105	0.091	0.150	0.096
Count	50	50	50	50

c.

Figure 31. Shear, one lane, interior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

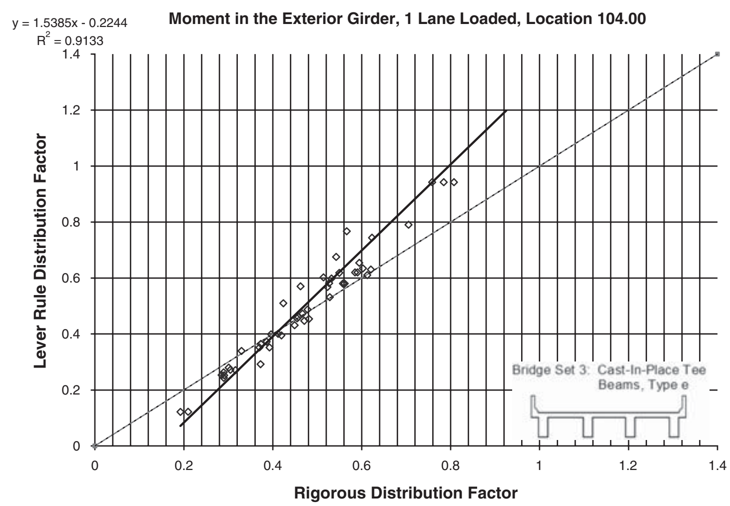


b.

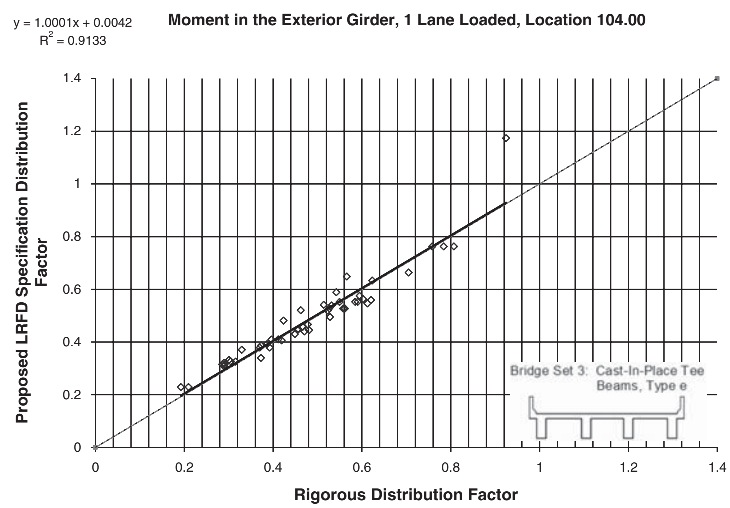
Bridge Set 3 - Cast-in-Place Tee Beams, Type e				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	0.960	1.134	1.004	0.990
Standard Deviation	0.104	0.178	0.105	0.141
Coefficient of Variation	0.108	0.157	0.105	0.142
Count	48	48	20	48

c.

Figure 32. Shear, multiple lanes, interior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

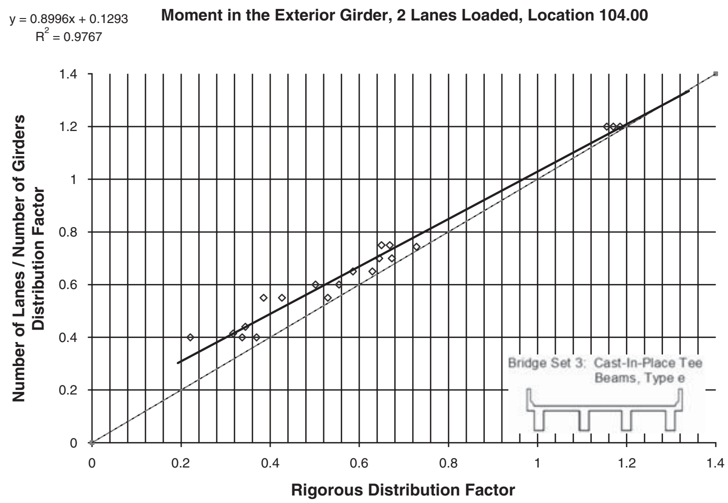


b.

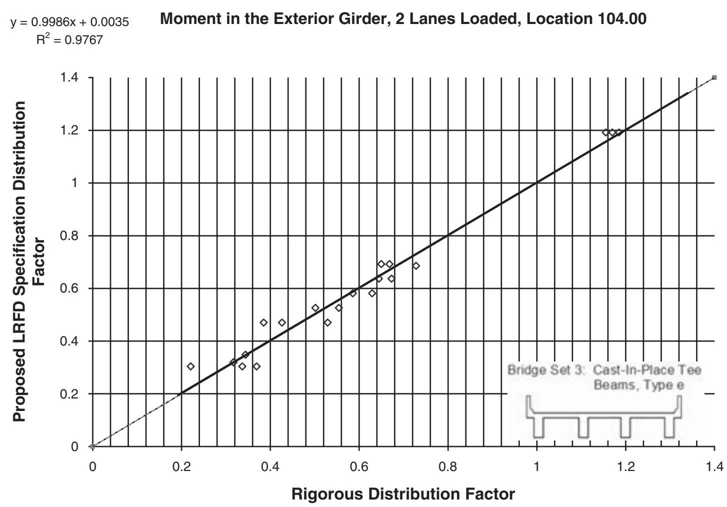
Bridge Set 3 - Cast-in-Place Tee Beams, Type e					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.175	1.415	1.002	1.016	1.036
Standard Deviation	0.247	0.207	0.170	0.081	0.565
Coefficient of Variation	0.210	0.147	0.170	0.080	0.546
Count	49	48	49	49	49

c.

Figure 33. Moment, one lane, exterior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



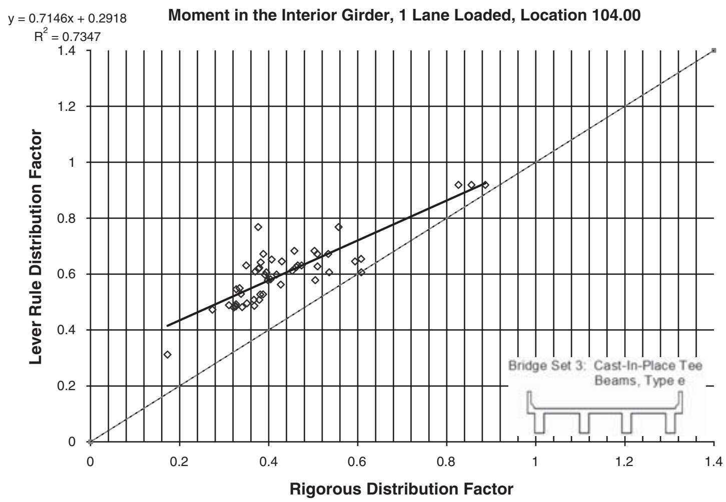
b.

Bridge Set 3 - Cast-in-Place Tee Beams, Type e

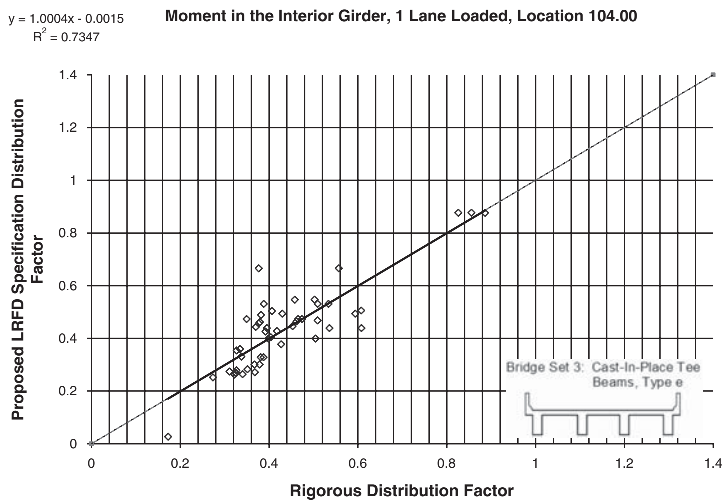
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.291	1.241	1.014	1.005	0.938
Standard Deviation	0.325	0.198	0.120	0.079	0.675
Coefficient of Variation	0.252	0.160	0.119	0.078	0.720
Count	47	46	20	47	45

c.

Figure 34. Moment, multiple lanes, exterior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

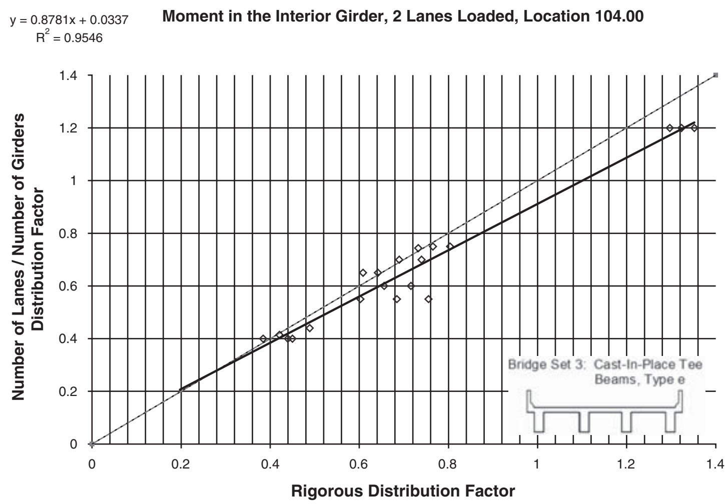


b.

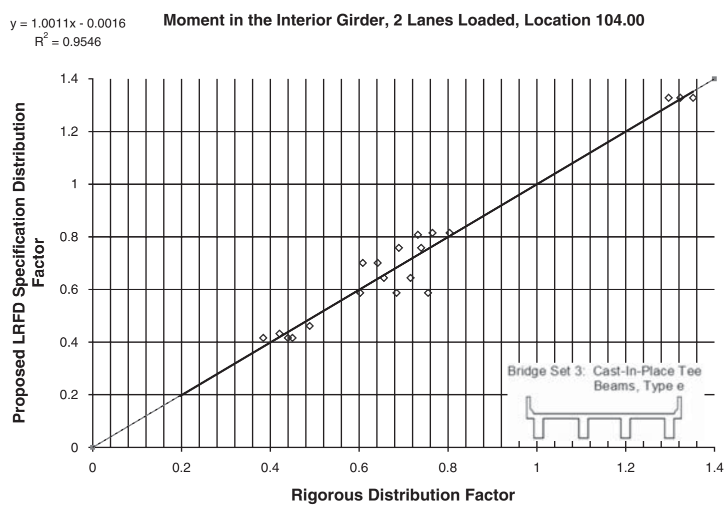
Bridge Set 3 - Cast-in-Place Tee Beams, Type e					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.251	1.264	1.012	0.989	1.004
Standard Deviation	0.211	0.168	0.306	0.231	0.272
Coefficient of Variation	0.169	0.133	0.303	0.233	0.271
Count	50	49	50	50	50

c.

Figure 35. Moment, one lane, interior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

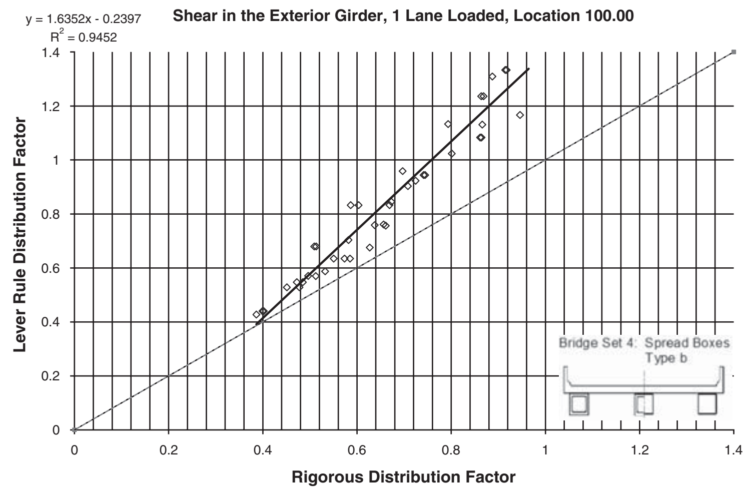


b.

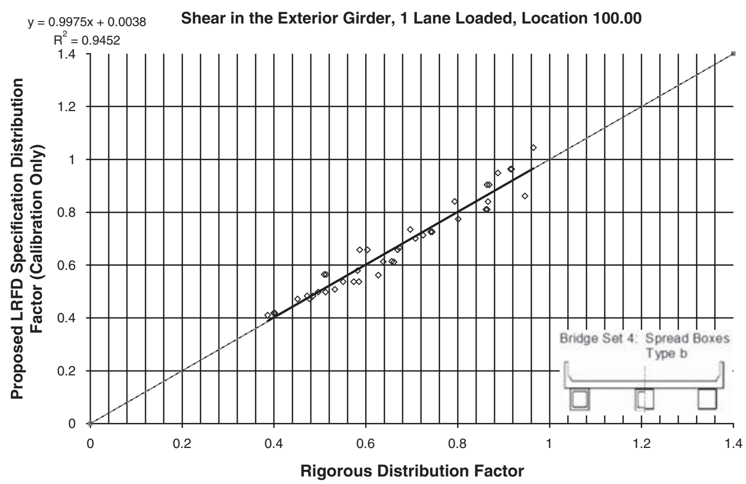
Bridge Set 3 - Cast-in-Place Tee Beams, Type e					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.050	1.074	0.999	0.989	1.003
Standard Deviation	0.145	0.135	0.091	0.235	0.276
Coefficient of Variation	0.138	0.125	0.091	0.238	0.275
Count	48	47	20	48	48

c.

Figure 36. Moment, multiple lanes, interior, cast-in-place tee beam. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

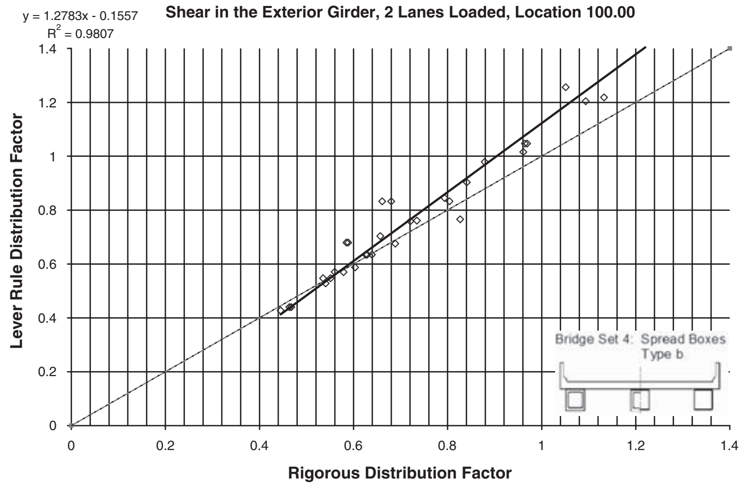


b.

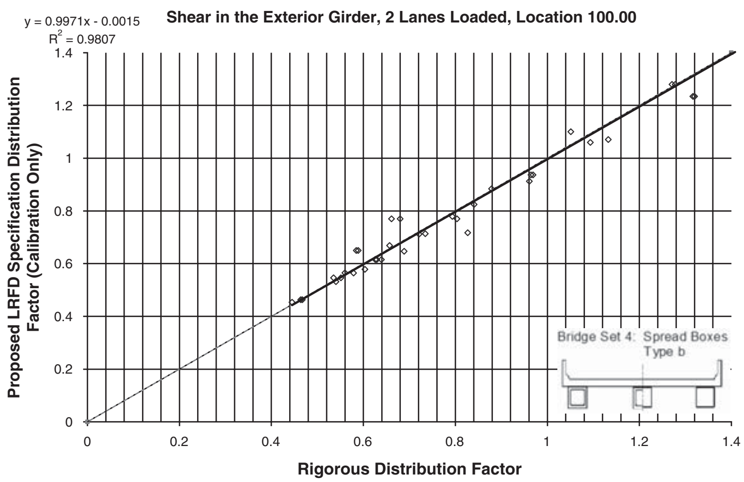
Bridge Set 4 - Spread Concrete Box Girders, Type b				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.138	1.516	1.003	1.005
Standard Deviation	0.260	0.147	0.103	0.059
Coefficient of Variation	0.229	0.097	0.103	0.058
Count	60	41	41	41

c.

Figure 37. Shear, one lane, exterior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

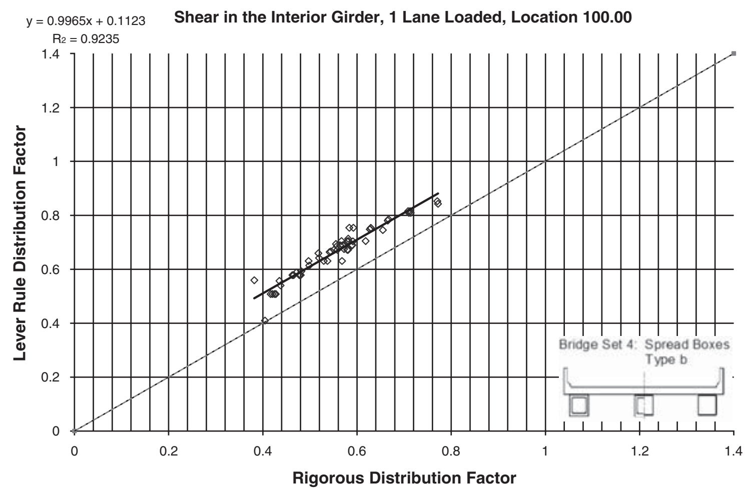


b.

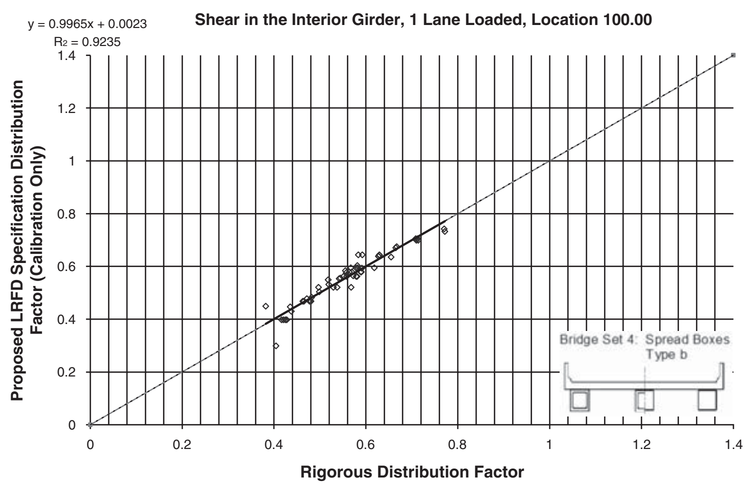
Bridge Set 4 - Spread Concrete Box Girders, Type b				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.122	1.236	0.989	0.998
Standard Deviation	0.232	0.097	0.032	0.058
Coefficient of Variation	0.206	0.079	0.032	0.058
Count	60	40	7	40

c.

Figure 38. Shear, multiple lanes, exterior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

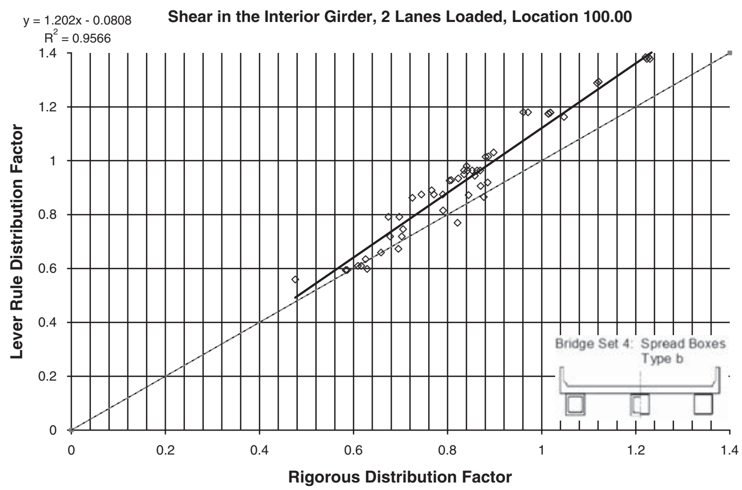


b.

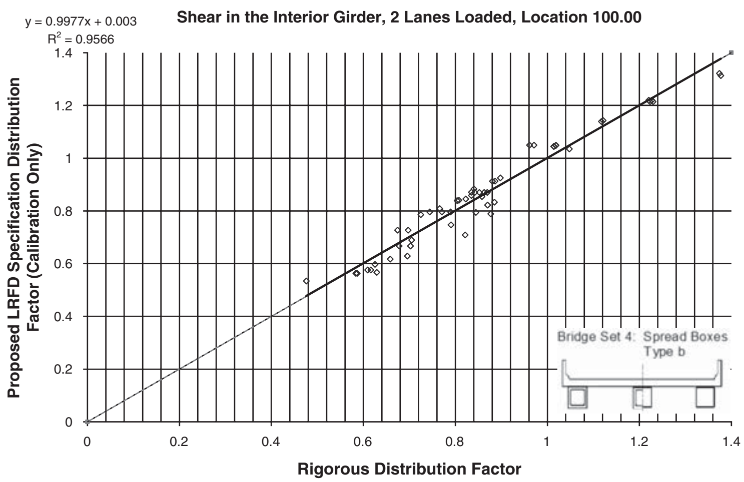
Bridge Set 4 - Spread Concrete Box Girders, Type b				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.136	1.308	0.999	1.000
Standard Deviation	0.111	0.086	0.082	0.056
Coefficient of Variation	0.097	0.066	0.082	0.056
Count	60	55	55	55

c.

Figure 39. Shear, one lane, interior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



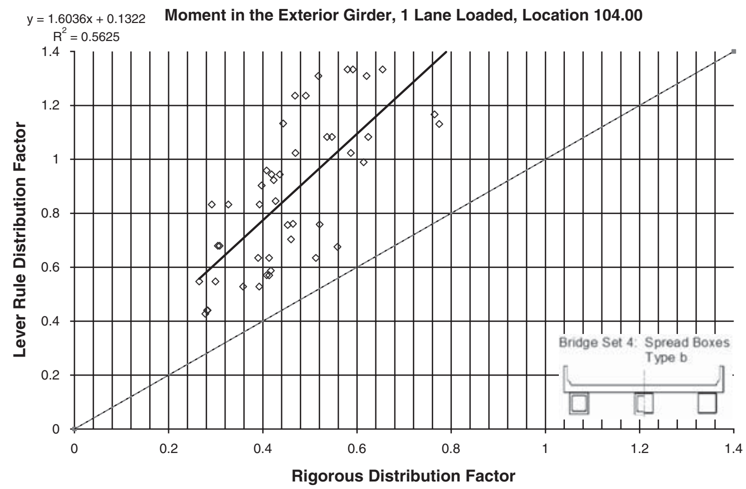
b.

Bridge Set 4 - Spread Concrete Box Girders, Type b

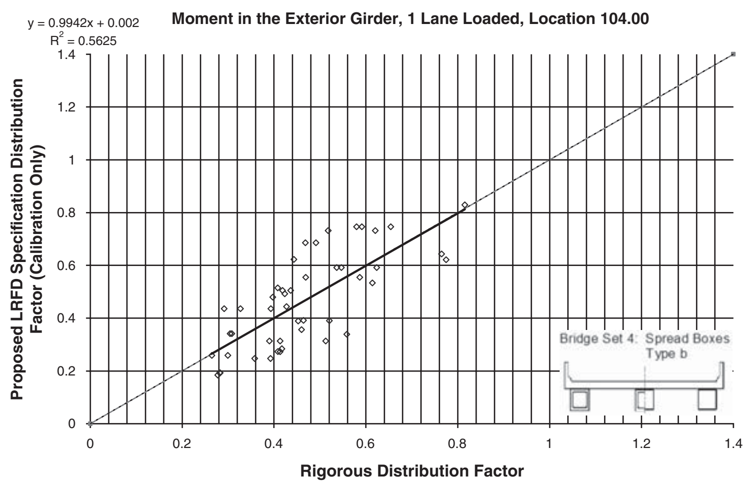
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.030	1.073	0.997	1.001
Standard Deviation	0.121	0.072	0.118	0.054
Coefficient of Variation	0.118	0.067	0.118	0.054
Count	60	54	11	54

c.

Figure 40. Shear, multiple lanes, interior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

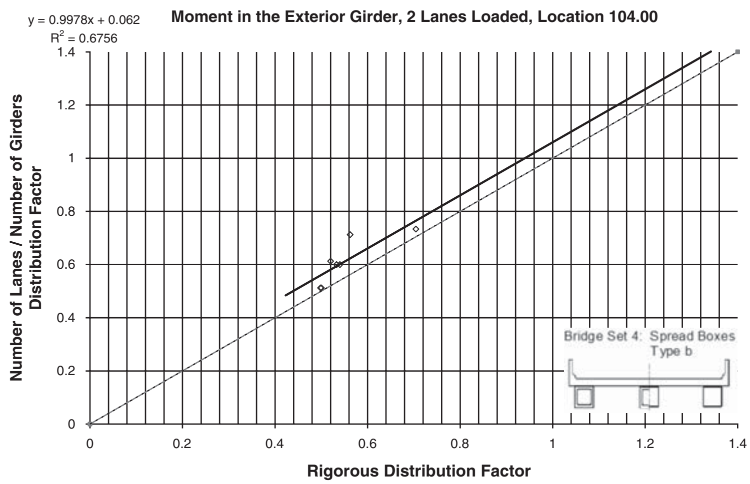


b.

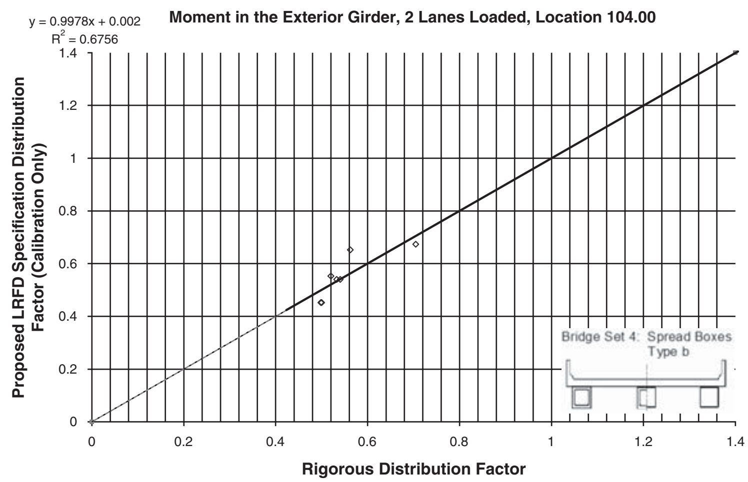
Bridge Set 4 - Spread Concrete Box Girders, Type b					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.564	2.181	0.998	0.995	0.982
Standard Deviation	0.500	0.405	0.183	0.262	0.212
Coefficient of Variation	0.320	0.186	0.184	0.264	0.216
Count	60	40	46	46	46

c.

Figure 41. Moment, one lane, exterior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

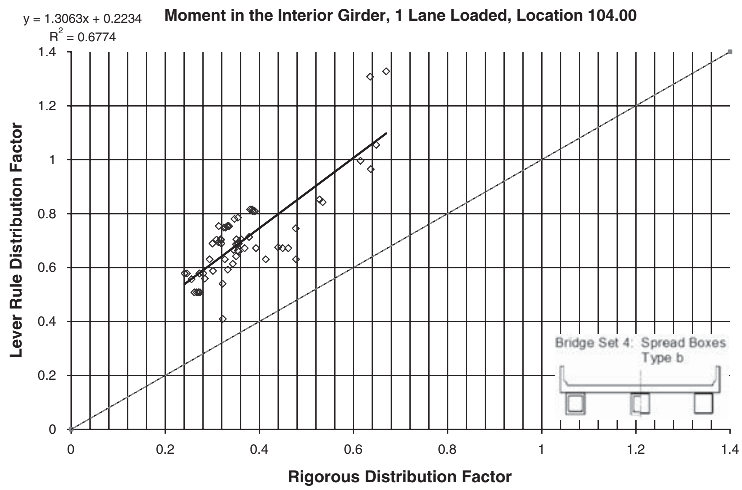


b.

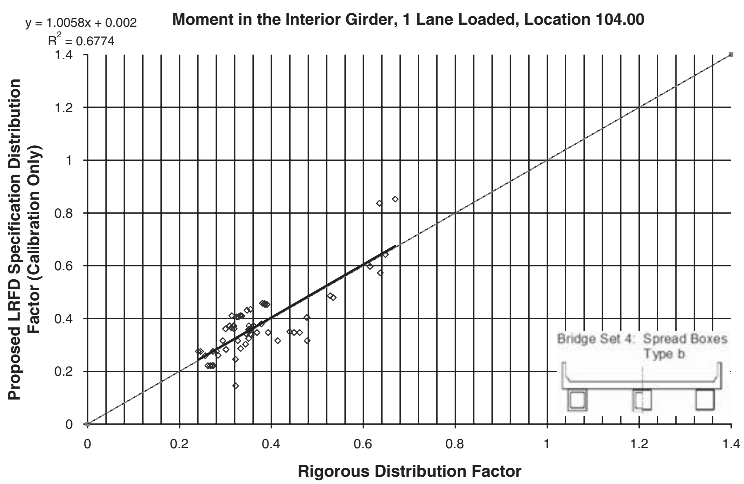
Bridge Set 4 - Spread Concrete Box Girders, Type b					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.285	1.395	1.001	0.994	0.985
Standard Deviation	0.279	0.262	0.091	0.136	0.462
Coefficient of Variation	0.218	0.188	0.091	0.137	0.469
Count	60	40	7	40	40

c.

Figure 42. Moment, multiple lanes, exterior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

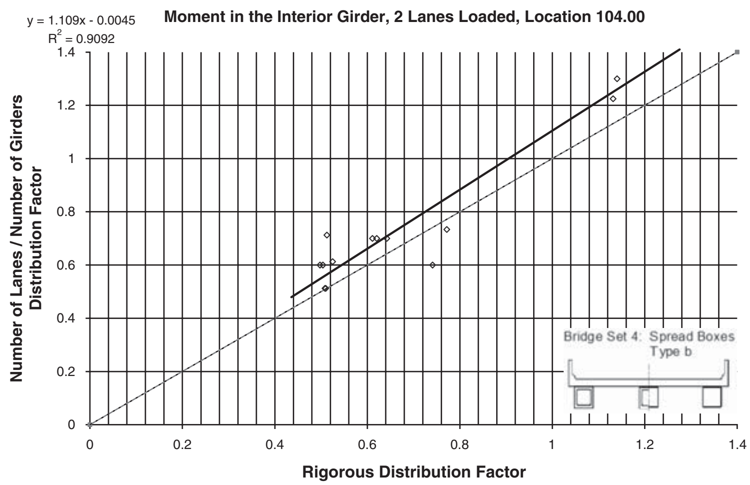


b.

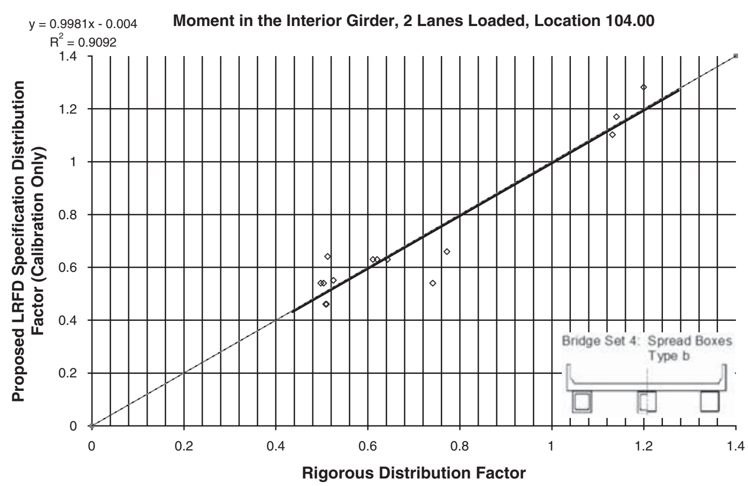
Bridge Set 4 - Spread Concrete Box Girders, Type b					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.853	1.609	1.007	1.014	0.994
Standard Deviation	0.311	0.615	0.355	0.181	0.212
Coefficient of Variation	0.168	0.382	0.352	0.179	0.214
Count	60	60	60	60	60

c.

Figure 43. Moment, one lane, interior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

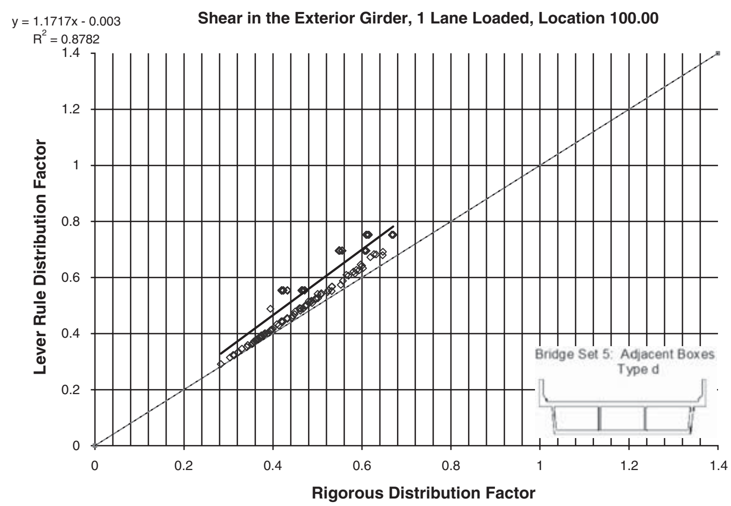


b.

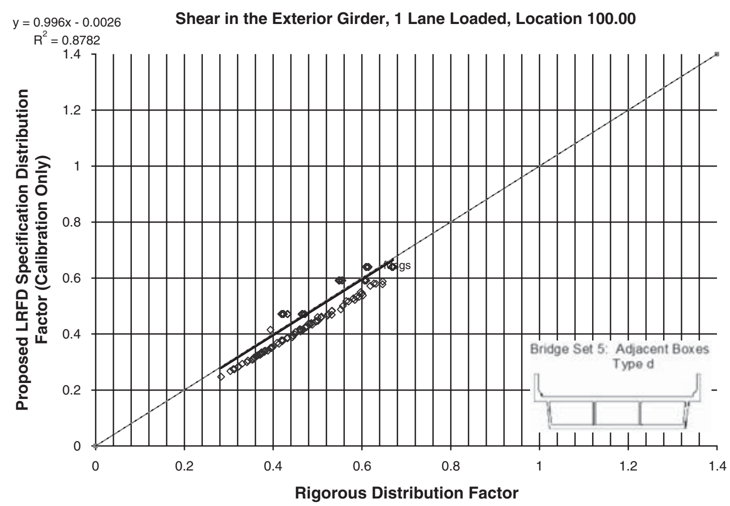
Bridge Set 4 - Spread Concrete Box Girders, Type b					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.423	1.259	0.997	0.990	0.992
Standard Deviation	0.276	0.301	0.123	0.241	0.262
Coefficient of Variation	0.194	0.239	0.124	0.244	0.264
Count	60	59	14	59	59

c.

Figure 44. Moment, multiple lanes, interior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

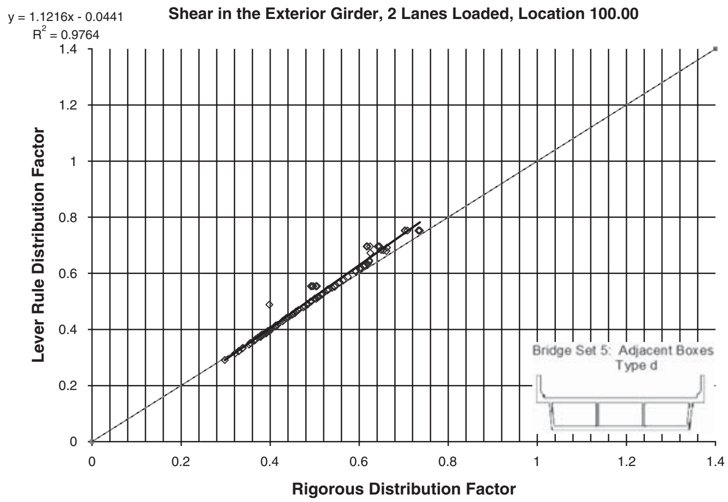


b.

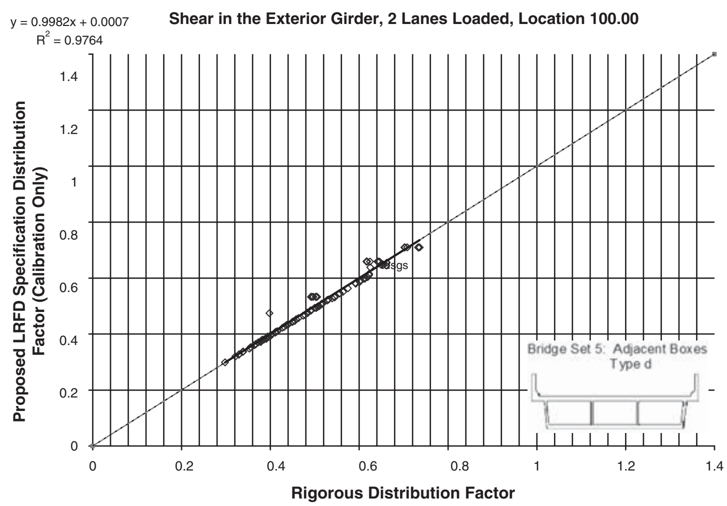
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.274	1.425	1.001	0.990
Standard Deviation	0.215	0.109	0.140	0.077
Coefficient of Variation	0.169	0.076	0.140	0.078
Count	80	272	272	272

c.

Figure 45. Shear, one lane, exterior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

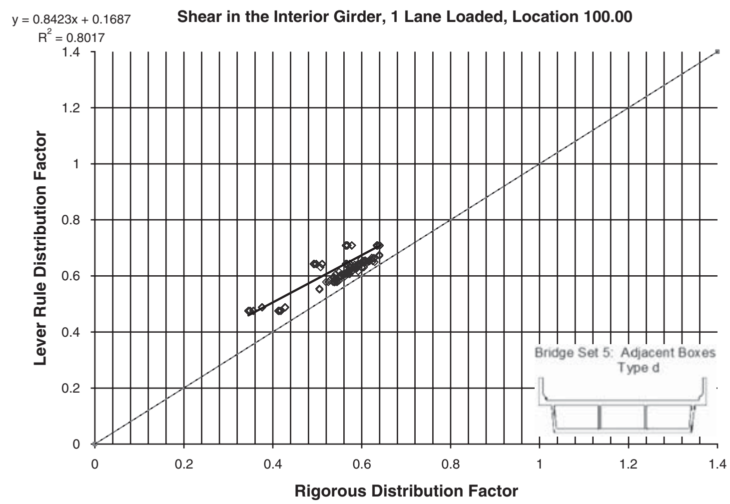


b.

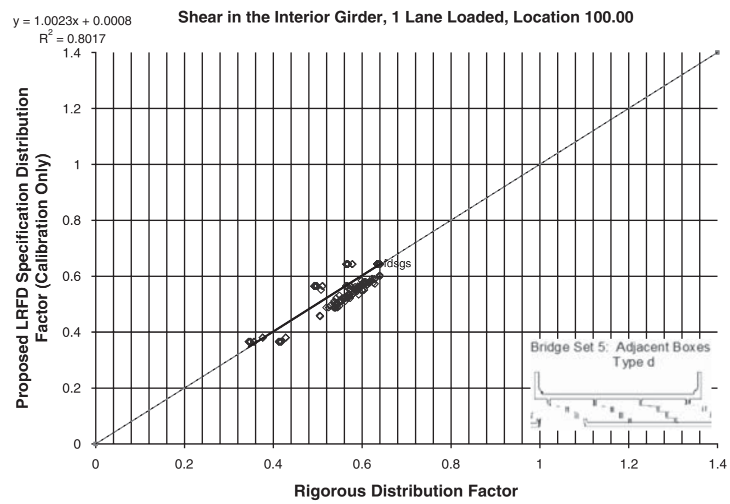
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.556	1.348	1.005	1.000
Standard Deviation	0.254	0.193	0.100	0.034
Coefficient of Variation	0.163	0.143	0.099	0.034
Count	80	104	31	104

c.

Figure 46. Shear, multiple lanes, exterior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

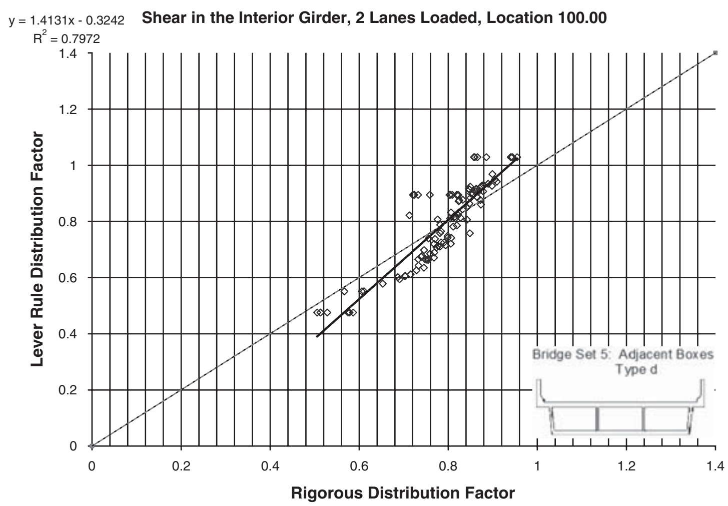


b.

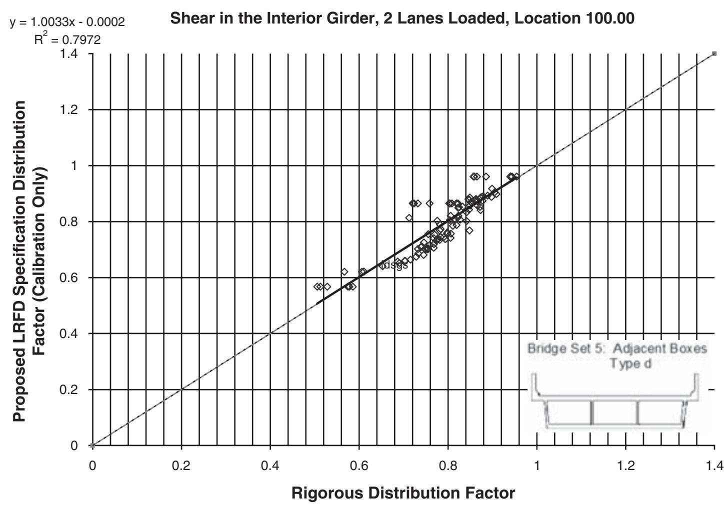
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	0.975	1.290	1.003	1.004
Standard Deviation	0.034	0.147	0.146	0.086
Coefficient of Variation	0.034	0.114	0.146	0.086
Count	80	272	272	272

c.

Figure 47. Shear, one lane, interior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

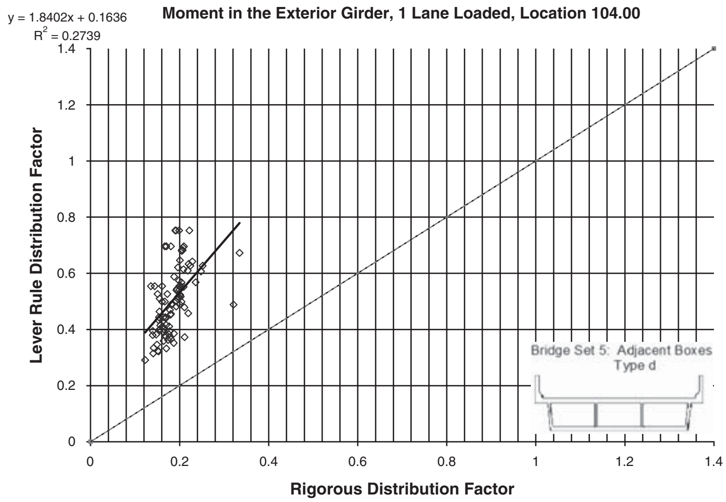


b.

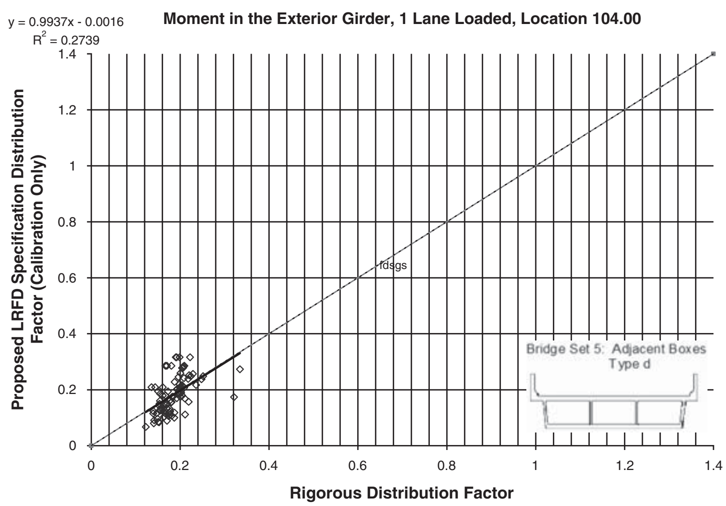
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	0.893	1.015	0.998	1.004
Standard Deviation	0.031	0.064	0.084	0.063
Coefficient of Variation	0.035	0.063	0.085	0.063
Count	80	104	31	104

c.

Figure 48. Shear, multiple lanes, interior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

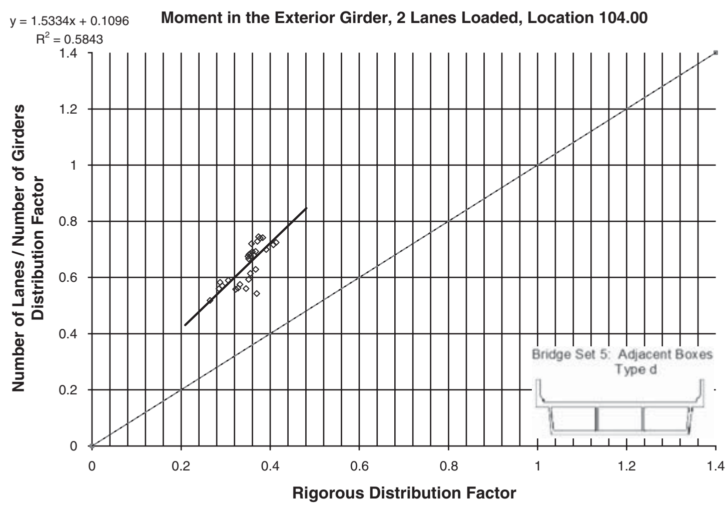


b.

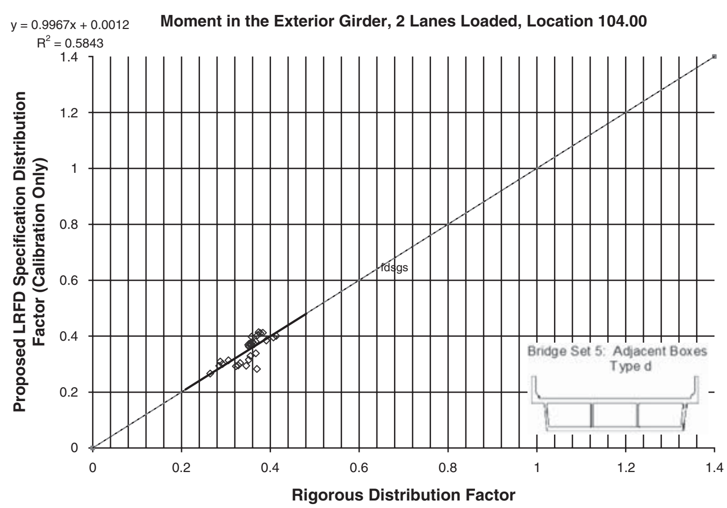
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.683	2.660	0.977	0.980	1.007
Standard Deviation	0.953	0.291	0.504	0.298	0.159
Coefficient of Variation	0.566	0.109	0.516	0.304	0.158
Count	80	38	92	92	92

c.

Figure 49. Moment, one lane, exterior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

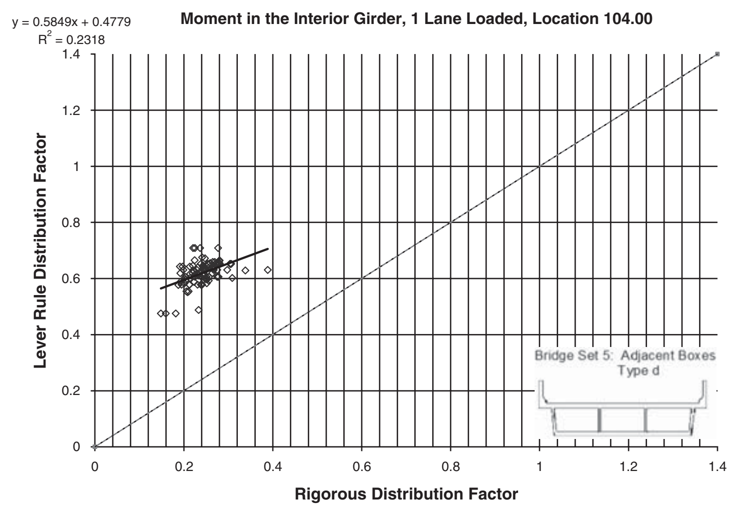


b.

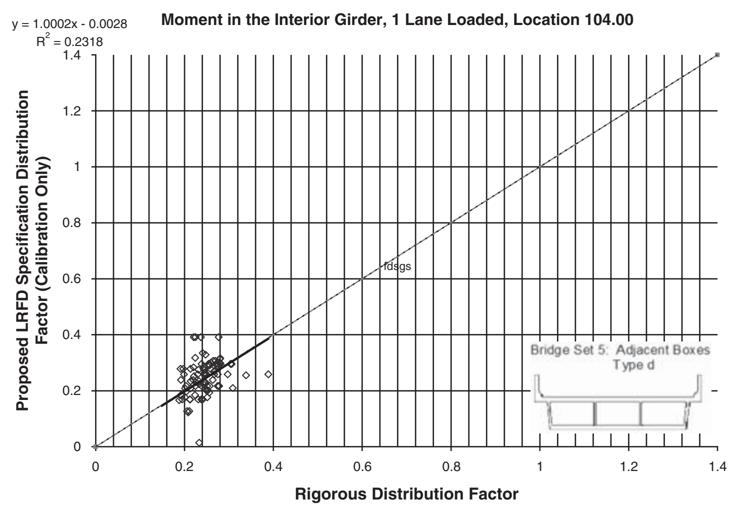
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.240	2.086	1.000	1.003	1.016
Standard Deviation	0.347	0.237	0.084	0.208	0.133
Coefficient of Variation	0.155	0.114	0.084	0.207	0.130
Count	80	92	29	92	92

c.

Figure 50. Moment, multiple lanes, exterior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

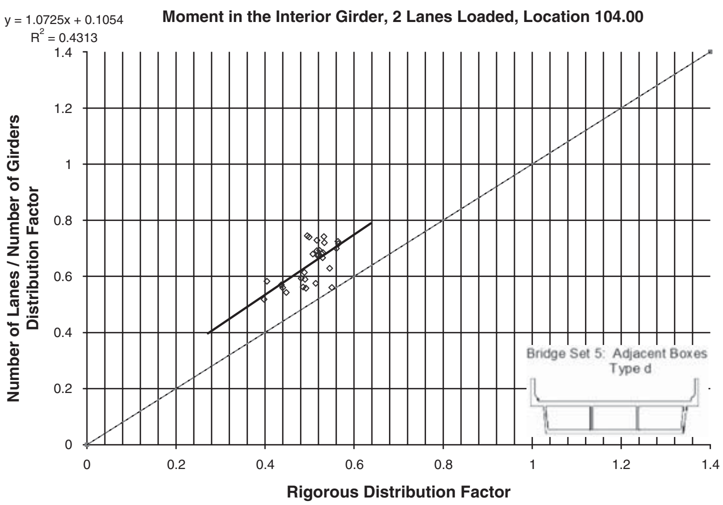


b.

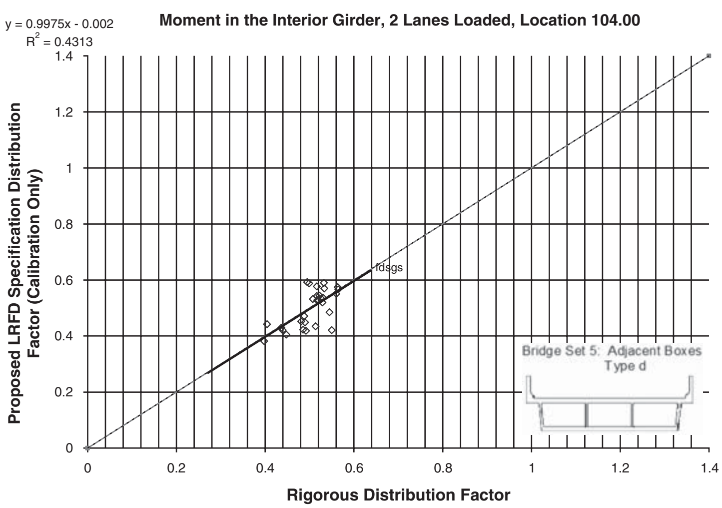
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.299	1.605	0.762	0.983	0.978
Standard Deviation	0.262	0.209	1.075	0.316	0.074
Coefficient of Variation	0.114	0.130	1.411	0.321	0.075
Count	80	86	86	92	92

c.

Figure 51. Moment, one lane, interior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

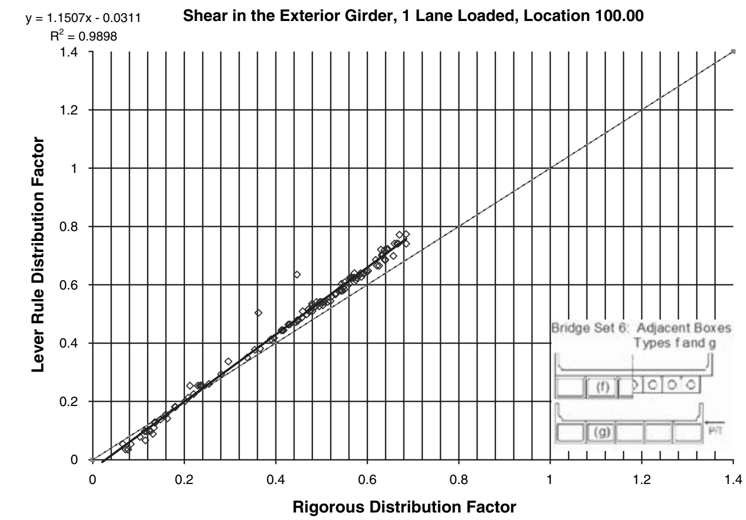


b.

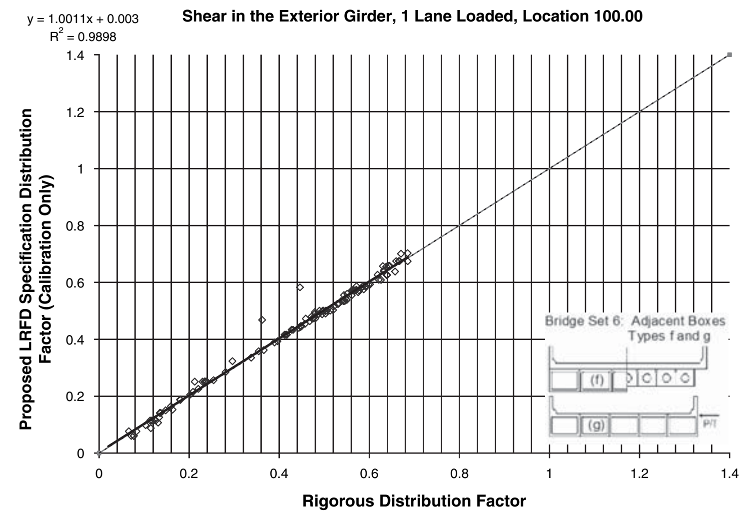
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.591	1.299	0.993	0.999	1.001
Standard Deviation	0.180	0.118	0.098	0.233	0.069
Coefficient of Variation	0.113	0.091	0.099	0.233	0.069
Count	80	92	29	92	92

c.

Figure 52. Moment, multiple lanes, interior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

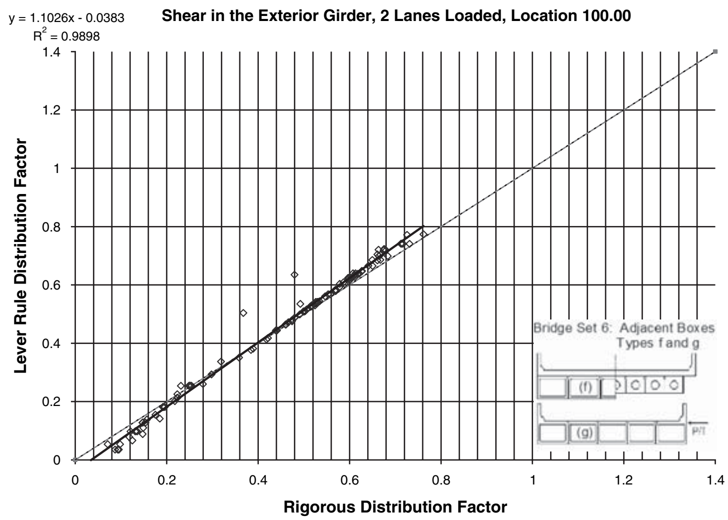


b.

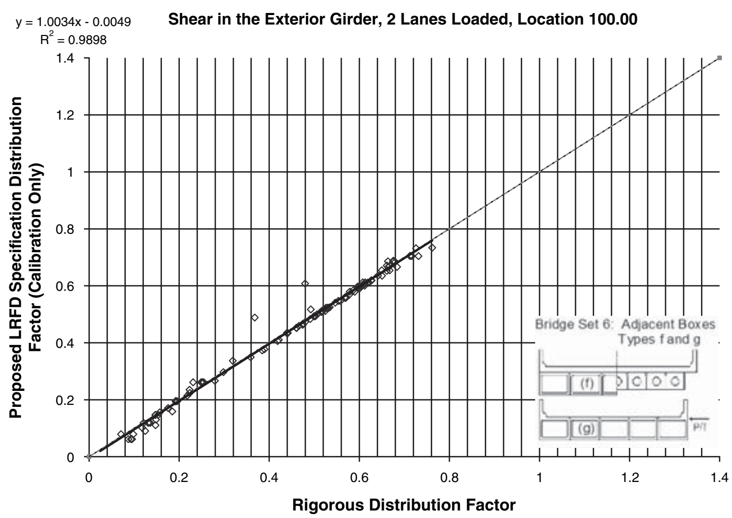
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.320	1.481	0.985	1.005
Standard Deviation	0.461	0.381	0.448	0.067
Coefficient of Variation	0.349	0.257	0.455	0.067
Count	117	118	145	122

c.

Figure 53. Shear, one lane, exterior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

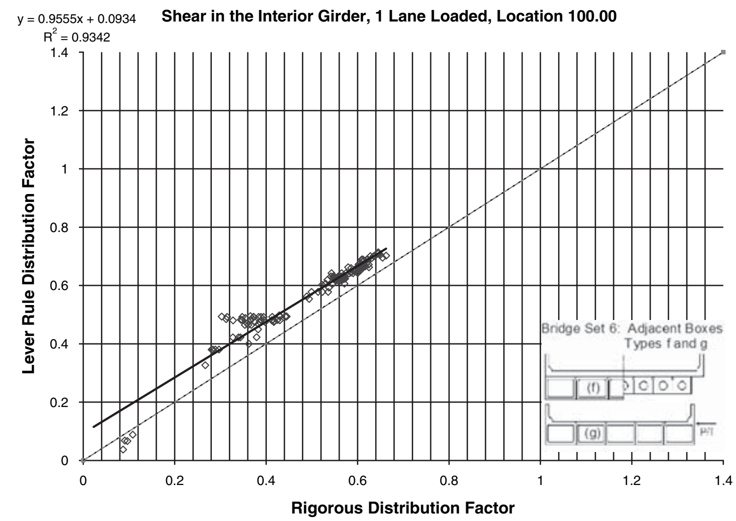


b.

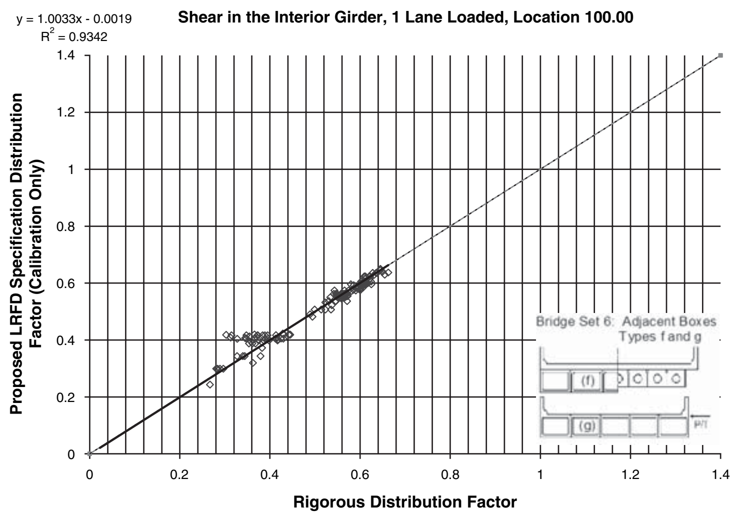
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	1.522	1.482	1.086	0.982
Standard Deviation	0.447	0.459	0.389	0.081
Coefficient of Variation	0.294	0.310	0.358	0.083
Count	113	116	30	122

c.

Figure 54. Shear, multiple lanes, exterior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

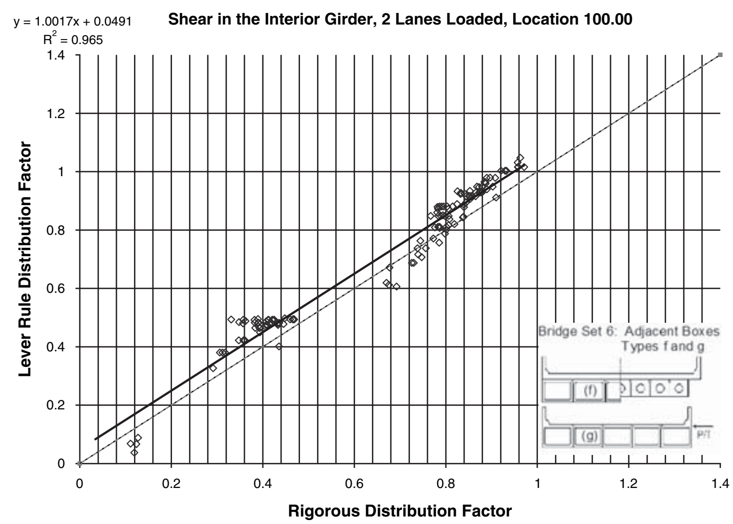


b.

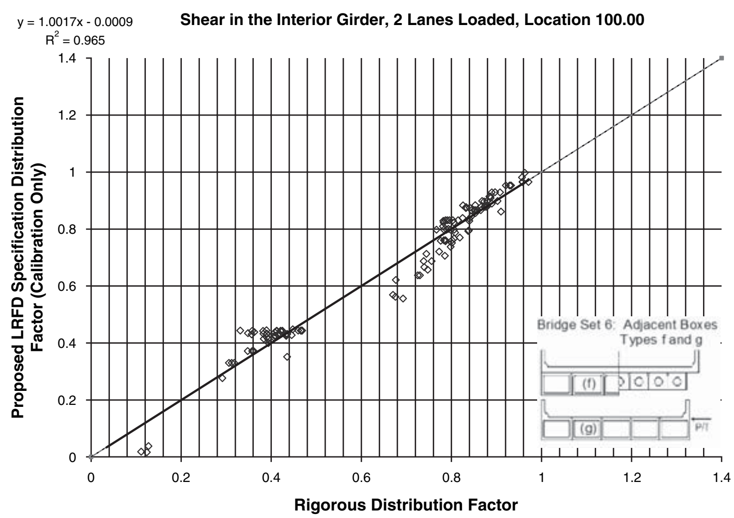
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	0.947	1.337	0.986	0.975
Standard Deviation	0.227	0.164	0.243	0.245
Coefficient of Variation	0.239	0.123	0.247	0.251
Count	136	137	137	137

c.

Figure 55. Shear, one lane, interior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

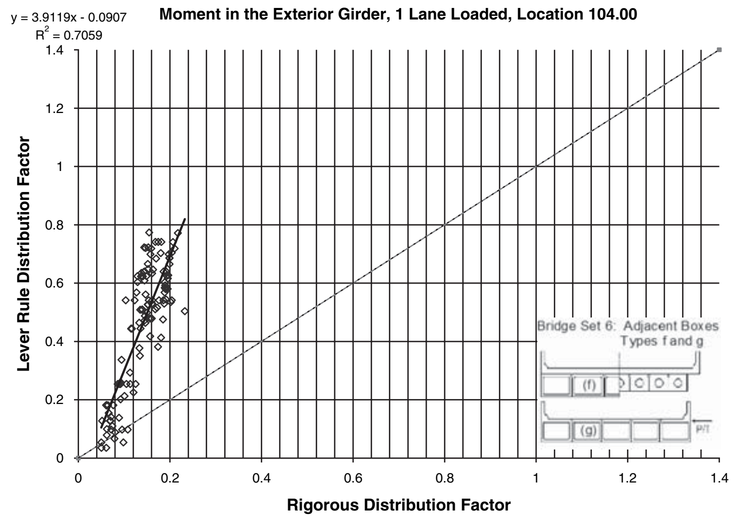


b.

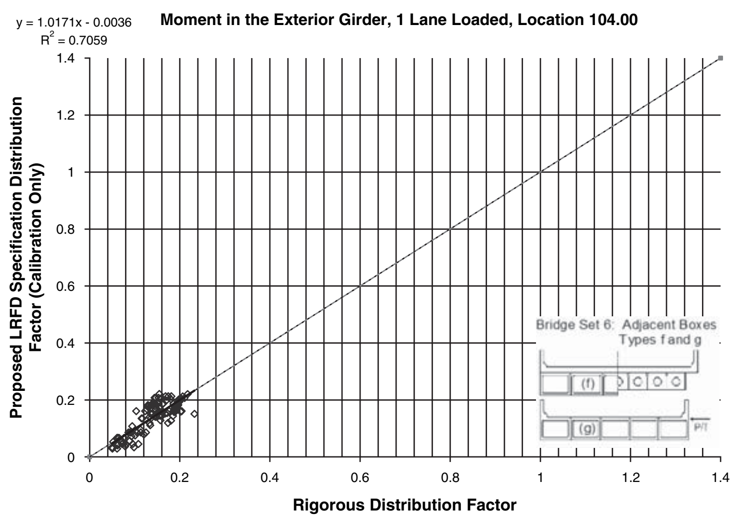
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g				
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule
Average (Simplified/Rigorous)	0.938	1.079	1.035	0.987
Standard Deviation	0.193	0.122	0.342	0.172
Coefficient of Variation	0.206	0.113	0.331	0.174
Count	132	133	28	134

c.

Figure 56. Shear, multiple lanes, interior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

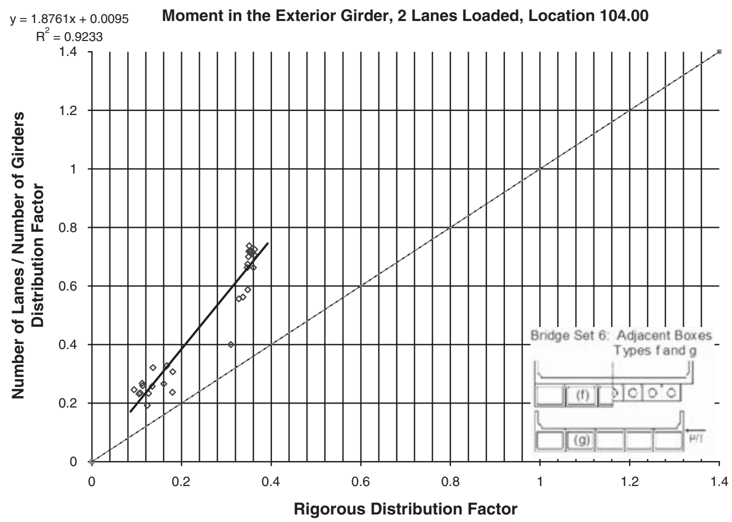


b.

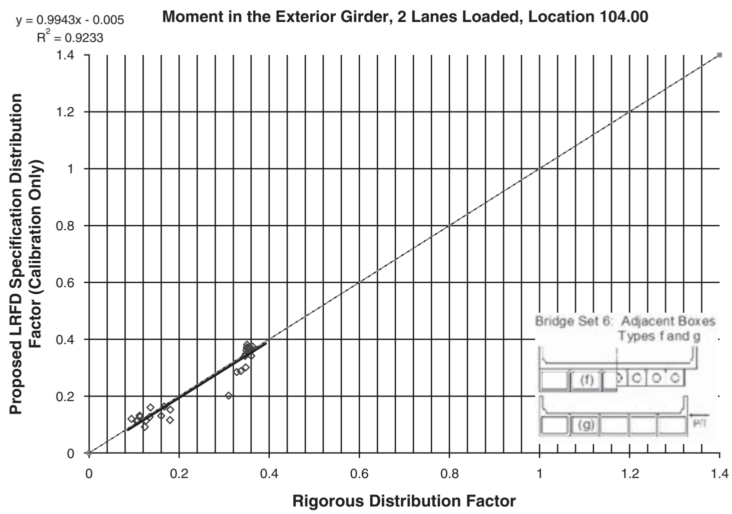
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.512	2.689	0.947	0.975	0.978
Standard Deviation	0.449	0.195	0.378	0.239	0.267
Coefficient of Variation	0.179	0.072	0.400	0.245	0.273
Count	27	16	144	121	144

c.

Figure 57. Moment, one lane, exterior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



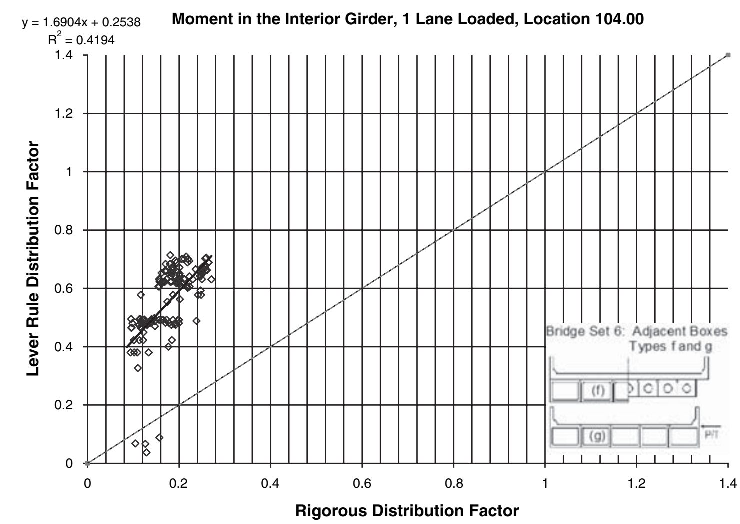
b.

Bridge Set 6 - Adjacent Concrete Boxes, Types f and g

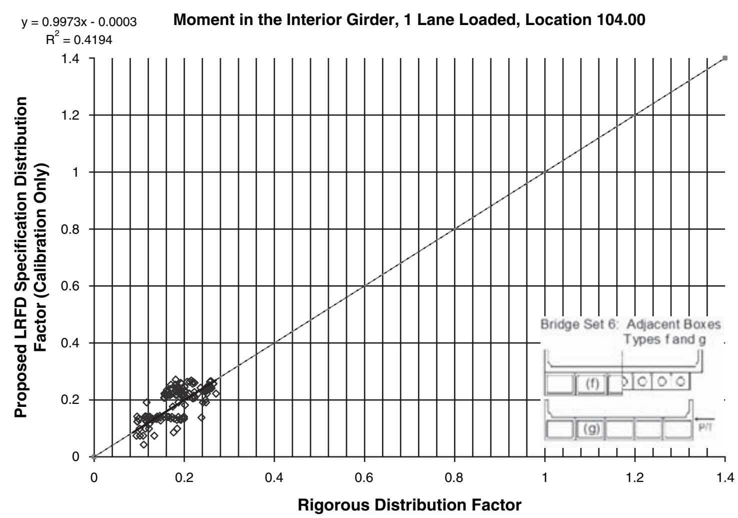
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.385	2.414	0.980	0.997	1.020
Standard Deviation	0.384	0.356	0.146	0.232	0.278
Coefficient of Variation	0.161	0.148	0.149	0.232	0.272
Count	93	122	30	122	140

c.

Figure 58. Moment, multiple lanes, exterior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

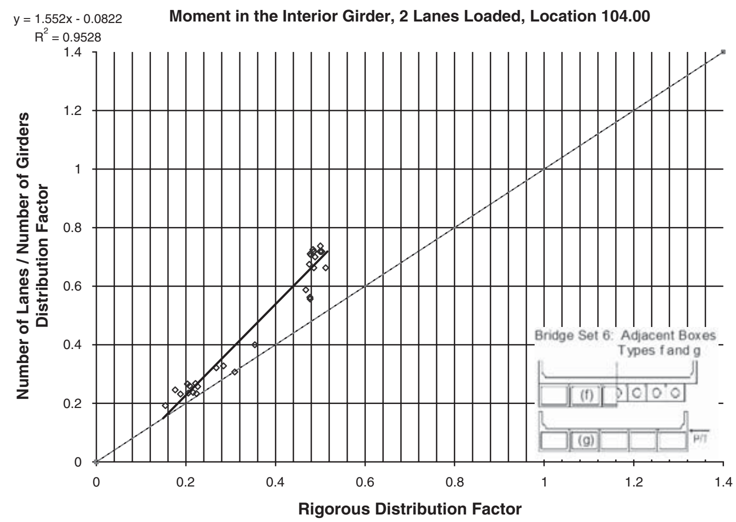


b.

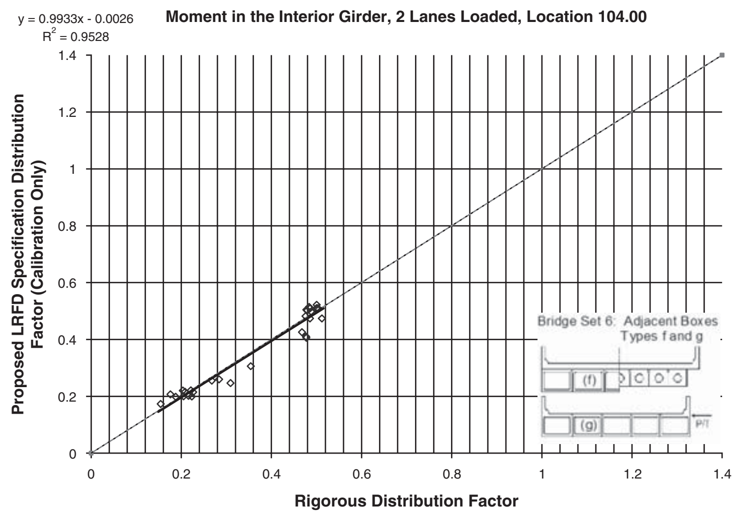
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.256	1.390	1.026	0.991	0.978
Standard Deviation	0.465	0.483	0.364	0.401	0.108
Coefficient of Variation	0.206	0.347	0.355	0.405	0.111
Count	100	50	144	137	144

c.

Figure 59. Moment, one lane, interior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.

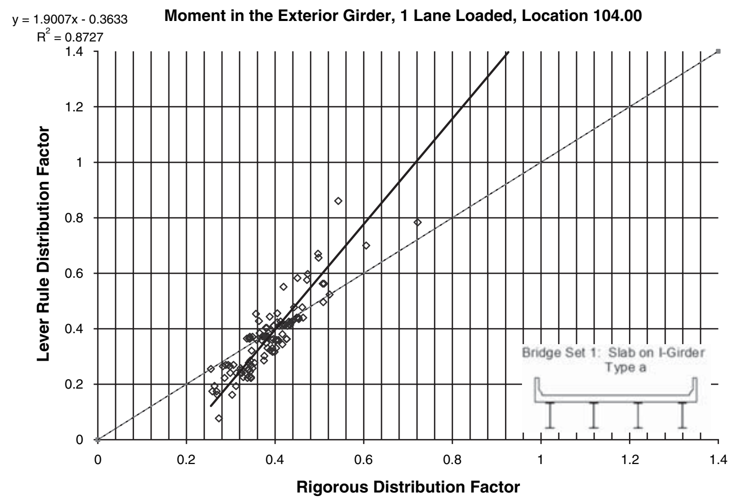


b.

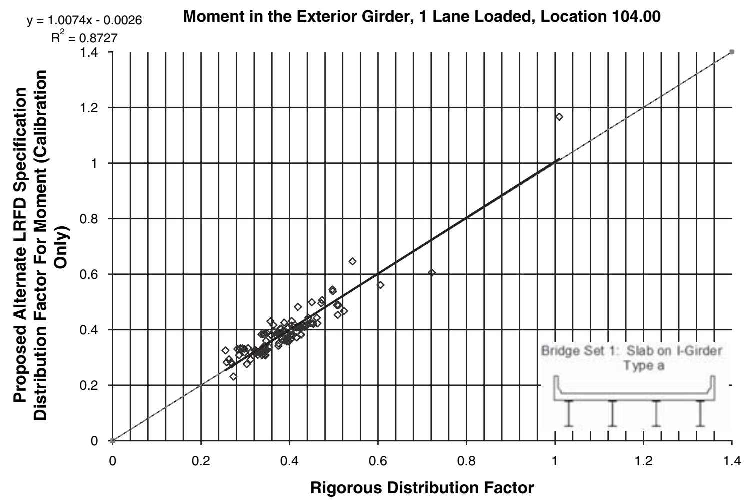
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.832	1.899	0.989	0.997	0.986
Standard Deviation	0.409	0.609	0.086	0.285	0.150
Coefficient of Variation	0.223	0.321	0.087	0.286	0.152
Count	139	138	30	134	140

c.

Figure 60. Moment, multiple lanes, interior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics.



a.



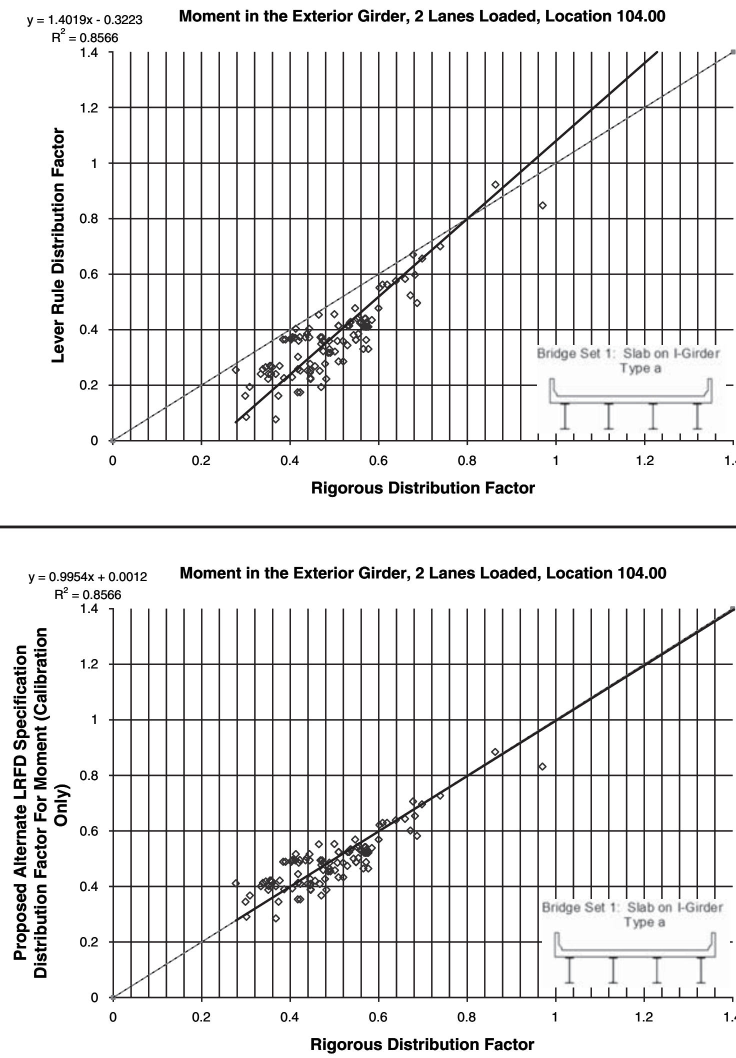
b.

Bridge Set 1 - Concrete Deck on Steel I Sections, Type a

	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.740	1.369	1.008	1.004	0.965
Standard Deviation	0.412	0.179	0.248	0.086	0.568
Coefficient of Variation	0.237	0.131	0.246	0.086	0.588
Count	107	108	108	108	107

c.

Figure 61. Moment, one lane, exterior, slab-on-steel I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



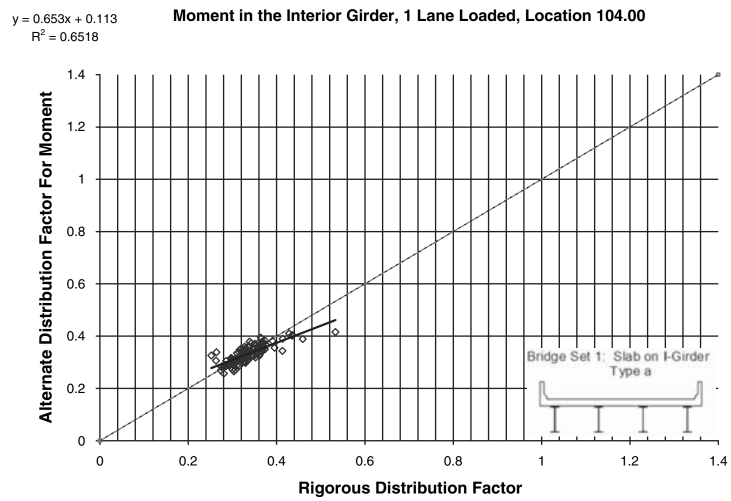
a.

b.

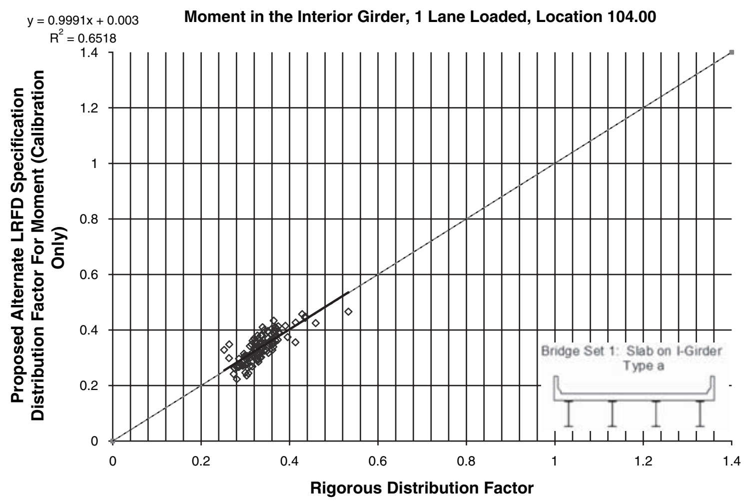
Bridge Set 1 - Concrete Deck on Steel I Sections, Type a					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.370	1.191	0.996	1.008	0.903
Standard Deviation	0.309	0.142	0.132	0.130	0.796
Coefficient of Variation	0.225	0.119	0.133	0.129	0.881
Count	109	109	42	109	106

c.

Figure 62. Moment, multiple lanes, exterior, slab-on-steel I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

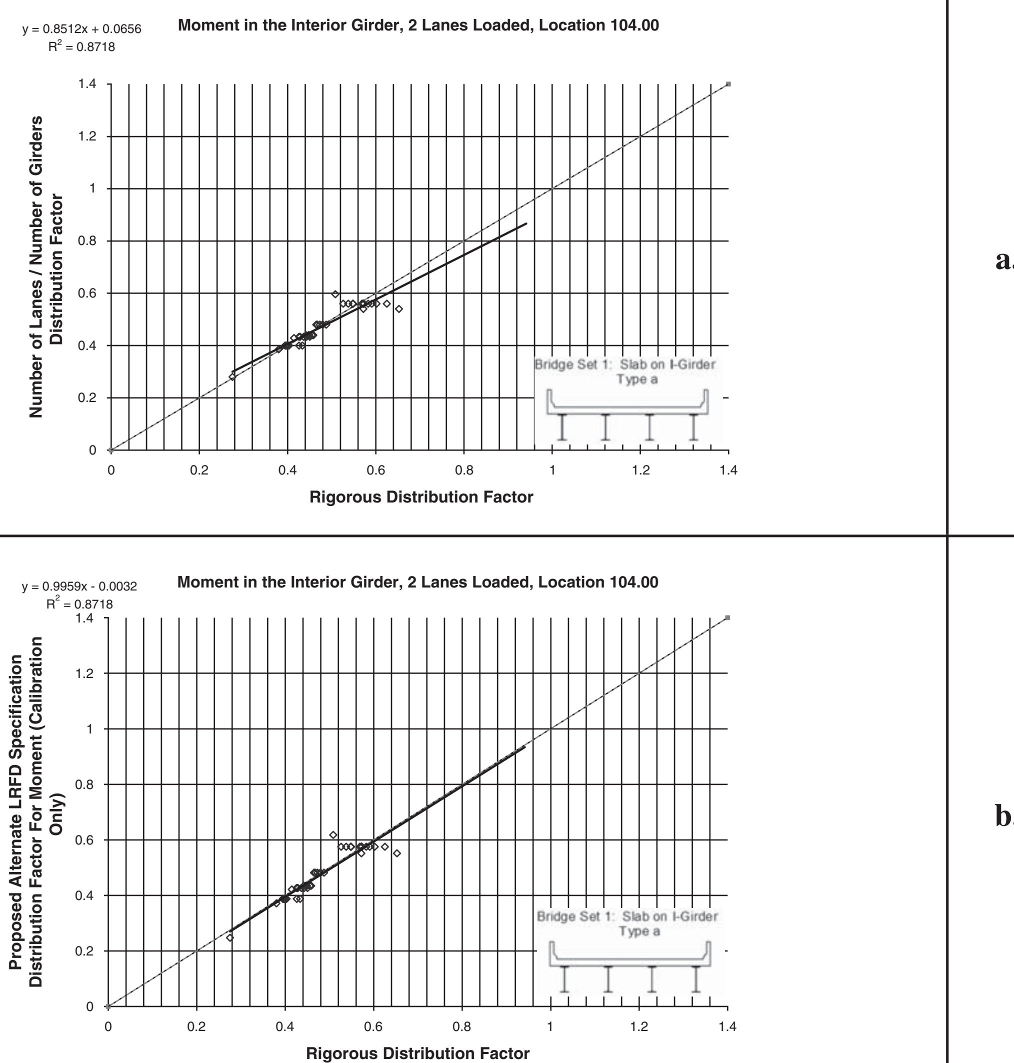


b.

Bridge Set 1 - Concrete Deck on Steel I Sections, Type a					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.977	1.294	1.008	0.993	1.008
Standard Deviation	0.353	0.094	0.198	0.197	0.099
Coefficient of Variation	0.179	0.072	0.196	0.198	0.099
Count	107	107	109	109	109

c.

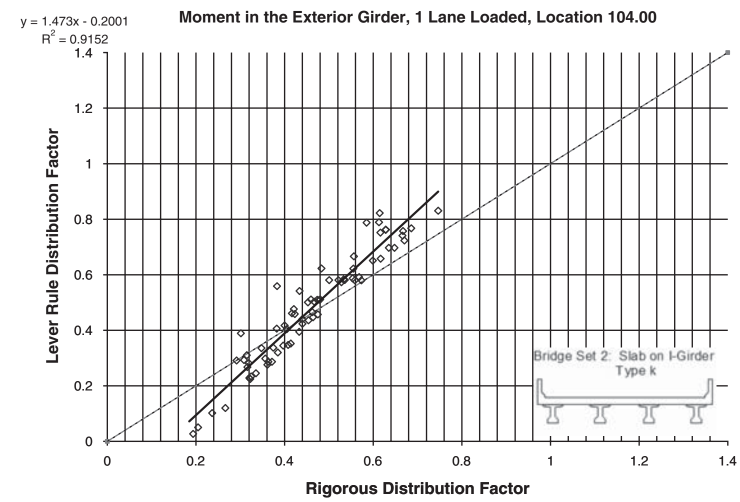
Figure 63. Moment, one lane, interior, slab-on-steel I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



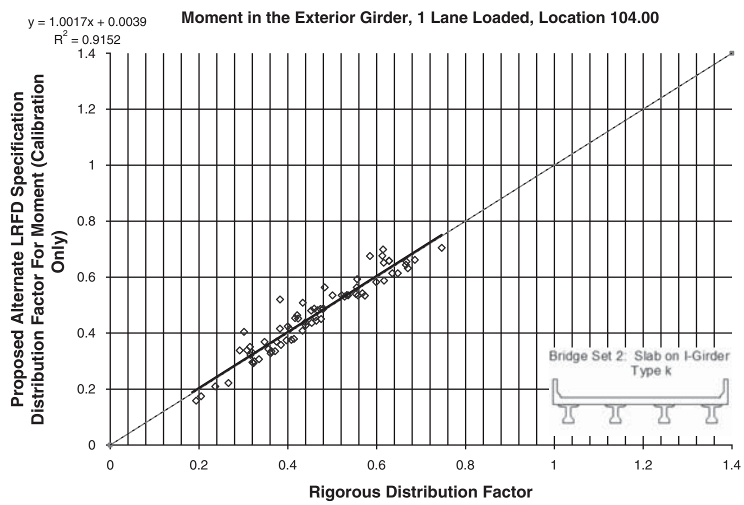
Bridge Set 1 - Concrete Deck on Steel I Sections, Type a					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.232	1.113	0.988	1.011	1.010
Standard Deviation	0.177	0.128	0.059	0.123	0.123
Coefficient of Variation	0.144	0.115	0.059	0.122	0.121
Count	112	112	42	112	112

c.

Figure 64. Moment, multiple lanes, interior, slab-on-steel I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.



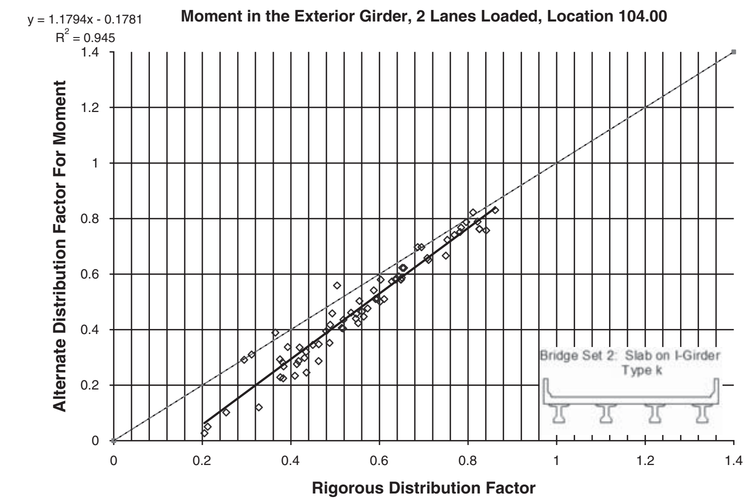
b.

Bridge Set 2 - Slab on Concrete I-Girders, Type k

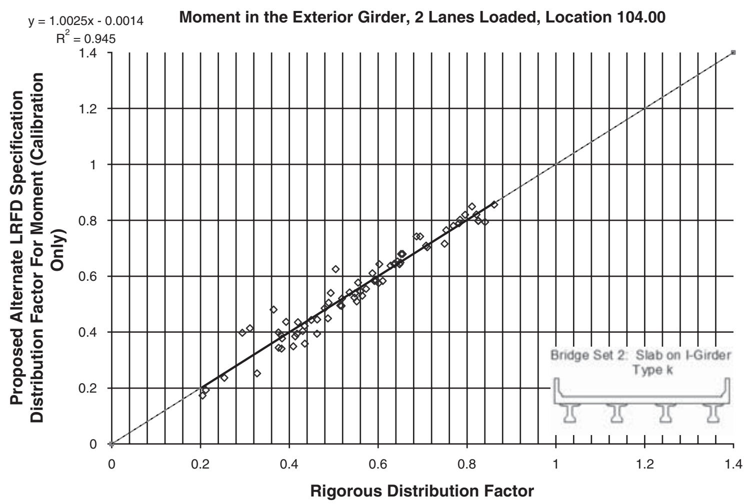
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.515	1.348	1.014	1.008	1.004
Standard Deviation	0.367	0.178	0.271	0.098	0.509
Coefficient of Variation	0.242	0.132	0.268	0.097	0.508
Count	70	73	73	72	73

c.

Figure 65. Moment, one lane, exterior, slab-on-concrete I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.



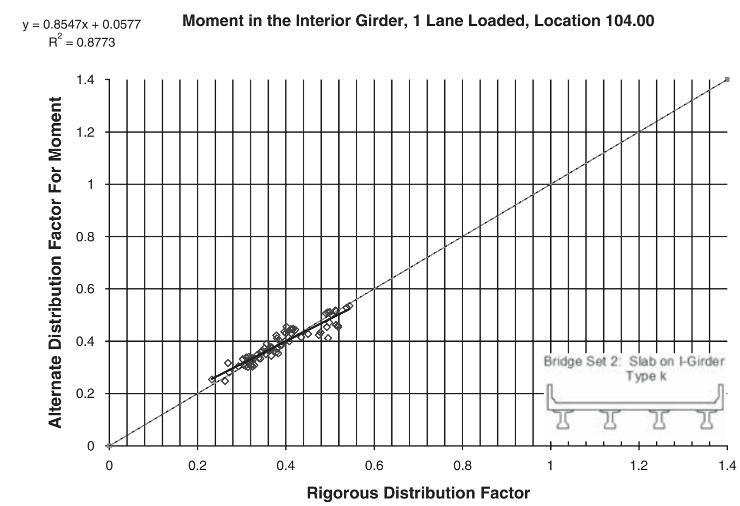
b.

Bridge Set 2 - Slab on Concrete I-Girders, Type k

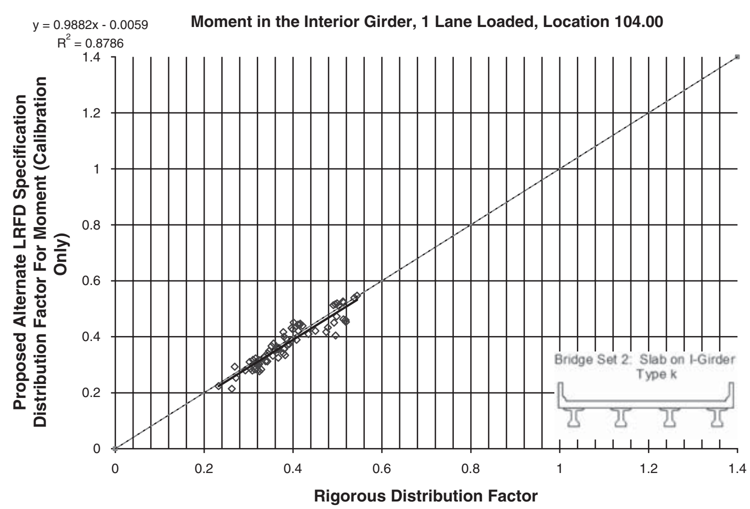
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.283	1.208	0.990	1.000	1.027
Standard Deviation	0.380	0.267	0.183	0.098	0.721
Coefficient of Variation	0.297	0.221	0.185	0.098	0.702
Count	71	73	15	72	73

c.

Figure 66. Moment, multiple lanes, exterior, slab-on-concrete I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.



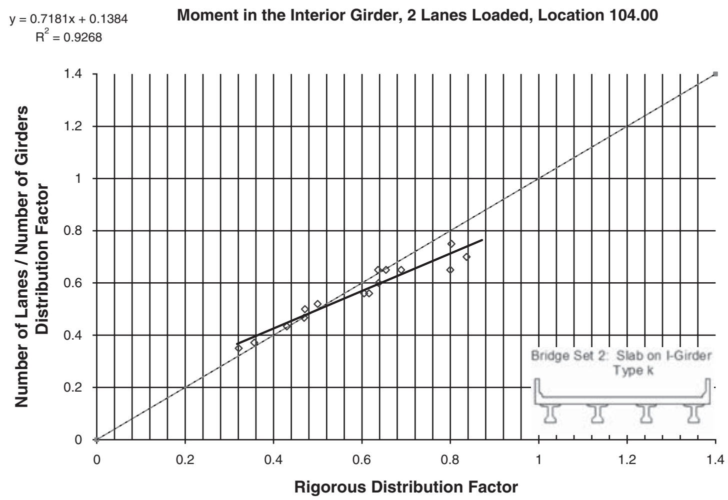
b.

Bridge Set 2 - Slab on Concrete I-Girders, Type k

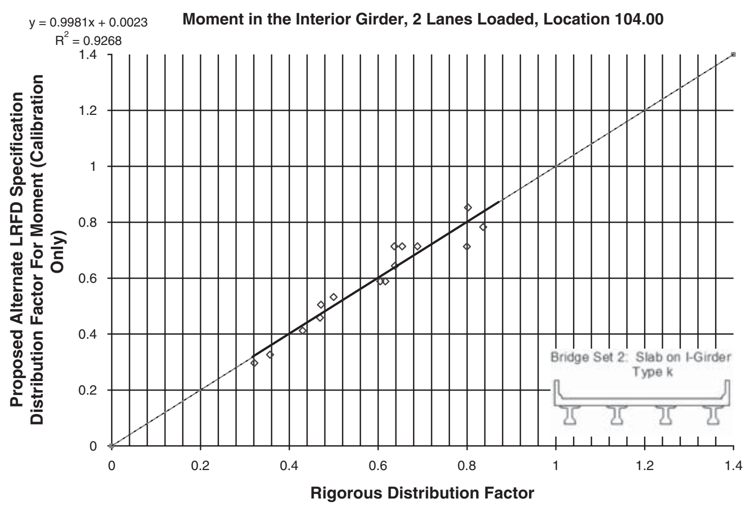
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.773	1.292	0.990	1.000	0.993
Standard Deviation	0.245	0.108	0.206	0.160	0.071
Coefficient of Variation	0.138	0.083	0.208	0.160	0.071
Count	73	73	73	73	73

c.

Figure 67. Moment, one lane, interior, slab-on-concrete I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.



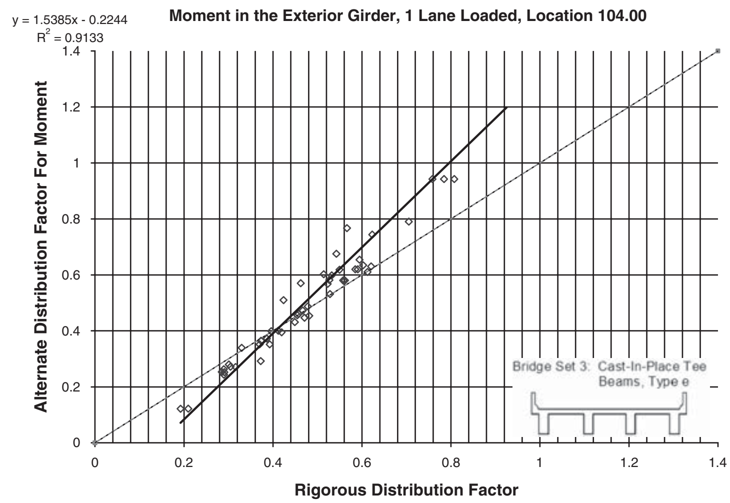
b.

Bridge Set 2 - Slab on Concrete I-Girders, Type k

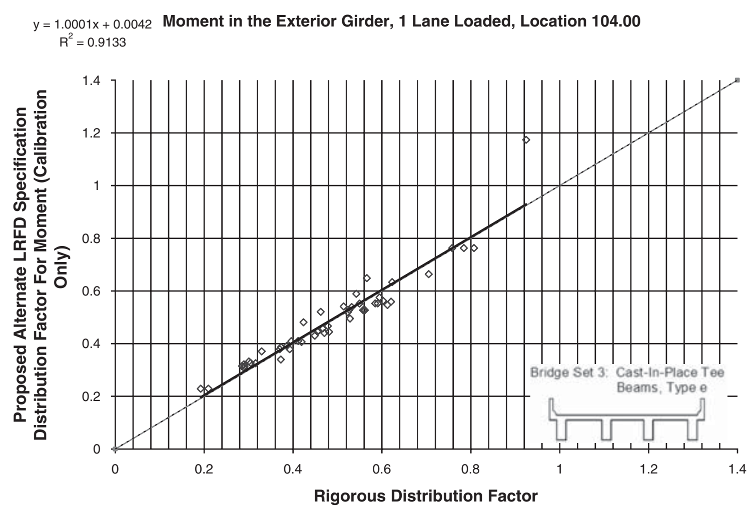
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.115	1.109	0.999	1.001	1.000
Standard Deviation	0.119	0.115	0.072	0.110	0.132
Coefficient of Variation	0.107	0.104	0.072	0.110	0.132
Count	73	73	15	73	73

c.

Figure 68. Moment, multiple lanes, interior, slab-on-concrete I-girders. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

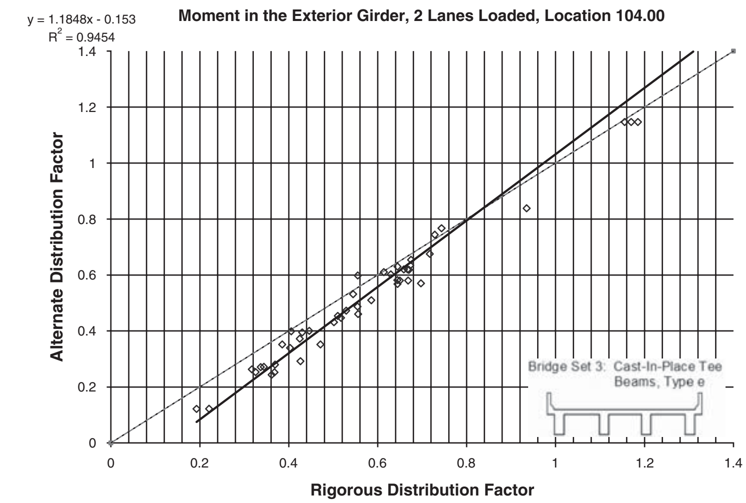


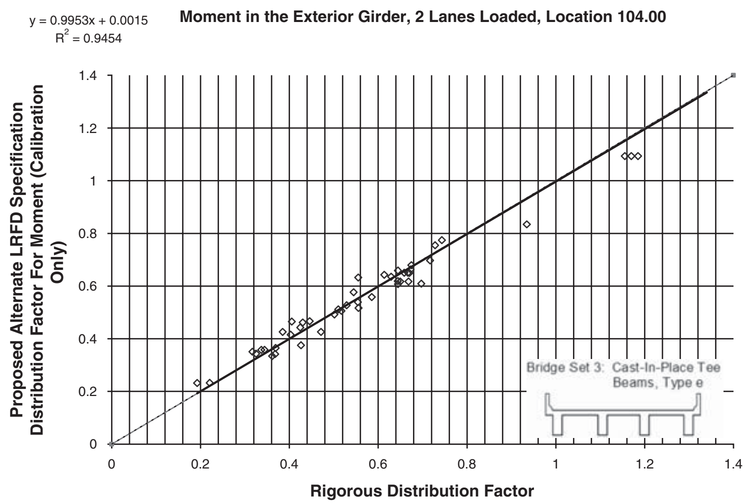
b.

Bridge Set 3 - Cast-in-Place Tee Beams, Type e					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.175	1.415	1.002	1.016	1.036
Standard Deviation	0.247	0.207	0.170	0.081	0.565
Coefficient of Variation	0.210	0.147	0.170	0.080	0.546
Count	49	48	49	49	49

c.

Figure 69. Moment, one lane, exterior, cast-in-place tee beams. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).

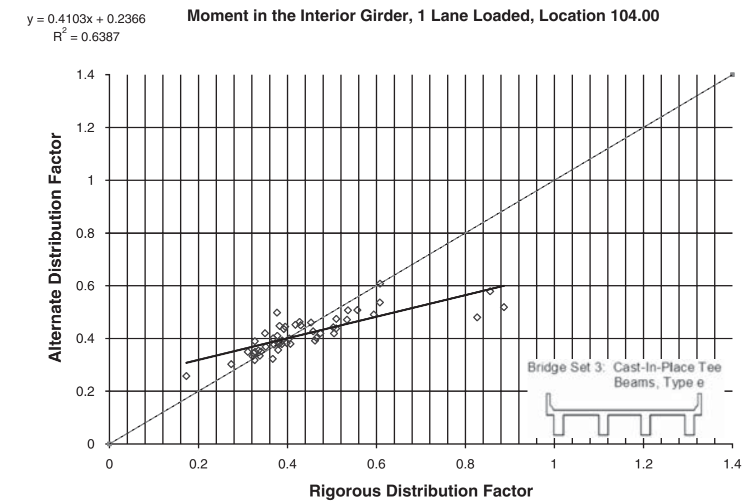




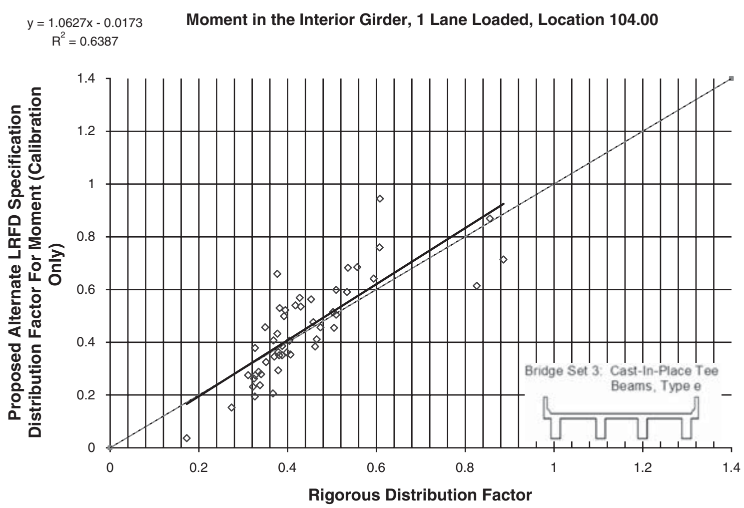
Bridge Set 3 - Cast-in-Place Tee Beams, Type e					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated NI/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.291	1.241	1.014	1.005	0.938
Standard Deviation	0.325	0.198	0.120	0.079	0.675
Coefficient of Variation	0.252	0.160	0.119	0.078	0.720
Count	47	46	20	47	45

c.

Figure 70. Moment, multiple lanes, exterior, cast-in-place tee beams. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

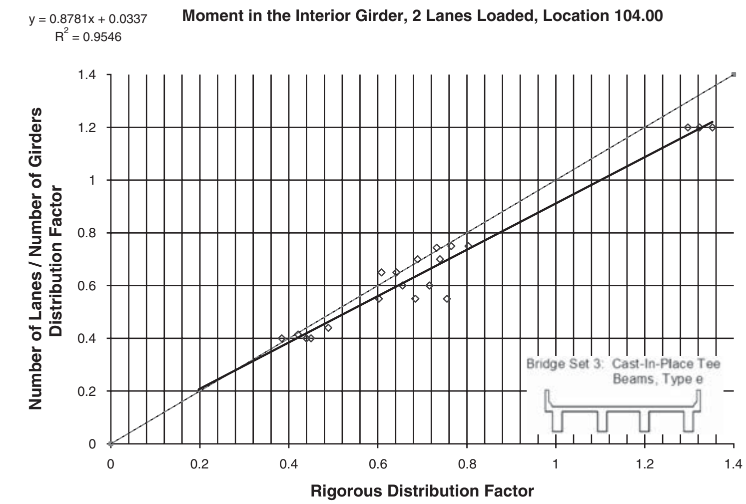


b.

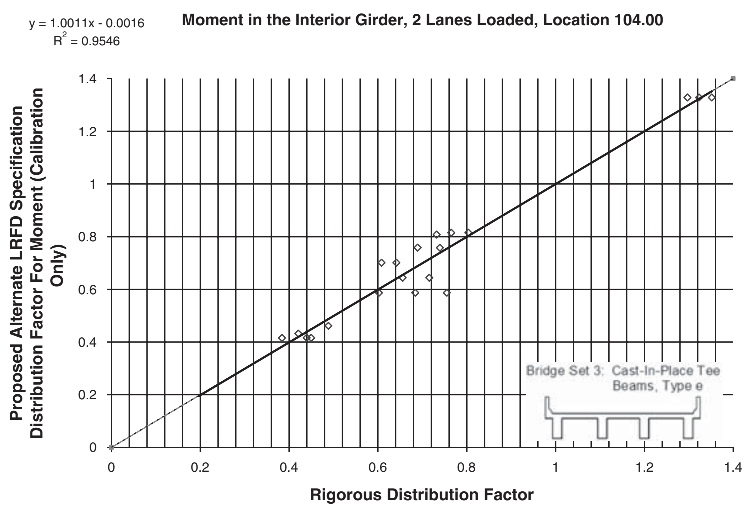
Bridge Set 3 - Cast-in-Place Tee Beams, Type e					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.251	1.264	1.012	0.989	1.004
Standard Deviation	0.211	0.168	0.306	0.231	0.272
Coefficient of Variation	0.169	0.133	0.303	0.233	0.271
Count	50	49	50	50	50

c.

Figure 71. Moment, one lane, interior, cast-in-place tee beams. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

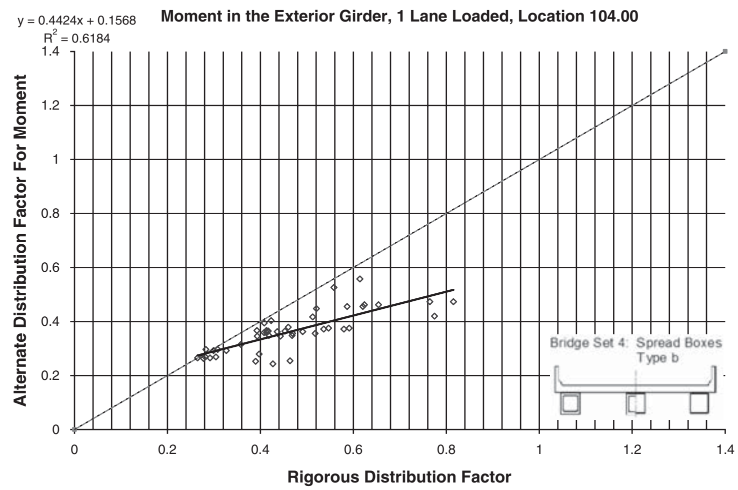


b.

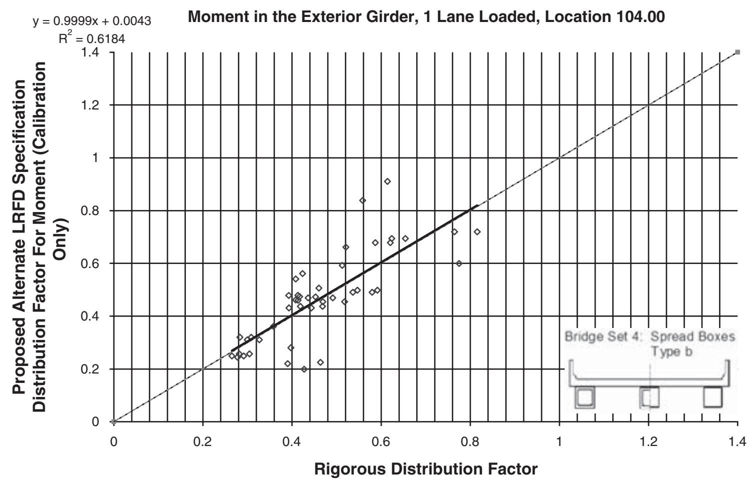
Bridge Set 3 - Cast-in-Place Tee Beams, Type e					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.050	1.074	0.999	0.989	1.003
Standard Deviation	0.145	0.135	0.091	0.235	0.276
Coefficient of Variation	0.138	0.125	0.091	0.238	0.275
Count	48	47	20	48	48

c.

Figure 72. Moment, multiple lanes, interior, cast-in-place tee beams. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

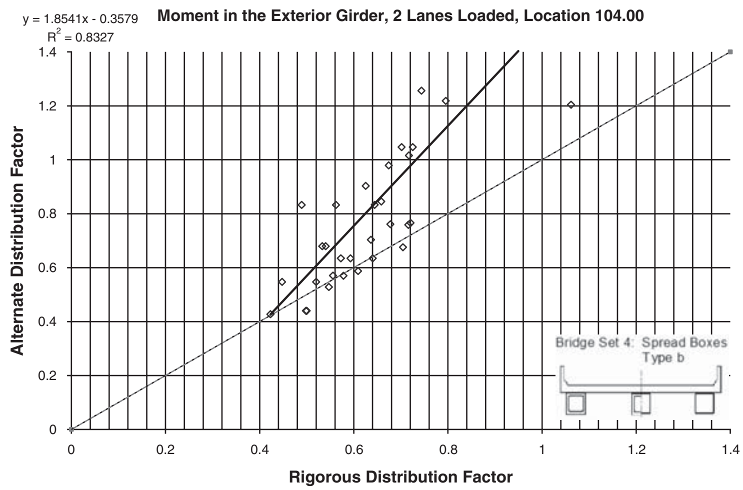


b.

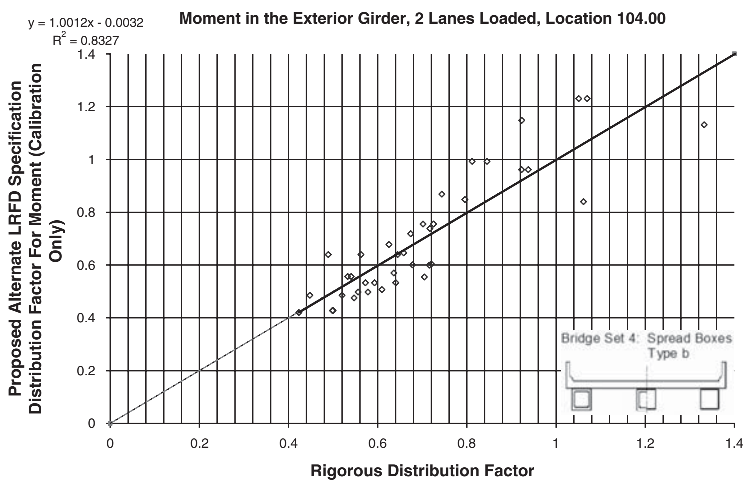
Bridge Set 4 - Spread Concrete Box Girders, Type b					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.564	2.181	0.998	0.995	0.982
Standard Deviation	0.500	0.405	0.183	0.262	0.212
Coefficient of Variation	0.320	0.186	0.184	0.264	0.216
Count	60	40	46	46	46

c.

Figure 73. Moment, one lane, exterior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

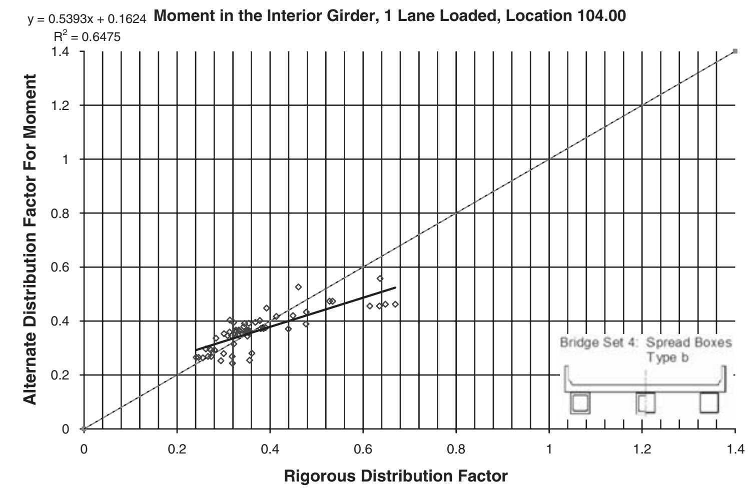


b.

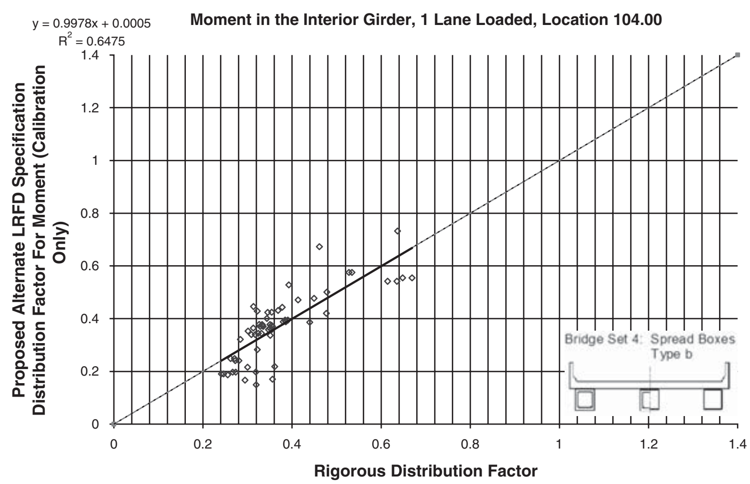
Bridge Set 4 - Spread Concrete Box Girders, Type b					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.285	1.395	1.001	0.994	0.985
Standard Deviation	0.279	0.262	0.091	0.136	0.462
Coefficient of Variation	0.218	0.188	0.091	0.137	0.469
Count	60	40	7	40	40

c.

Figure 74. Moment, multiple lanes, exterior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.



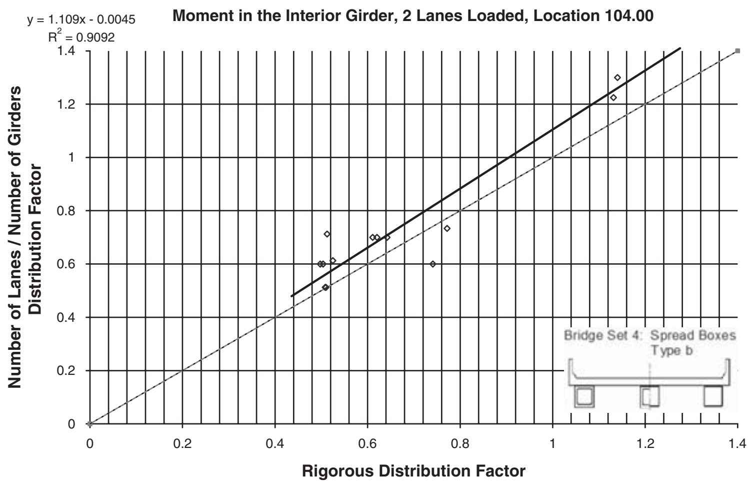
b.

Bridge Set 4 - Spread Concrete Box Girders, Type b

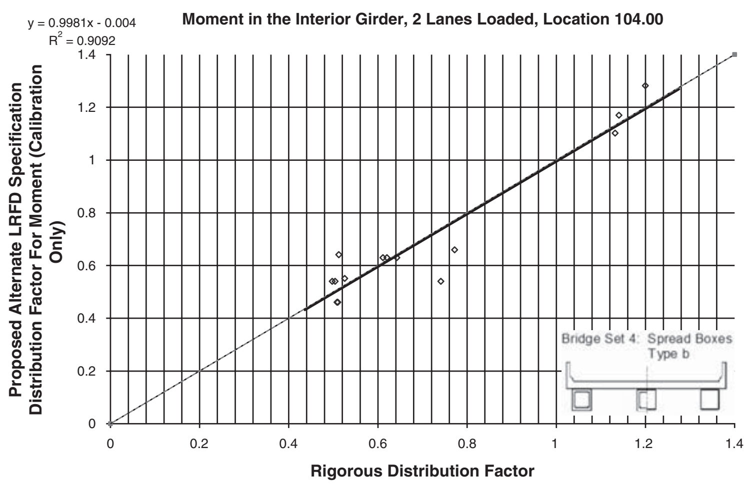
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.853	1.609	1.007	1.014	0.994
Standard Deviation	0.311	0.615	0.355	0.181	0.212
Coefficient of Variation	0.168	0.382	0.352	0.179	0.214
Count	60	60	60	60	60

c.

Figure 75. Moment, one lane, interior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

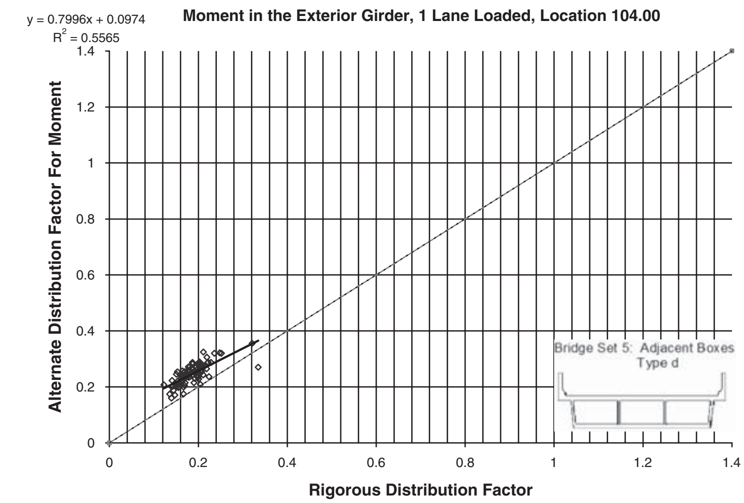


b.

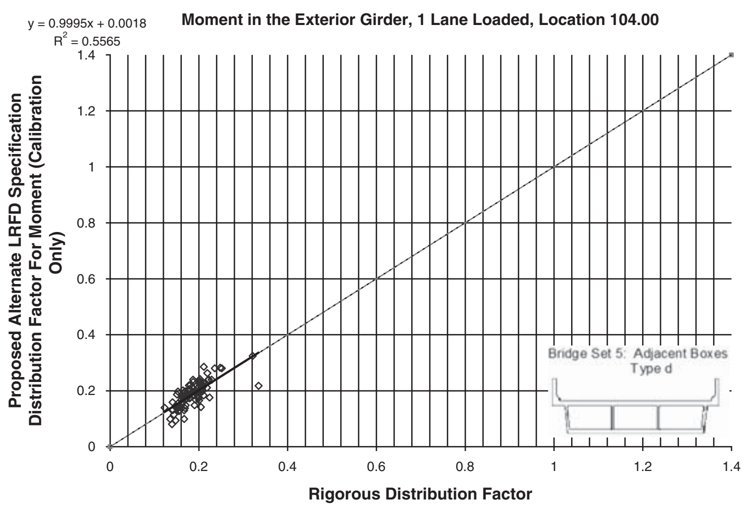
Bridge Set 4 - Spread Concrete Box Girders, Type b					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.423	1.259	0.997	0.990	0.992
Standard Deviation	0.276	0.301	0.123	0.241	0.262
Coefficient of Variation	0.194	0.239	0.124	0.244	0.264
Count	60	59	14	59	59

c.

Figure 76. Moment, multiple lanes, interior, spread boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

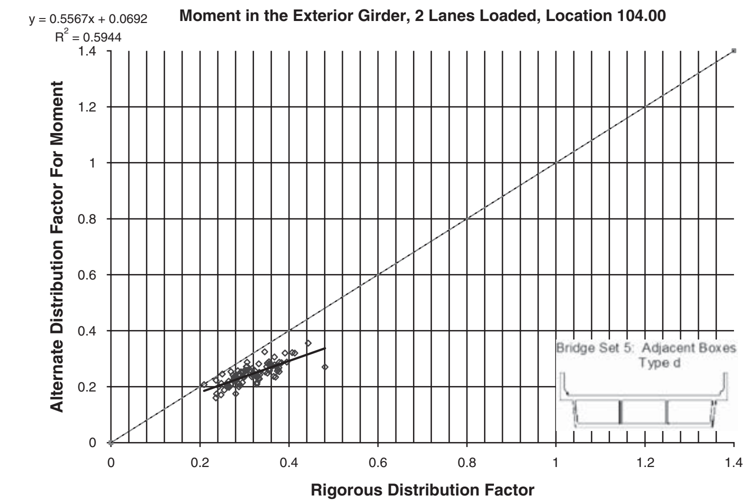


b.

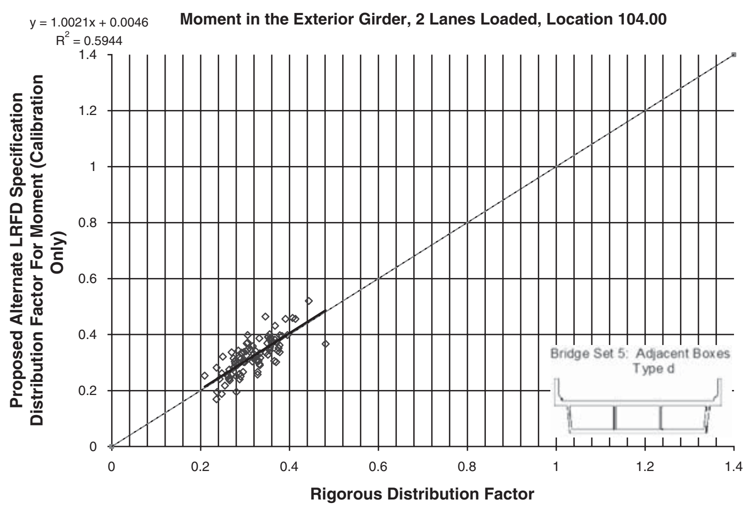
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.683	2.660	0.977	0.980	1.007
Standard Deviation	0.953	0.291	0.504	0.298	0.159
Coefficient of Variation	0.566	0.109	0.516	0.304	0.158
Count	80	38	92	92	92

c.

Figure 77. Moment, one lane, exterior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

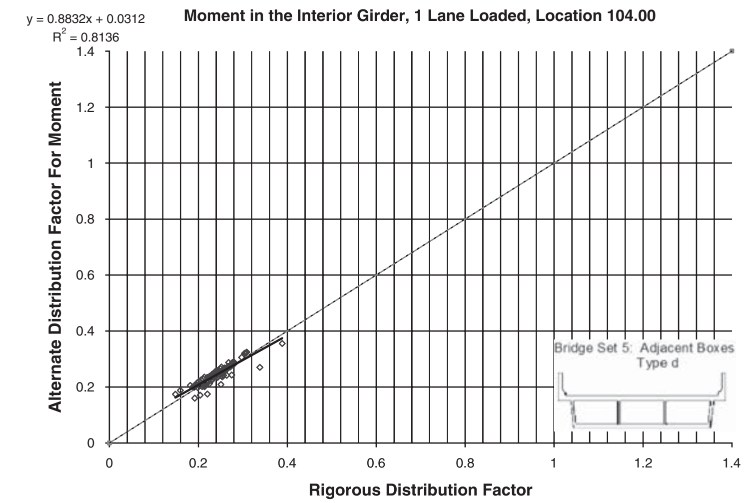


b.

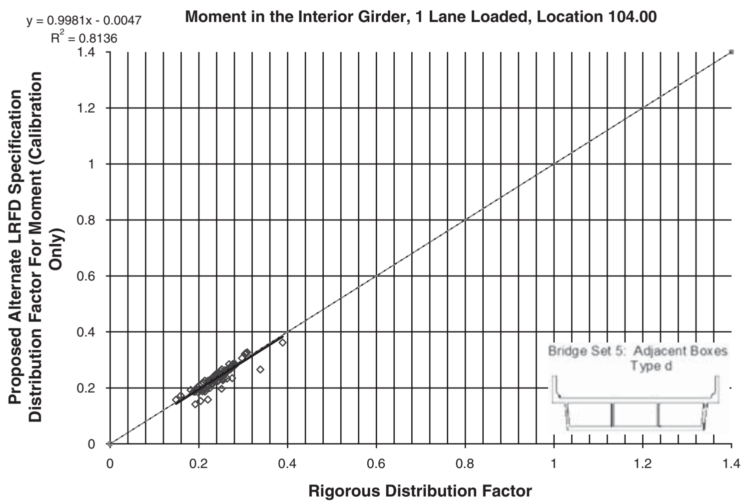
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.240	2.086	1.000	1.003	1.016
Standard Deviation	0.347	0.237	0.084	0.208	0.133
Coefficient of Variation	0.155	0.114	0.084	0.207	0.130
Count	80	92	29	92	92

c.

Figure 78. Moment, multiple lanes, exterior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

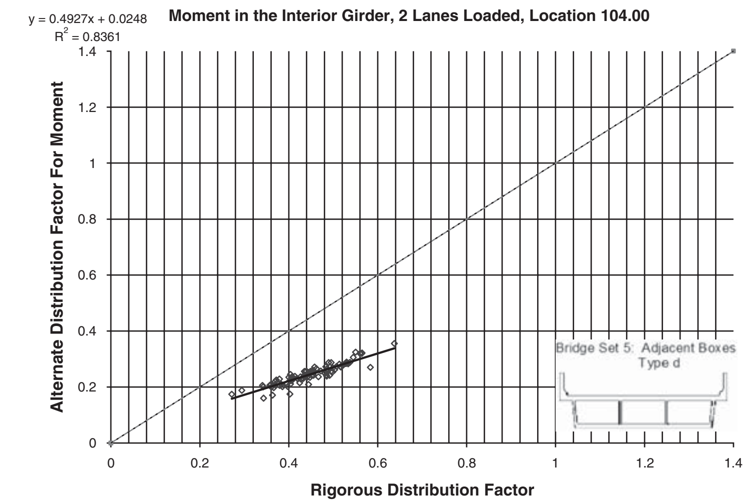


b.

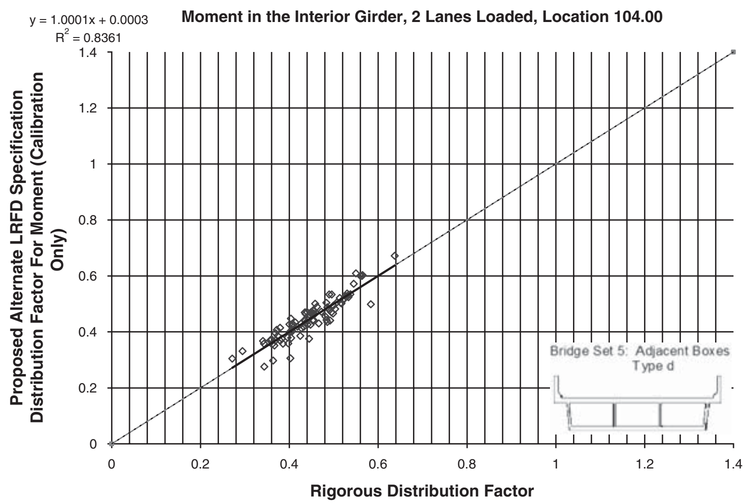
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.299	1.605	0.762	0.983	0.978
Standard Deviation	0.262	0.209	1.075	0.316	0.074
Coefficient of Variation	0.114	0.130	1.411	0.321	0.075
Count	80	86	86	92	92

c.

Figure 79. Moment, one lane, interior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

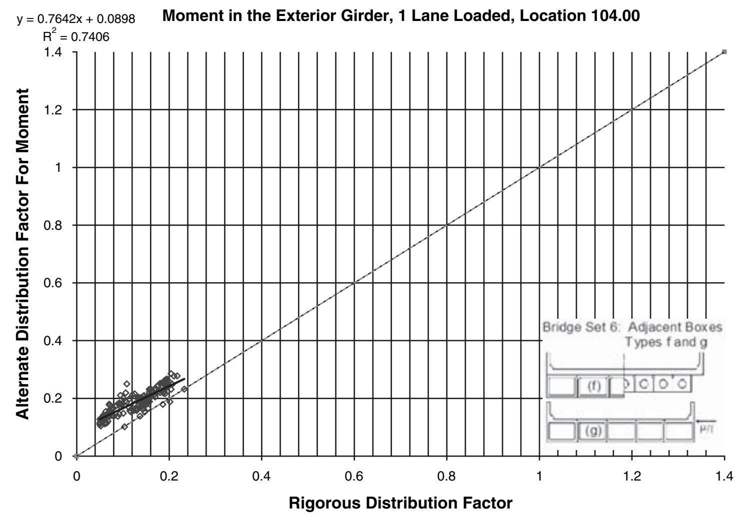


b.

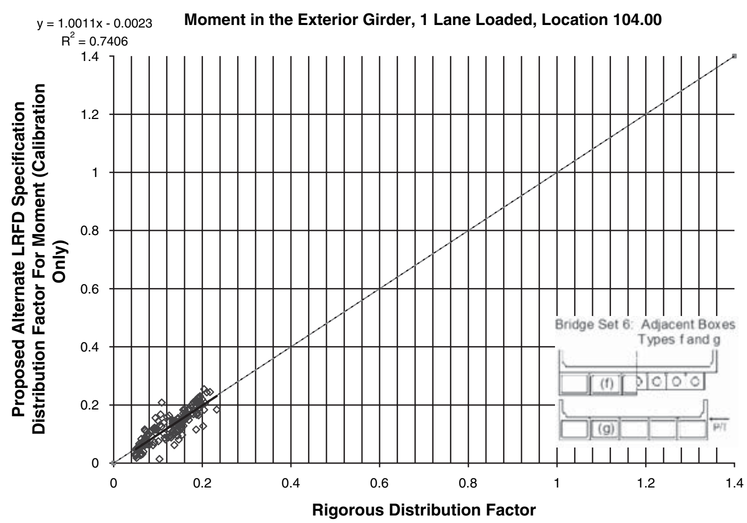
Bridge Set 5 - Cast-in-Place Concrete Boxes, Type d					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.591	1.299	0.993	0.999	1.001
Standard Deviation	0.180	0.118	0.098	0.233	0.069
Coefficient of Variation	0.113	0.091	0.099	0.233	0.069
Count	80	92	29	92	92

c.

Figure 80. Moment, multiple lanes, interior, cast-in-place multi-cell box. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

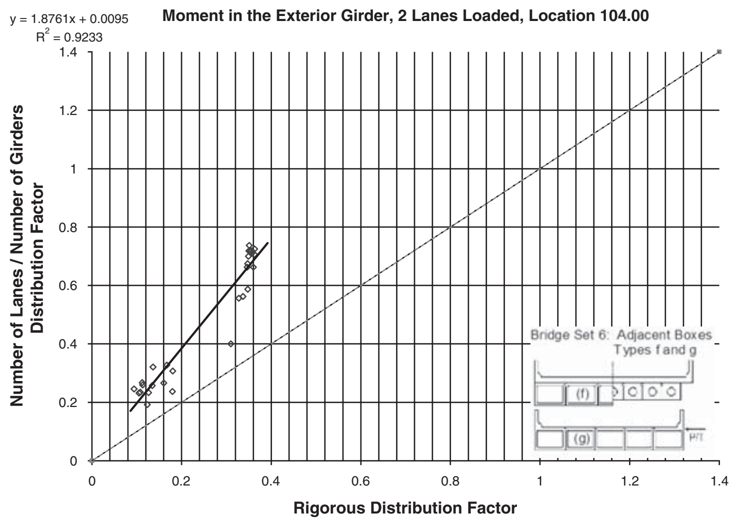


b.

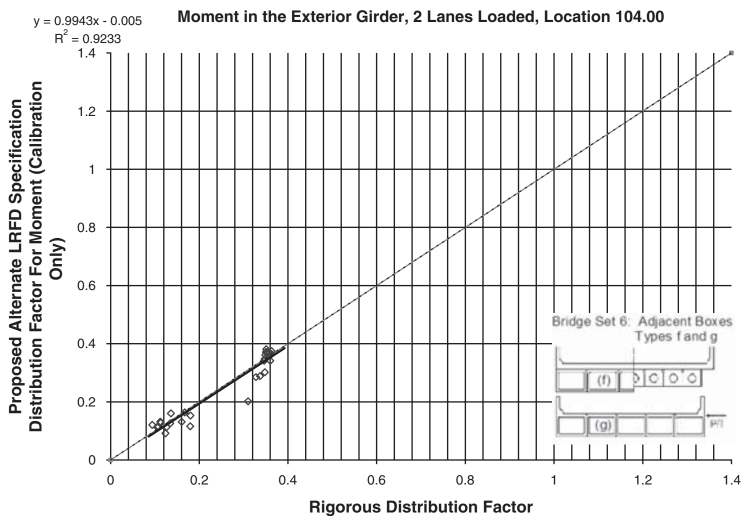
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.512	2.689	0.947	0.975	0.978
Standard Deviation	0.449	0.195	0.378	0.239	0.267
Coefficient of Variation	0.179	0.072	0.400	0.245	0.273
Count	27	16	144	121	144

c.

Figure 81. Moment, one lane, exterior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

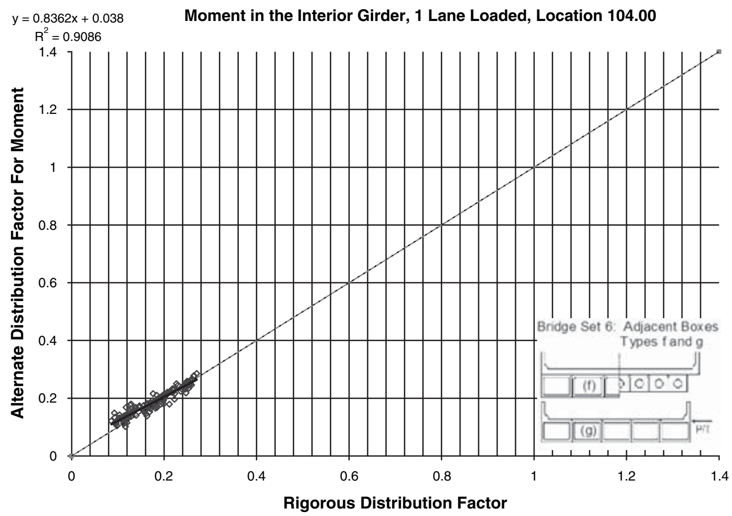


b.

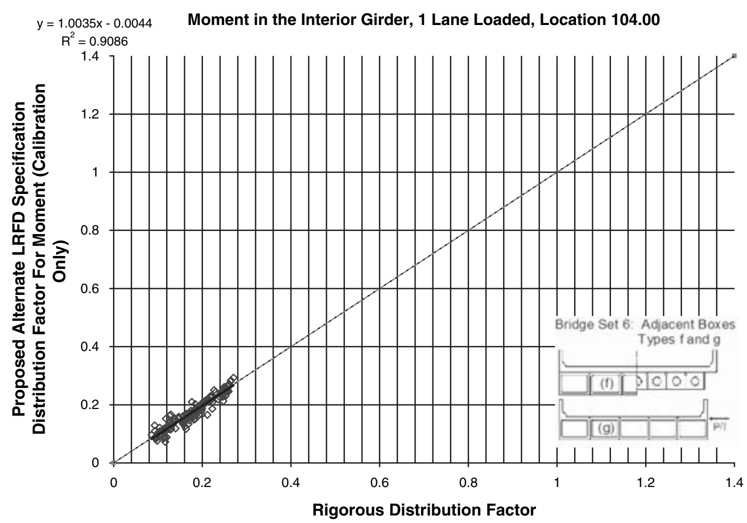
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.385	2.414	0.980	0.997	1.020
Standard Deviation	0.384	0.356	0.146	0.232	0.278
Coefficient of Variation	0.161	0.148	0.149	0.232	0.272
Count	93	122	30	122	140

c.

Figure 82. Moment, multiple lanes, exterior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.

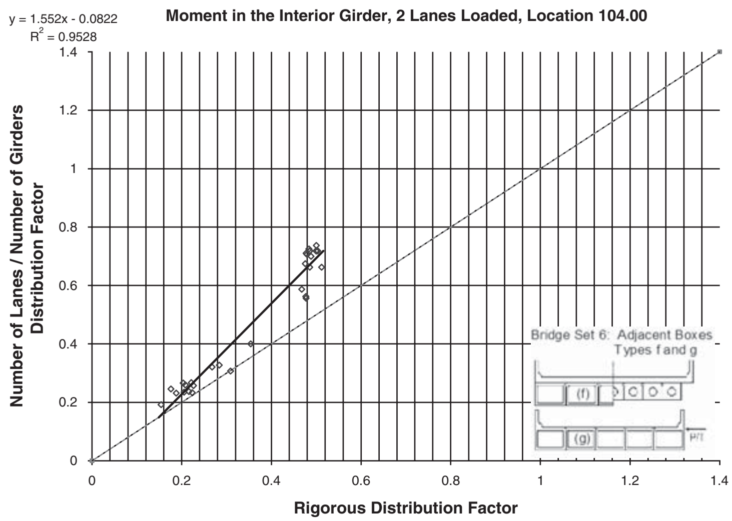


b.

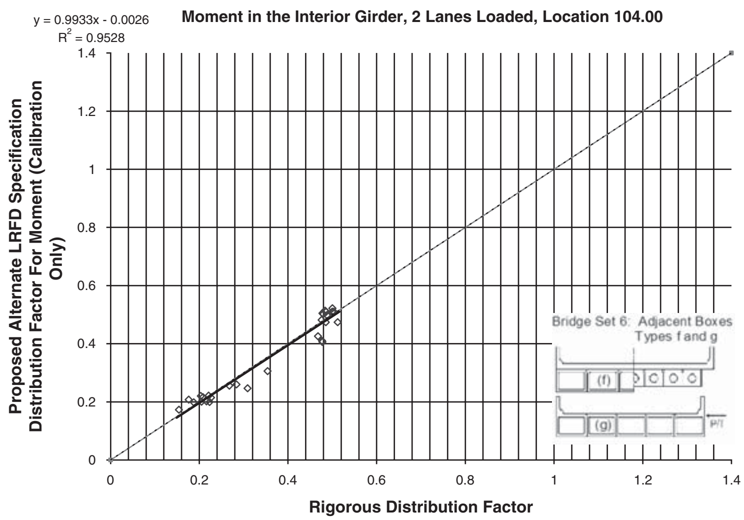
Bridge Set 6 - Adjacent Concrete Boxes, Types f and g					
	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	2.256	1.390	1.026	0.991	0.978
Standard Deviation	0.465	0.483	0.364	0.401	0.108
Coefficient of Variation	0.206	0.347	0.355	0.405	0.111
Count	100	50	144	137	144

c.

Figure 83. Moment, one lane, interior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).



a.



b.

Bridge Set 6 - Adjacent Concrete Boxes, Types f and g

	AASHTO Standard Specification	2005 AASHTO LRFD	Calibrated Nl/Ng	Calibrated Lever Rule	Calibrated Alternate Moment Distribution Factor
Average (Simplified/Rigorous)	1.832	1.899	0.989	0.997	0.986
Standard Deviation	0.409	0.609	0.086	0.285	0.150
Coefficient of Variation	0.223	0.321	0.087	0.286	0.152
Count	139	138	30	134	140

c.

Figure 84. Moment, multiple lanes, interior, adjacent boxes. a. Before calibration, b. After calibration, c. Comparative statistics (alternative method).

Summary of Calibrations

The calibrations are summarized in Table 14 (for slab-on-steel I-girders), Table 15 (for slab-on-concrete I-girders), Table 16 (for cast-in-place tee girders), Table 17 (for precast concrete spread boxes), Table 18 (for cast-in-place concrete boxes), and Table 19 (for adjacent boxes). See Table 1 for more information about the bridges in each set. The action type (shear or moment) is split into two sections for exterior and interior girders. These sections are further split into subsections for one and multiple lanes loaded. For each subsection, the slope and intercept of the original (i.e., uncalibrated) method are provided, along with the initial correlation coefficient (R^2) and a reference to a relevant figure from Appendix N. Following these data are the computed calibration constants (a, b) and the recommended calibration constants (a, b), which have been rounded to two digits past the decimal (the specification writers can round further as desired). Finally, a reference to the regression plots from Appendix K is provided, along with the final correlation coefficient (R^2) using the recommended constants. The R^2 values change little between the calibrated and draft specification values. The difference is the lower bound of uniform distribution outlined earlier, which was not included in the initial plots. The difference between the recommended specification method and the rigorous method is shown in the referenced regression plot.

The plots and data in Figure 13 through Figure 84 illustrate the comparisons of the initial ("a") and draft specification ("b") values versus rigorous values for all cases. Again, R^2 values above 0.9 are excellent. Additionally, as part of the regression study (comparison with existing methods) outlined in Chapter 3, values in the "c" section of each figure provide comparisons with the AASHTO Standard Specifications, the AASHTO LRFD Specifications, the uniform distribution method, and the calibrated lever rule. The critical value here is the coefficient of variation (COV) of the normal distribution of the simple method distribution factor ratioed to the rigorous analysis data. Comparison of the COV data illustrates why these methods were selected.

Tables 14 through 19 also illustrate the calibration constants and regression coefficients for the alternative method for moment. These values illustrate the improved accuracy with the alternative method and the tradeoff of increased complexity.

Application of Multiple Presence to Simplified Methods

Multiple presence factors were included in *current* LRFD live load distribution factor equations. For multiple-lane cases, the controlling value is unknown. When using the current LRFD specifications, these factors should only be explicitly applied to distribution factor values when the lever rule, rigid method, or rigorous analysis is used. This section outlines the application of multiple presence factors to the uniform distribution method and the calibrated lever rule.

Uniform Method with Multiple Presence

The current LRFD specifications state that the total number of design lanes, N_L (also $N_{Total\ Number\ of\ Lanes}$ defined previously) is determined by taking the integer part of the ratio

$$N_L = \frac{W_c}{12} \qquad (2\text{-}17)$$

where W_c is the clear roadway width in feet between barriers/curbs. The integer part of the ratio is then used to determine which multiple presence factor to apply. Typically, two or three lanes with multiple presence factors applied to the rigorous results yields the critical situation. Therefore, the multiple presence factor is limited to $m = 0.85$ for bridges with four or more lanes.

Calibrated Lever Rule with Multiple Presence

For the calibrated lever rule, only one and two lanes loaded are considered. A study determined that when the multiple presence factors are included in the distribution factor values, the two-lane loaded case typically controls (see Appendix O). The difference between the two- and three-lane loaded cases was small when the three-lane loaded case controlled. This greatly simplifies the distribution factor computations because the three-or-more-lane loaded cases need not be considered. Therefore, only on one and two lanes loaded are the multiple presence factors used (see Table 20).

Skew Correction Factors

The skew adjust correction factors were kept fundamentally the same as the present LRFD specifications, with the exception of simplification to include only the following parameters: girder spacing, span length, and girder depth. These parameters are readily available or easily estimated at the beginning of the process. Limited basis exists to make significant changes here. For types a, e, h, i, and j, the following term was calculated for the entire NCHRP 12-26 bridge set:

$$0.20\left(\frac{12.0Lt_s^3}{K_g}\right)^{0.3}$$

The average value of this term (0.20) was substituted into the skew correction factor equation, and the new results were com-

Table 14. Calibration constants for steel I-girder bridges (type a).

Action	Girder Location	Basic Method	Lanes Loaded	Calibration Constants										
				Initial Trend Line - Lever Rule and Uniform Distribution				Computed Calibration Factors		Recommended Calibration Factors				
				Slope	*Intercept*	*R^2*	*Figures*	*a*	*b*	*a*	*b*	*Regression Plot*	*R^2*	
Shear	Exterior	Calibrated Lever	1 Lane	1.4231	-0.1840	0.9446	N-114	0.7027	0.1293	0.70	0.13	K-10	0.9446	Proposed 4.6.2.2
			2 or More Lanes	1.2062	-0.1317	0.9683	N-107	0.8290	0.1092	0.83	0.11	K-9	0.9581	
	Interior		1 Lane	0.9659	0.1202	0.8934	N-86	1.0353	-0.1244	1.04	-0.12	K-8	0.8934	
			2 or More Lanes	1.0111	-0.0054	0.9000	N-79	0.9890	0.0053	0.99	0.01	K-7	0.9000	
Moment	Exterior	Calibrated Lever	1 Lane	1.9007	-0.3633	0.8727	N-57	0.5261	0.1911	0.53	0.19	K-6	0.8727	
		Uniform Distribution	2 or More Lanes	0.8751	0.1048	0.6297	N-50	1.1427	-0.1198	1.14	-0.12	K-4	0.6146	
	Interior	Calibrated Lever	1 Lane	1.0357	0.2436	0.3355	N-25	0.9655	-0.2352	0.97	-0.24	K-2	0.3355	
		Uniform Distribution	2 or More Lanes	0.8512	0.0656	0.8718	N-18	1.1748	-0.0771	1.17	-0.08	K-1	0.8718	
Alternate Method for Moments														
Moment	Exterior	Calibrated Lever	1 Lane	1.9007	-0.3633	0.8727	N-57	0.5261	0.1911	0.53	0.19	K-6	0.8727	Proposed Appendix C
		Calibrated Lever	2 or More Lanes	1.4019	-0.3223	0.8566	N-49	0.7133	0.2299	0.71	0.23	K-5	0.8566	
	Interior	Alternate Method	1 Lane	0.6530	0.1130	0.6518	N-27	1.5314	-0.1730	1.53	-0.17	K-3	0.6518	
		Uniform Distribution	2 or More Lanes	0.8512	0.0656	0.8718	N-18	1.1748	-0.0771	1.17	-0.08	K-1	0.8718	

Table 15. Calibration constants for concrete I-girder bridges (types h, I, j, k).

Action	Girder Location	Basic Method	Lanes Loaded	Calibration Constants										
				Initial Trend Line - Lever Rule and Uniform Distribution				Computed Calibration Factors		Recommended Calibration Factors				
				Slope	*Intercept*	*R^2*	*Figures*	*abab*				*Regression Plot*	*R^2*	
Shear	Exterior	Calibrated Lever	1 Lane	1.2015	-0.0896	0.9889	N-234	0.8323	0.0746	0.83	0.07	K-20	0.9889	Proposed 4.6.2.2
			2 or More Lanes	1.0815	-0.0637	0.9834	N-227	0.9246	0.0589	0.92	0.06	K-19	0.9756	
	Interior		1 Lane	0.9252	0.1224	0.9146	N-206	1.0808	-0.1323	1.08	-0.13	K-18	0.9146	
			2 or More Lanes	1.0652	-0.0275	0.8870	N-199	0.9388	0.0258	0.94	0.03	K-17	0.8870	
Moment	Exterior	Calibrated Lever	1 Lane	1.4730	-0.2001	0.9152	N-177	0.6789	0.1358	0.68	0.14	K-16	0.9152	
		Uniform Distribution	2 or More Lanes	0.8005	0.1574	0.6586	N-170	1.2492	-0.1966	1.25	-0.20	K-14	0.6586	
	Interior	Calibrated Lever	1 Lane	0.7522	0.3090	0.6213	N-145	1.3294	-0.4108	1.33	-0.41	K-12	0.6213	
		Uniform Distribution	2 or More Lanes	0.7181	0.1384	0.9268	N-138	1.3926	-0.1927	1.39	-0.19	K-11	0.9268	
Alternate Method for Moments														
Moment	Exterior	Calibrated Lever	1 Lane	1.4730	-0.2001	0.9152	N-177	0.6789	0.1358	0.68	0.14	K-16	0.9152	Proposed Appendix C
		Calibrated Lever	2 or More Lanes	1.1794	-0.1787	0.9450	N-169	0.8479	0.1515	0.85	0.15	K-15	0.9450	
	Interior	Alternate Method	1 Lane	0.8547	0.0577	0.8773	N-147	1.1700	-0.0675	1.17	-0.07	K-13	0.8786	
		Uniform Distribution	2 or More Lanes	0.7181	0.1384	0.9268	N-138	1.3926	-0.1927	1.39	-0.19	K-11	0.9268	

Table 16. Calibration constants for cast-in-place tee girder bridges (type e).

Action	Girder Location	Basic Method	Lanes Loaded	Calibration Constants										
				Initial Trend Line - Lever Rule and Uniform Distribution				Computed Calibration Factors		Recommended Calibration Factors				
				Slope	*Intercept*	R^2	*Figures*	*a*	*b*	*a*	*b*	*Regression Plot*	R^2	
Shear	Exterior	Calibrated Lever	1 Lane	1.2652	-0.1096	0.9309	N-354	0.7904	0.0866	0.79	0.09	K-30	0.9309	Proposed 4.6.2.2
Shear	Exterior	Calibrated Lever	2 or More Lanes	1.0659	-0.0499	0.9530	N-347	0.9382	0.0468	0.94	0.05	K-29	0.9313	Proposed 4.6.2.2
Shear	Interior	Calibrated Lever	1 Lane	0.8050	0.1784	0.9168	N-326	1.2422	-0.2216	1.24	-0.22	K-28	0.9168	Proposed 4.6.2.2
Shear	Interior	Calibrated Lever	2 or More Lanes	0.8261	0.1416	0.8368	N-319	1.2105	-0.1714	1.21	-0.17	K-27	0.8368	Proposed 4.6.2.2
Moment	Exterior	Calibrated Lever	1 Lane	1.5385	-0.2244	0.9133	N-297	0.6500	0.1459	0.65	0.15	K-26	0.9133	Proposed 4.6.2.2
Moment	Exterior	Uniform Distribution	2 or More Lanes	0.8996	0.1293	0.9767	N-290	1.1116	-0.1437	1.11	-0.14	K-24	0.9767	Proposed 4.6.2.2
Moment	Interior	Calibrated Lever	1 Lane	0.7146	0.2918	0.7347	N-265	1.3994	-0.4083	1.40	-0.41	K-22	0.7347	Proposed 4.6.2.2
Moment	Interior	Uniform Distribution	2 or More Lanes	0.8781	0.0337	0.9546	N-258	1.1388	-0.0384	1.14	-0.04	K-21	0.9546	Proposed 4.6.2.2
Alternate Method for Moments														
Moment	Exterior	Calibrated Lever	1 Lane	1.5385	-0.2244	0.9133	N-297	0.6500	0.1459	0.65	0.15	K-26	0.9133	Proposed Appendix C
Moment	Exterior	Calibrated Lever	2 or More Lanes	1.1848	-0.1530	0.9454	N-289	0.8440	0.1291	0.84	0.13	K-25	0.9341	Proposed Appendix C
Moment	Interior	Alternate Method	1 Lane	0.4103	0.2366	0.6387	N-267	2.4372	-0.5767	2.44	-0.58	K-23	0.6387	Proposed Appendix C
Moment	Interior	Uniform Distribution	2 or More Lanes	0.8781	0.0337	0.9546	N-258	1.1388	-0.0384	1.14	-0.04	K-21	0.9546	Proposed Appendix C

Table 17. Calibration constants for concrete spread boxes (type b).

Action	Girder Location	Basic Method	Lanes Loaded	Calibration Constants										
				Initial Trend Line - Lever Rule and Uniform Distribution				Computed Calibration Factors		Recommended Calibration Factors				
				Slope	*Intercept*	R^2	*Figures*	*a*	*b*	*a*	*b*	*Regression Plot*	R^2	
Shear	Exterior	Calibrated Lever	1 Lane	1.6352	-0.2397	0.9452	N-474	0.6115	0.1466	0.61	0.15	K-63	0.9452	Proposed 4.6.2.2
			2 or More Lanes	1.2783	-0.1557	0.9807	N-467	0.7823	0.1218	0.78	0.12	K-62	0.9805	
	Interior		1 Lane	0.9965	0.1123	0.9235	N-446	1.0035	-0.1127	1.00	-0.11	K-61	0.9266	
			2 or More Lanes	1.2020	-0.0808	0.9566	N-439	0.8319	0.0672	0.83	0.07	K-60	0.9566	
Moment	Exterior	Calibrated Lever	1 Lane	1.6036	0.1322	0.5625	N-417	0.6236	-0.0824	0.62	-0.08	K-58	0.5602	
		Uniform Distribution	2 or More Lanes	0.9978	0.0620	0.6756	N-410	1.0022	-0.0621	1.00	-0.06	K-56	0.7111	
	Interior	Calibrated Lever	1 Lane	1.3063	0.2234	0.6774	N-385	0.7655	-0.1710	0.77	-0.17	K-54	0.6968	
		Uniform Distribution	2 or More Lanes	1.1090	-0.0045	0.9092	N-378	0.9017	0.0041	0.90	0.00	K-53	0.9092	
Alternate Method for Moments														
Moment	Exterior	Alternate Method	1 Lane	0.4424	0.1568	0.6184	N-419	2.2604	-0.3544	2.26	-0.35	K-59	0.6184	Proposed Appendix C
		Calibrated Lever	2 or More Lanes	1.8541	-0.3579	0.8327	N-409	0.5393	0.1930	0.54	0.19	K-57	0.8381	
	Interior	Alternate Method	1 Lane	0.5393	0.1624	0.6475	N-387	1.8543	-0.3011	1.85	-0.30	K-55	0.6475	
		Uniform Distribution	2 or More Lanes	1.1090	-0.0045	0.9092	N-378	0.9017	0.0041	0.90	0.00	K-53	0.9092	

Table 18. Calibration constants for cast-in-place concrete boxes (type d).

Action	Girder Location	Basic Method	Lanes Loaded	Calibration Constants										
				Initial Trend Line - Lever Rule and Uniform Distribution				Computed Calibration Factors		Recommended Calibration Factors				
				Slope	*Intercept*	R^2	*Figures*	*a*	*b*	*a*	*b*	*Regression Plot*	R^2	
Shear	Exterior	Calibrated Lever	1 Lane	1.1717	-0.0030	0.8782	N-594	0.8535	0.0026	0.85	0.00	K-42	0.8782	Proposed 4.6.2.2
Shear	Exterior	Calibrated Lever	2 or More Lanes	1.2160	-0.0441	0.9764	N-587	0.8224	0.0363	0.82	0.04	K-41	0.9343	Proposed 4.6.2.2
Shear	Interior	Calibrated Lever	1 Lane	0.8423	0.1687	0.8017	N-566	1.1872	-0.2003	1.19	-0.20	K-40	0.8017	Proposed 4.6.2.2
Shear	Interior	Calibrated Lever	2 or More Lanes	1.4131	-0.3242	0.7972	N-559	0.7077	0.2294	0.71	0.23	K-39	0.7972	Proposed 4.6.2.2
Moment	Exterior	Calibrated Lever	1 Lane	1.8402	0.1636	0.2739	N-537	0.5434	-0.0889	0.54	-0.09	K-37	0.298	Proposed 4.6.2.2
Moment	Exterior	Uniform Distribution	2 or More Lanes	1.5334	0.1096	0.5843	N-530	0.6521	-0.0715	0.65	-0.07	K-35	0.5843	Proposed 4.6.2.2
Moment	Interior	Calibrated Lever	1 Lane	0.5849	0.4779	0.2318	N-505	1.7097	-0.8171	1.71	-0.82	K-33	0.2132	Proposed 4.6.2.2
Moment	Interior	Uniform Distribution	2 or More Lanes	1.0725	0.1054	0.4313	N-498	0.9324	-0.0983	0.93	-0.10	K-31	0.5208	Proposed 4.6.2.2
Alternate Method for Moments														
Moment	Exterior	Alternate Method	1 Lane	0.7996	0.09740	.5565	N-539	1.2506	-0.1218	1.25	-0.12	K-38	0.5159	Proposed Appendix C
Moment	Exterior	Alternate Method	2 or More Lanes	0.5567	0.06920	.5944	N-531	1.7963	-0.1243	1.80	-0.12	K-36	0.5726	Proposed Appendix C
Moment	Interior	Alternate Method	1 Lane	0.8832	0.03120	.8136	N-507	1.1322	-0.0353	1.13	-0.04	K-34	0.8147	Proposed Appendix C
Moment	Interior	Alternate Method	2 or More Lanes	0.4927	0.02480	.8361	N-499	2.0296	-0.0503	2.03	-0.05	K-32	0.8361	Proposed Appendix C

Table 19. Calibration constants for adjacent boxes (types f, g).

Action	Girder Location	Basic Method	Lanes Loaded	Calibration Constants										
				Initial Trend Line - Lever Rule and Uniform Distribution				Computed Calibration Factors		Recommended Calibration Factors				
				Slope	*Intercept*	R^2	*Figures*	*a*	*b*	*a*	*b*	*Regression Plot*	R^2	
Shear	Exterior	Calibrated Lever	1 Lane	1.1507	-0.0311	0.9898	N-714	0.8690	0.0270	0.87	0.03	K-52	0.9898	Proposed 4.6.2.2
Shear	Exterior	Calibrated Lever	2 or More Lanes	1.1026	-0.0383	0.9898	N-707	0.9069	0.0347	0.91	0.03	K-51	0.9811	Proposed 4.6.2.2
Shear	Interior	Calibrated Lever	1 Lane	0.9555	0.0934	0.9342	N-686	1.0466	-0.0977	1.05	-0.10	K-50	0.9477	Proposed 4.6.2.2
Shear	Interior	Calibrated Lever	2 or More Lanes	1.0017	0.0491	0.9650	N-679	0.9983	-0.0490	1.00	-0.05	K-49	0.965	Proposed 4.6.2.2
Moment	Exterior	Calibrated Lever	1 Lane	3.9119	-0.0907	0.7059	N-657	0.2556	0.0232	0.26	0.02	K-47	0.8101	Proposed 4.6.2.2
Moment	Exterior	Uniform Distribution	2 or More Lanes	1.8761	0.0095	0.9233	N-650	0.5330	-0.0051	0.53	-0.01	K-46	0.9427	Proposed 4.6.2.2
Moment	Interior	Calibrated Lever	1 Lane	1.6904	0.2538	0.4194	N-625	0.5916	-0.1501	0.59	-0.15	K-44	0.5506	Proposed 4.6.2.2
Moment	Interior	Uniform Distribution	2 or More Lanes	1.5520	-0.0822	0.9528	N-618	0.6443	0.0530	0.64	0.05	K-43	0.9795	Proposed 4.6.2.2
Alternate Method for Moments														
Moment	Exterior	Alternate Method	1 Lane	0.7642	0.0898	0.7406	N-659	1.3086	-0.1175	1.31	-0.12	K-45	0.7072	Proposed Appendix C
Moment	Exterior	Uniform Distribution	2 or More Lanes	1.8761	0.0095	0.9233	N-650	0.5330	-0.0051	0.53	-0.01	K-46	0.9427	Proposed Appendix C
Moment	Interior	Alternate Method	1 Lane	0.8362	0.0380	0.9086	N-627	1.1959	-0.0454	1.20	-0.05	K-45	0.9117	Proposed Appendix C
Moment	Interior	Uniform Distribution	2 or More Lanes	1.5520	-0.0822	0.9528	N-618	0.6443	0.0530	0.64	0.05	K-43	0.9795	Proposed Appendix C

Table 20. Multiple presence factors.

Number of Loaded Lanes	Multiple Presence Factor "m"
1	1.20
2	1.00
3	0.85
4 or more	0.65

pared to the values from the previous equation. Some results of this comparison are shown in Figure 85 and Figure 86. This result is consistent with experience with this computation and the present LRFD specifications.

It was noted that type "k" bridges have different stiffness characteristics, so a value of 0.09 was determined for this bridge type. The results using 0.09 for type "k" bridges are shown in Figure 87. This coefficient was based upon the average of the following term for the type "k" bridges:

$$0.20\left(\frac{12.0Lt_s^3}{K_g}\right)^{0.3}$$

The recommended skew correction factors are summarized in Table 21. The range of application remains the same as in the present specifications.

Bridges Used to Test Ranges of Applicability

Eleven simply supported steel I-beam bridges were developed for testing the limits of application for the new distribution factor equations. The span length, girder spacing, and overhang length were chosen so that the current LRFD limits would be tested. The initial dimensions of the steel I-beam sections were determined by using the stiffness parameters, α and θ, as explained in other texts (for example, Sanders and Elleby [*7*]). The final section proportions for the steel I-sections were determined by use of the design criteria in the AASHTO Standard Specifications. The following criteria were used: the ratio of span to depth was between 20 and 25; the ratio of top flange width to top flange thickness was between 16 and 20; the ratio of bottom flange thickness to top flange thickness was between 1.5 and 2.0; the minimum web thickness was determined by dividing the web depth by 140; and the minimum slab thickness was a function of the beam spacing, where:

$$\frac{(S+10)}{30} \geq 0.542$$

See Appendix P.

The uniform distribution method and the calibrated lever rule are compared to the rigorous analysis in Figures 88 through 92. The test bridges performed well in most cases. The calibrated lever rule predicted the live load moment distribution factor for the exterior girder with one lane loaded better than the uniform method, as shown in Figure 88 and Figure 89. The uniform distribution method resulted in an R^2 value of 0.878 for moment in the interior girder with two or more lanes loaded, as shown in Figure 90. The calibrated lever rule correlated reasonably well with the rigorous analysis for shear in both the exterior and interior girder, as shown in Figure 91 and Figure 92. The R^2 values for the latter two cases are 0.762 and 0.841 for the exterior and interior girder, respectively. Additional figures showing the comparison to rigorous analysis are shown in Appendix N.

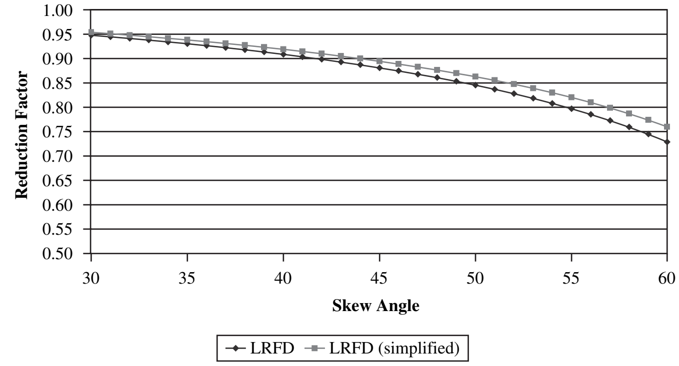


Figure 86. Average reduction factors for moment on type "e" bridges.

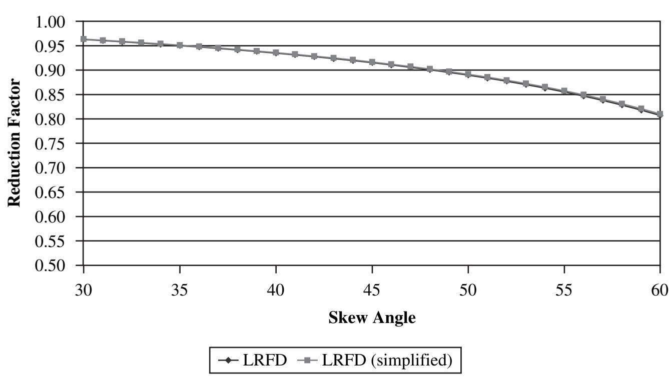


Figure 85. Average reduction factors for moment on type "a" bridges.

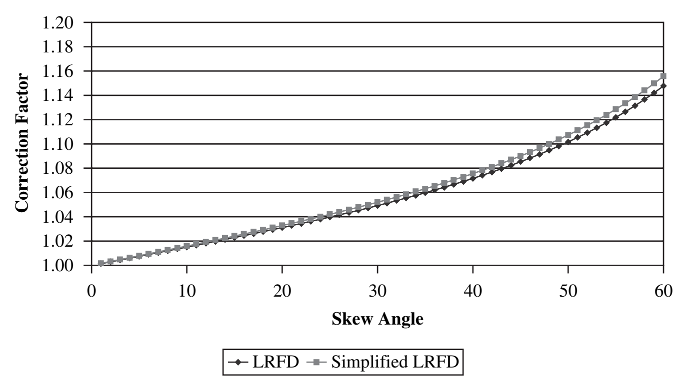


Figure 87. Average correction factors for type "k" bridges.

Table 21. Skew adjustment factor summary.

Type of Superstructure	Applicable Cross Section from Table 4.6.2.2.1-1	Correction Factor	Range of Applicability
Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T- and Double T-Section	a, e and also h, i, j if sufficiently connected to act as a unit	$1.0 + 0.20 \tan\theta$	$0° \leq \theta \leq 60°$ $3.5 \leq S \leq 16.0$ $20 \leq L \leq 240$ $N_b \geq 4$
Precast Concrete I- and Bulb-Tee Beams	k	$1.0 + 0.09 \tan\theta$	$0° \leq \theta \leq 60°$ $3.5 \leq S \leq 16.0$ $20 \leq L \leq 240$ $N_b \geq 4$
Cast-in-Place Concrete Multicell Box	d	$1.0 + \left(0.25 + \frac{12.0L}{70d}\right)\tan\theta$	$0° < \theta \leq 60°$ $6.0 < S \leq 13.0$ $20 \leq L \leq 240$ $35 \leq d \leq 110$ $N_c \geq 3$
Concrete Deck on Spread Concrete Box Beams	B, c	$1.0 + \frac{\sqrt{\frac{Ld}{12.0}}}{6S}\tan\theta$	$0° < \theta \leq 60°$ $6.0 \leq S \leq 11.5$ $20 \leq L \leq 140$ $18 \leq d \leq 65$ $N_b \geq 3$
Concrete Box Beams Used in Multibeam Decks	f, g	$1.0 + \frac{12.0L}{90d}\sqrt{\tan\theta}$	$0° < \theta \leq 60°$ $20 \leq L \leq 120$ $17 \leq d \leq 60$ $35 \leq b \leq 60$ $5 \leq N_b \leq 20$

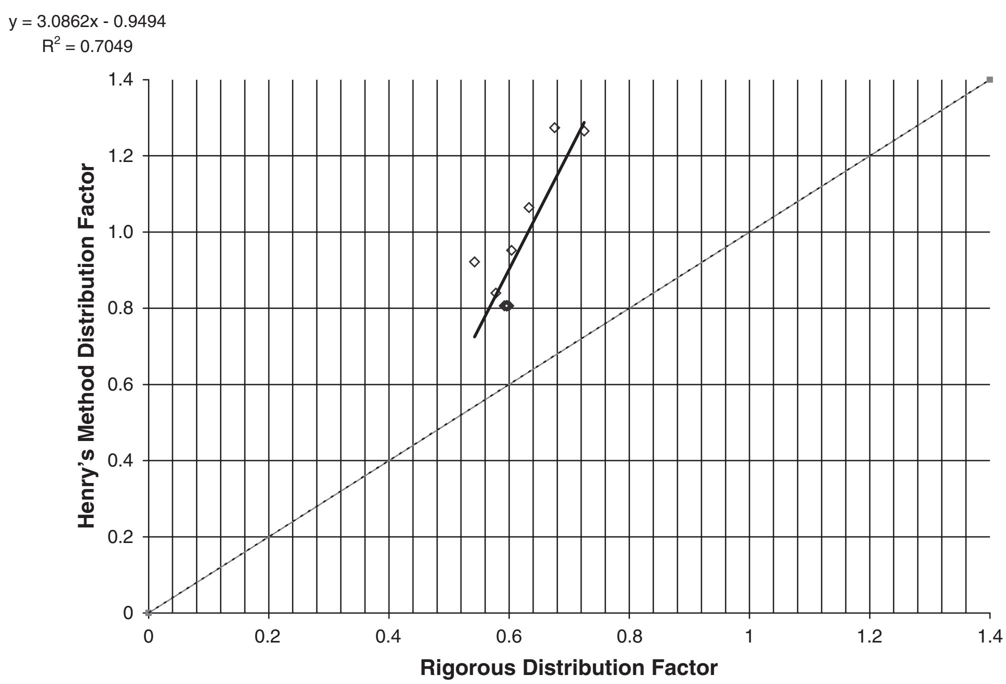


Figure 88. Uniform distribution (Henry's) method versus rigorous analysis for moment in exterior girder, one lane loaded, Location 104.00 (note Henry's method is NOT proposed for this case).

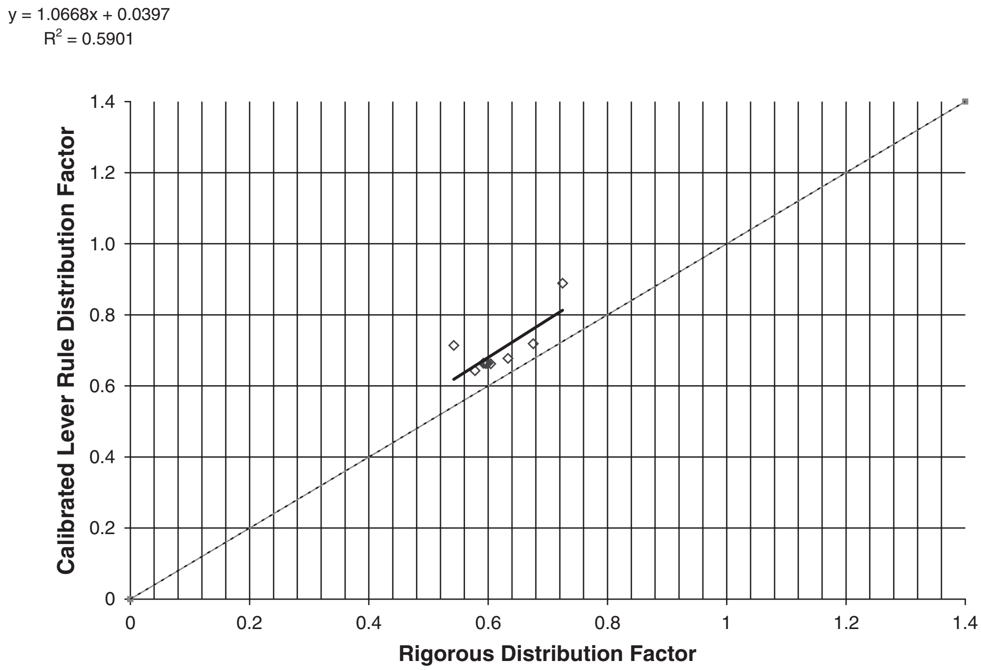


Figure 89. Calibrated lever rule formula versus rigorous analysis for moment in exterior girder, one lane loaded, Location 104.00.

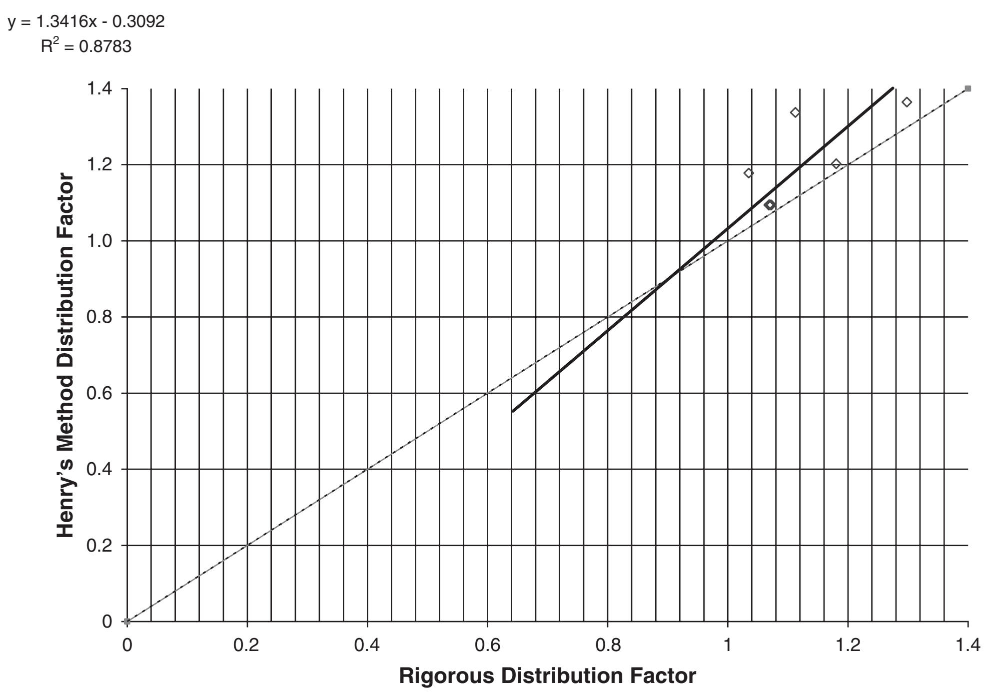


Figure 90. Uniform distribution (Henry's) method versus rigorous analysis for moment in interior girder, two or more lanes loaded, Location 104.00.

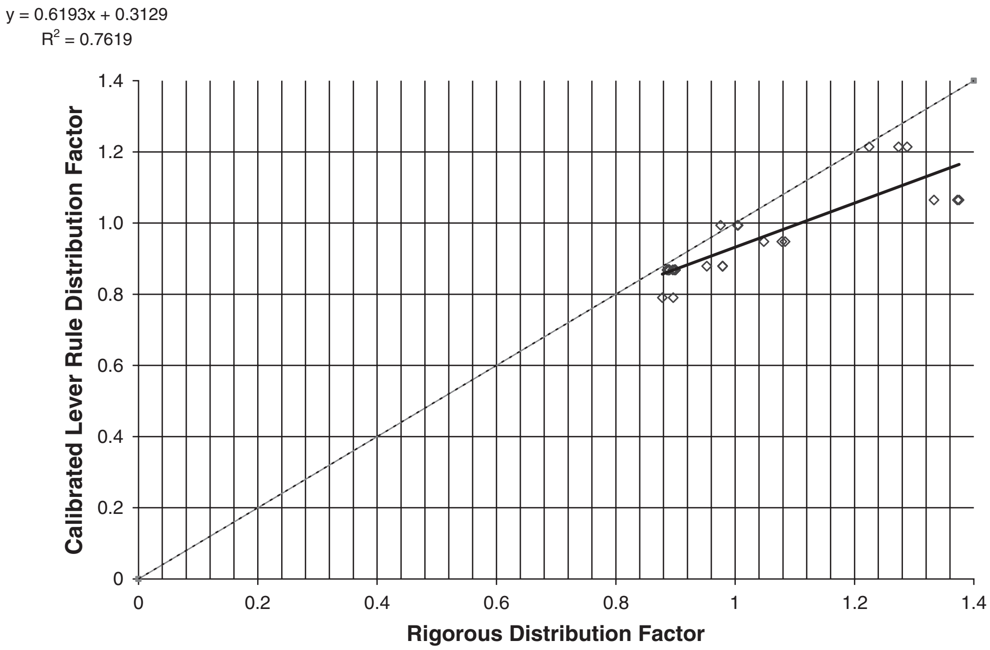


Figure 91. Calibrated lever rule formula versus rigorous analysis for shear in exterior girder, two or more lanes loaded, Location 100.00.

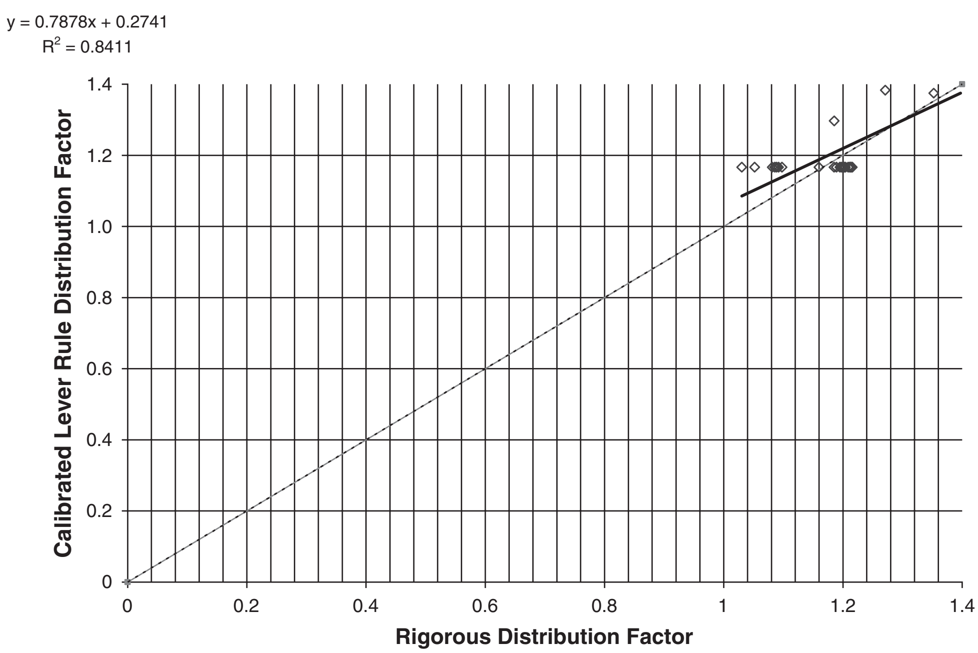


Figure 92. Calibrated lever rule formula versus rigorous analysis for shear in interior girder, two or more lanes loaded, Location 100.00.

Calibration and Distribution Simplification (Variability) Factors

The proposed method predicts the rigorous results well, but the results vary from case to case. This variation is expected and is addressed in a systematic manner. The proposed method was calibrated to the mean and then adjusted according to the statistical characteristics by application of the live load DSF. If the simplified method predicts the rigorous distribution factor well, the DSF approaches unity. Cases where variability is high may warrant a DSF significantly higher than unity (1.0).

For all results, the simplified and rigorous distribution factors were ratioed to create a new data set, the simple-to-rigorous (S/R) data. Assuming normality, these data may be represented by a mean and a standard deviation. These statistics are summarized in Table 22 through Table 27.

The procedure used to estimate the DSF is outlined below. The DSF shifts the mean as

$$\gamma_s \mu_{S/R} = 1 + z_a(\sigma_{S/R}) \qquad (2\text{-}18)$$

Where:

γ_s = DSF,

$\mu_{S/R}$ = mean of the ratio of the simple to rigorous for each set $\frac{S_i}{R_i}$

$\sigma_{S/R}$ = standard deviation of the ratio of the simple to rigorous for each sample, and

z_a = number of standard deviations of offset from the mean.

Solve for γ_s to give:

$$\gamma_s = \frac{1 + z_a(\sigma_{S/R})}{\mu_{S/R}} = \left(\frac{1}{\mu_{S/R}}\right) + z_a(COV_{S/R}) \qquad (2\text{-}19)$$

where $COV_{S/R}$ is the coefficient of variation.

Using one standard deviation for the offset, i.e., $z_a = 0.5$, a substitution gives:

$$\gamma_s = \frac{1 + 0.5(\sigma_{S/R})}{\mu_{S/R}} = \left(\frac{1}{\mu_{S/R}}\right) + 0.5(COV_{S/R}) \qquad (2\text{-}20)$$

One-half standard deviation was used for the specification language (see Appendix H).

A more formal way to compute the DSF is to perform a regression analysis on the 1:1 plots using various confidence intervals, such as 95% or 99%. Part of the variation is associated with the confidence of predicting the mean, and part is associated with the inherent variation within the bridge samples. The split varies along the 1:1 curve. For example, in an area where there is a lot of data (e.g., a distribution factor of around 0.6), the confidence in the mean is high. In the outer area (e.g., an area with a distribution factor of around 1.2), the mean prediction is less certain. This level of regression analysis is possible, but is considered beyond the project scope and beyond the goal of keeping the results and analysis simple.

Table 22. DSFs for steel I-girder bridges (type a).

Action	Basic Method	Girder Location	Lanes Loaded	Figures	Live Load Distribution Simplification Factor (DSF) Computations, γ_s												
					Ratio of Means	Inverse	COV	No. of Std. Dev. Offset $z_a = 1$			No. of Std. Dev. Offset $z_a = 0.5$			No. of Std. Dev. Offset $z_a = 0.0$			
								No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 1$)	No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.5$)	No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.0$)	
					S/R	$(S/R)^{-1}$	$V_{S/R}$	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	
Shear	Calibrated Lever	Exterior	1 Lane	13c	1.006	0.994	0.056	1.0	1.050	1.05	0.5	1.022	1.00	0.0	0.994	1.00	Proposed 4.6.2.2
			2 or More Lanes	14c	1.011	0.989	0.072	1.0	1.061	1.05	0.5	1.025	1.00	0.0	0.989	1.00	
		Interior	1 Lane	15c	1.016	0.984	0.078	1.0	1.062	1.05	0.5	1.023	1.00	0.0	0.984	1.00	
			2 or More Lanes	16c	1.015	0.985	0.116	1.0	1.101	1.10	0.5	1.043	1.05	0.0	0.985	1.00	
Moment	Calibrated Lever	Exterior	1 Lane	17c	1.004	0.996	0.086	1.0	1.082	1.10	0.5	1.039	1.05	0.0	0.996	1.00	
	Uniform Distribution		2 or More Lanes	18c	0.996	1.004	0.133	1.0	1.137	1.15	0.5	1.071	1.10	0.0	1.004	1.00	
	Calibrated Lever	Interior	1 Lane	19c	0.993	1.007	0.198	1.0	1.205	1.20	0.5	1.106	1.10	0.0	1.007	1.00	
	Uniform Distribution		2 or More Lanes	20c	0.988	1.012	0.059	1.0	1.071	1.10	0.5	1.042	1.05	0.0	1.012	1.00	
Alternate Method for Moments																	
Moment	Calibrated Lever	Exterior	1 Lane	61c	1.004	0.996	0.086	1.0	1.082	1.10	0.5	1.039	1.05	0.0	0.996	1.00	Proposed Appendix C
	Calibrated Lever		2 or More Lanes	62c	1.008	0.992	0.129	1.0	1.121	1.15	0.5	1.057	1.05	0.0	0.992	1.00	
	Alternate Method	Interior	1 Lane	63c	1.008	0.992	0.099	1.0	1.091	1.10	0.5	1.042	1.05	0.0	0.992	1.00	
	Uniform Distribution		2 or More Lanes	64c	0.988	1.012	0.059	1.0	1.071	1.10	0.5	1.042	1.05	0.0	1.012	1.00	

Table 23. DSFs for concrete I-girder bridges (type h, l, j, k).

Action	Basic Method	Girder Location	Lanes Loaded	Figures	Live Load Distribution Simplification Factor (DSF) Computations: Ratio of Means	Inverse	COV	No. of Std. Dev. Offset $z_a = 1$: No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 1$)	No. of Std. Dev. Offset $z_a = 0.5$: No. of Std. Dev Offset.	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.5$)	No. of Std. Dev. Offset $z_a = 0.0$: No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.0$)	
					S/R	$(S/R)^{-1}$	$V_{S/R}$	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	
Shear	Calibrated Lever	Exterior	1 Lane	21c	0.988	1.012	0.033	1.0	1.046	1.05	0.5	1.029	1.00	0.0	1.012	1.00	Proposed 4.6.2.2
			2 or More Lanes	22c	0.998	1.002	0.043	1.0	1.045	1.05	0.5	1.024	1.00	0.0	1.002	1.00	
		Interior	1 Lane	23c	1.003	0.997	0.048	1.0	1.045	1.05	0.5	1.021	1.00	0.0	0.997	1.00	
			2 or More Lanes	24c	1.011	0.989	0.093	1.0	1.082	1.10	0.5	1.036	1.05	0.0	0.989	1.00	
Moment	Calibrated Lever	Exterior	1 Lane	25c	1.008	0.992	0.097	1.0	1.089	1.10	0.5	1.040	1.05	0.0	1.992	1.00	
	Uniform Distribution		2 or More Lanes	26c	0.990	1.010	0.185	1.0	1.195	1.20	0.5	1.103	1.10	0.0	1.010	1.00	
	Calibrated Lever	Interior	1 Lane	27c	1.000	1.000	0.160	1.0	1.160	1.20	0.5	1.080	1.10	0.0	1.000	1.00	
	Uniform Distribution		2 or More Lanes	28c	0.999	1.001	0.072	1.0	1.073	1.10	0.5	1.037	1.05	0.0	1.001	1.00	
Alternate Method for Moments																	
Moment	Calibrated Lever	Exterior	1 Lane	65c	1.008	0.992	0.097	1.0	1.089	1.10	0.5	1.040	1.05	0.0	0.992	1.00	Proposed Appendix C
	Calibrated Lever		2 or More Lanes	66c	1.000	1.000	0.098	1.0	1.098	1.10	0.5	1.049	1.05	0.0	1.000	1.00	
	Alternate Method	Interior	1 Lane	67c	0.993	1.007	0.071	1.0	1.078	1.10	0.5	1.043	1.05	0.0	1.007	1.00	
	Uniform Distribution		2 or More Lanes	68c	0.999	1.001	0.072	1.0	1.073	1.10	0.5	1.037	1.05	0.0	1.001	1.00	

Table 24. DSFs for cast-in-place tee girder bridges (type a).

Action	Basic Method	Girder Location	Lanes Loaded	Figures	Ratio of Means	Inverse	COV	No. of Std. Dev. Offset $z_a = 1$: No. of Std. Dev. Offset	No. of Std. Dev. Offset $z_a = 1$: Computed Analysis Factor	No. of Std. Dev. Offset $z_a = 1$: Rounded Analysis Factor ($z_a = 1$)	No. of Std. Dev. Offset $z_a = 0.5$: No. of Std. Dev. Offset	No. of Std. Dev. Offset $z_a = 0.5$: Computed Analysis Factor	No. of Std. Dev. Offset $z_a = 0.5$: Rounded Analysis Factor ($z_a = 0.5$)	No. of Std. Dev. Offset $z_a = 0.0$: No. of Std. Dev. Offset	No. of Std. Dev. Offset $z_a = 0.0$: Computed Analysis Factor	No. of Std. Dev. Offset $z_a = 0.0$: Rounded Analysis Factor ($z_a = 0.0$)	
					S/R	$(S/R)^{-1}$	$V_{S/R}$	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	
Shear	Calibrated Lever	Exterior	1 Lane	29c	1.018	0.982	0.087	1.0	1.070	1.10	0.5	1.026	1.00	0.0	0.982	1.00	Proposed 4.6.2.2
			2 or More Lanes	30c	1.015	0.985	0.083	1.0	1.068	1.10	0.5	1.027	1.00	0.0	0.985	1.00	
		Interior	1 Lane	31c	0.998	1.002	0.096	1.0	1.098	1.10	0.5	1.050	1.05	0.0	1.002	1.00	
			2 or More Lanes	32c	0.990	1.010	0.142	1.0	1.152	1.15	0.5	1.081	1.10	0.0	1.010	1.00	
Moment	Calibrated Lever	Exterior	1 Lane	33c	1.016	0.984	0.080	1.0	1.064	1.10	0.5	1.024	1.00	0.0	0.984	1.00	
	Uniform Distribution		2 or More Lanes	34c	1.014	0.986	0.119	1.0	1.105	1.10	0.5	1.046	1.05	0.0	0.986	1.00	
	Calibrated Lever	Interior	1 Lane	35c	0.989	1.011	0.233	1.0	1.244	1.25	0.5	1.128	1.10	0.0	1.011	1.00	
	Uniform Distribution		2 or More Lanes	36c	0.999	1.001	0.091	1.0	1.092	1.10	0.5	1.047	1.05	0.0	1.001	1.00	
Alternate Method for Moments																	
Moment	Calibrated Lever	Exterior	1 Lane	69c	1.016	0.984	0.080	1.0	1.064	1.10	0.5	1.024	1.00	0.0	0.984	1.00	Proposed Appendix C
	Calibrated Lever		2 or More Lanes	70c	1.005	0.995	0.078	1.0	1.073	1.10	0.5	1.034	1.05	0.0	0.995	1.00	
	Alternate Method	Interior	1 Lane	71c	1.004	0.996	0.271	1.0	1.267	1.30	0.5	1.132	1.10	0.0	0.996	1.00	
	Uniform Distribution		2 or More Lanes	72c	0.999	1.001	0.091	1.0	1.092	1.10	0.5	1.047	1.05	0.0	1.001	1.00	

Live Load Distribution Simplification Factor (DSF) Computations

Table 25. DSFs for precast spread box girders (type b).

Action	Basic Method	Girder Location	Lanes Loaded	Figures	Live Load Distribution Simplification Factor (DSF) Computations													
					Ratio of Means	Inverse	COV	No. of Std. Dev. Offset $z_a = 1$			No. of Std. Dev. Offset $z_a = 0.5$			No. of Std. Dev. Offset $z_a = 0.0$			
								No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 1$)	No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.5$)	No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.0$)	
					S/R	$(S/R)^{-1}$	$V_{S/R}$	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	
Shear	Calibrated Lever	Exterior	1 Lane	37c	1.005	0.995	0.058	1.0	1.053	1.05	0.5	1.024	1.05	0.0	0.995	1.00	Proposed 4.6.2.2
			2 or More Lanes	38c	0.998	1.002	0.058	1.0	1.060	1.10	0.5	1.031	1.05	0.0	1.002	1.00	
		Interior	1 Lane	39c	1.000	1.000	0.056	1.0	1.056	1.05	0.5	1.028	1.05	0.0	1.000	1.00	
			2 or More Lanes	40c	1.001	0.999	0.054	1.0	1.053	1.05	0.5	1.026	1.05	0.0	0.999	1.00	
Moment	Calibrated Lever	Exterior	1 Lane	41c	0.995	1.005	0.264	1.0	1.269	1.30	0.5	1.137	1.15	0.0	1.005	1.00	
	Uniform Distribution		2 or More Lanes	42c	1.001	0.999	0.091	1.0	1.090	1.10	0.5	1.045	1.05	0.0	0.999	1.00	
	Calibrated Lever	Interior	1 Lane	43c	1.014	0.986	0.179	1.0	1.165	1.20	0.5	1.076	1.10	0.0	0.986	1.00	
	Uniform Distribution		2 or More Lanes	44c	0.997	1.003	0.124	1.0	1.127	1.15	0.5	1.065	1.10	0.0	1.003	1.00	
Alternate Method for Moments																	
Moment	Alternate Method	Exterior	1 Lane	73c	0.982	1.018	0.216	1.0	1.234	1.20	0.5	1.126	1.15	0.0	1.018	1.00	Proposed Appendix C
	Calibrated Lever		2 or More Lanes	74c	0.994	1.006	0.137	1.0	1.143	1.15	0.5	1.075	1.10	0.0	1.006	1.00	
	Alternate Method	Interior	1 Lane	75c	0.994	1.006	0.214	1.0	1.220	1.25	0.5	1.113	1.15	0.0	1.006	1.00	
	Uniform Distribution		2 or More Lanes	76c	0.997	1.003	0.124	1.0	1.127	1.15	0.5	1.065	1.10	0.0	1.003	1.00	

Table 26. DSFs for cast-in-place concrete boxes (type d).

Action	Basic Method	Girder Location	Lanes Loaded	Figures	Live Load Distribution Simplification Factor (DSF) Computations: Ratio of Means S/R	Inverse $(S/R)^{-1}$	COV $V_{S/R}$	No. of Std. Dev. Offset $z_a = 1$: No. of Std. Dev. Offset z_a	Computed Analysis Factor γ_s	Rounded Analysis Factor ($z_a = 1$) γ_s (rounded)	No. of Std. Dev. Offset $z_a = 0.5$: No. of Std. Dev. Offset z_a	Computed Analysis Factor γ_s	Rounded Analysis Factor ($z_a = 0.5$) γ_s (rounded)	No. of Std. Dev. Offset $z_a = 0.0$: No. of Std. Dev. Offset z_a	Computed Analysis Factor γ_s	Rounded Analysis Factor ($z_a = 0.0$) γ_s (rounded)	
Shear	Calibrated Lever	Exterior	1 Lane	45c	0.990	1.010	0.078	1.0	1.088	1.10	0.5	1.049	1.05	0.0	1.010	1.00	Proposed 4.6.2.2
			2 or More Lanes	46c	1.000	1.000	0.034	1.0	1.034	1.05	0.5	1.017	1.00	0.0	1.000	1.00	
		Interior	1 Lane	47c	1.004	0.996	0.086	1.0	1.082	1.10	0.5	1.039	1.05	0.0	0.996	1.00	
			2 or More Lanes	48c	1.004	0.996	0.063	1.0	1.059	1.05	0.5	1.028	1.00	0.0	0.996	1.00	
Moment	Calibrated Lever	Exterior	1 Lane	49c	0.980	1.020	0.304	1.0	1.324	1.35	0.5	1.172	1.20	0.0	1.020	1.00	
	Uniform Distribution		2 or More Lanes	50c	1.000	1.000	0.084	1.0	1.084	1.10	0.5	1.042	1.05	0.0	1.000	1.00	
	Calibrated Lever	Interior	1 Lane	51c	0.983	1.017	0.321	1.0	1.338	1.35	0.5	1.178	1.20	0.0	1.017	1.00	
	Uniform Distribution		2 or More Lanes	52c	0.993	1.007	0.099	1.0	1.106	1.10	0.5	1.057	1.05	0.0	1.007	1.00	
Alternate Method for Moments																	
Moment	Alternate Method	Exterior	1 Lane	77c	1.007	0.993	0.158	1.0	1.151	1.15	0.5	1.072	1.10	0.0	0.993	1.00	Proposed Appendix C
	Alternate Method		2 or More Lanes	78c	1.016	0.984	0.130	1.0	1.114	1.10	0.5	1.049	1.05	0.0	0.984	1.00	
	Alternate Method	Interior	1 Lane	79c	0.978	1.022	0.075	1.0	1.097	1.10	0.5	1.060	1.10	0.0	1.022	1.00	
	Alternate Method		2 or More Lanes	80c	1.001	0.999	0.069	1.0	1.068	1.10	0.5	1.034	1.05	0.0	0.999	1.00	

Table 27. DSFs for adjacent boxes (types f, g).

Action	Basic Method	Girder Location	Lanes Loaded	Figures	Live Load Distribution Simplification Factor (DSF) Computations												
					Ratio of Means	Inverse	COV	No. of Std. Dev. Offset $z_a = 1$			No. of Std. Dev. Offset $z_a = 0.5$			No. of Std. Dev. Offset $z_a = 0.0$			
								No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 1$)	No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.5$)	No. of Std. Dev. Offset	Computed Analysis Factor	Rounded Analysis Factor ($z_a = 0.0$)	
					S/R	$(S/R)^{-1}$	$V_{S/R}$	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	z_a	γ_s	γ_s (rounded)	
Shear	Calibrated Lever	Exterior	1 Lane	53c	1.005	0.995	0.067	1.0	1.062	1.10	0.5	1.029	1.05	0.0	1.995	1.00	Proposed 4.6.2.2
			2 or More Lanes	54c	0.982	1.018	0.083	1.0	1.101	1.10	0.5	1.060	1.05	0.0	1.018	1.00	
		Interior	1 Lane	55c	0.975	1.026	0.251	1.0	1.277	1.30	0.5	1.151	1.15	0.0	1.026	1.00	
			2 or More Lanes	56c	0.987	1.013	0.174	1.0	1.187	1.20	0.5	1.100	1.10	0.0	1.013	1.00	
Moment	Calibrated Lever	Exterior	1 Lane	57c	0.975	1.026	0.245	1.0	1.271	1.30	0.5	1.148	1.15	0.0	1.026	1.00	
	Uniform Distribution		2 or More Lanes	58c	0.980	1.020	0.149	1.0	1.169	1.20	0.5	1.095	1.10	0.0	1.020	1.00	
	Calibrated Lever	Interior	1 Lane	59c	0.991	1.009	0.405	1.0	1.414	1.45	0.5	1.212	1.20	0.0	1.009	1.00	
	Uniform Distribution		2 or More Lanes	60c	0.989	1.011	0.087	1.0	1.098	1.10	0.5	1.055	1.05	0.0	1.011	1.00	
Alternate Method for Moments																	
Moment	Alternate Method	Exterior	1 Lane	81c	0.978	1.022	0.273	1.0	1.295	1.30	0.5	1.159	1.15	0.0	1.022	1.00	Proposed Appendix C
	Uniform Distribution		2 or More Lanes	82c	0.980	1.020	0.149	1.0	1.169	1.20	0.5	1.095	1.10	0.0	1.020	1.00	
	Alternate Method	Interior	1 Lane	83c	0.978	1.022	0.111	1.0	1.133	1.15	0.5	1.078	1.10	0.0	1.022	1.00	
	Uniform Distribution		2 or More Lanes	84c	0.989	1.011	0.087	1.0	1.098	1.10	0.5	1.055	1.05	0.0	1.011	1.00	

CHAPTER 3

Interpretation, Appraisal, and Application

Introduction

The previous chapters presented the research approach and findings. This information is critical in understanding the research. However, practical considerations are paramount in the transfer of this research into professional practice. It is clear that practitioners expect validation of research work in a formal manner. For example, validation has been provided by studies to support the recent adoption of the new LRFD articles 6.10 and 6.11 for steel plate girders and boxes, testing of the LRFR specifications, and several new NCHRP projects. One of the most effective means to provide interpretation and appraisal of a proposed specification is to perform the computations and compare with the existing method. This is termed *regression testing*.

Appendix K presents the regression test results by bridge cross-section type, with three plots presented for every load case, action, and girder location. Figures 93 through 95 show examples of these plots. The first plot shows the proposed method with multiple presence factors and DSFs included compared to the LRFD distribution factors. Then, for the same load case, action, and girder location, a plot of the proposed and the rigorous results are shown. The values in this plot do not contain the multiple presence factors or DSFs. Finally, a plot of the current LRFD specifications versus the rigorous distribution factors is shown. Multiple presence factors are included in the LRFD values, but not in the rigorous values. This inconsistency is necessary because the LRFD equations include these factors. In the case of multiple lanes loaded, one does not know which case controlled (in the current LRFD specifications). The multiple presence factor would rotate the plot, but not affect the quality of the regression coefficient.

The quality of the results when compared to the rigorous distribution factors is best indicated by the scatter of the data. Data that lie closely along a line indicate that the method is easily calibrated (either upward or downward). The comparison of the proposed method versus rigorous method indicates the quality of the proposed method. The comparison of the proposed method versus current LRFD method indicates the expected change from present practice. Finally, the comparison of the current LRFD method versus rigorous method indicates the quality of the present methods. These plots provide valuable information about the implications to practice. The comparison of the standard specification method with the rigorous analysis is available in Appendix N. Typically, these comparisons are poor and therefore are not included in the formal regression results.

Regression Testing

The proposed simplified method was compared to the current LRFD specifications. The comparisons were made using all DSFs and multiple presence factors as specified in both the recommend specifications (Appendix H) and the current specifications. For example, Figure 93 shows three plots for moment distribution to the exterior girder with one lane loaded for Bridge Set 1 (slab-on-girder bridges). The top plot illustrates the proposed method against the LRFD method. Note that for both methods, the lever rule is specified for distribution factor calculation.

The proposed method differs from the LRFD method in two ways: (1) the inclusion of calibration factors to set the data as near as possible to the rigorous result and (2) the inclusion of DSFs to provide a shift of the simple method above the mean of the rigorous results. Based on the use of these two factors, one would expect the two implementations of the lever rule to be linearly related, and therefore the graph would be a straight line with a correlation coefficient (R^2) of 1.0. However, this is not the case, because of the use of the so-called *rigid* method for exterior girders in the LRFD specifications. The top plot in Figure 93 clearly

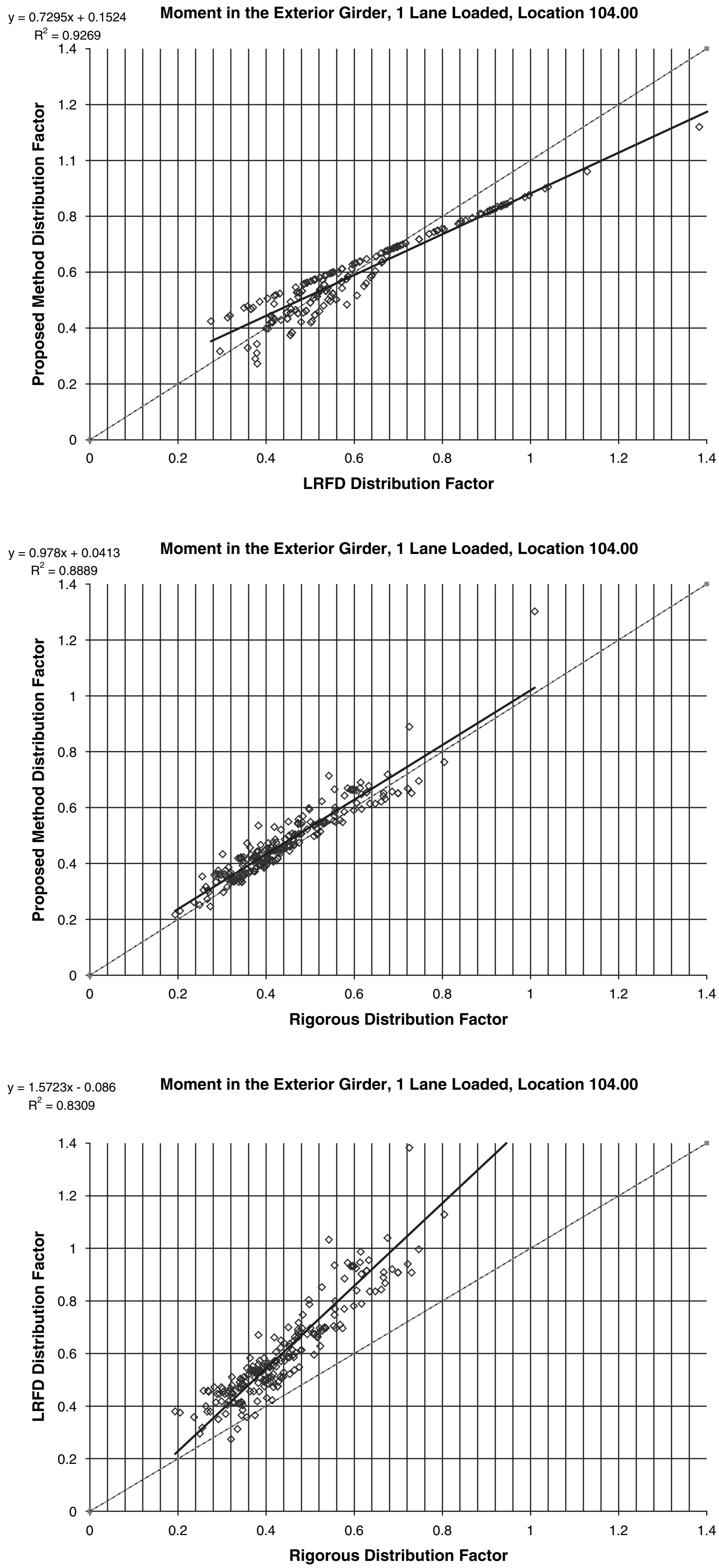
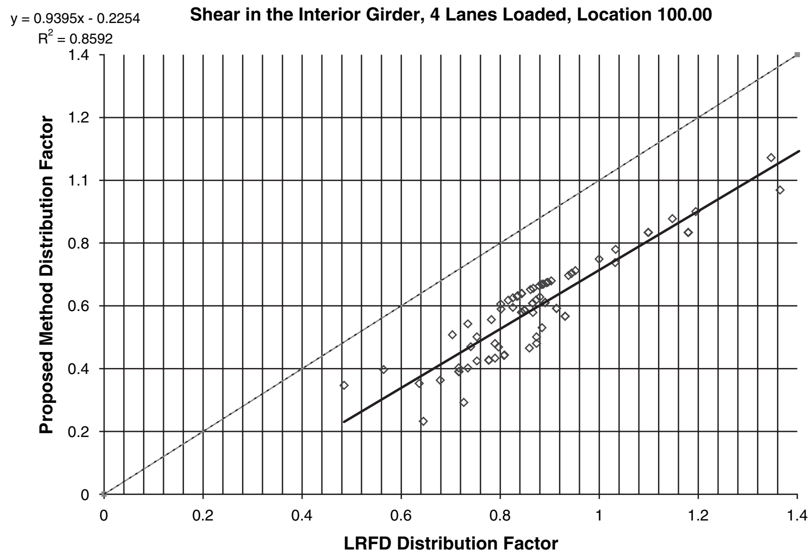


Figure 93. Slab-on-girder, moment, exterior girder, one lane loaded (example of a regression plot).



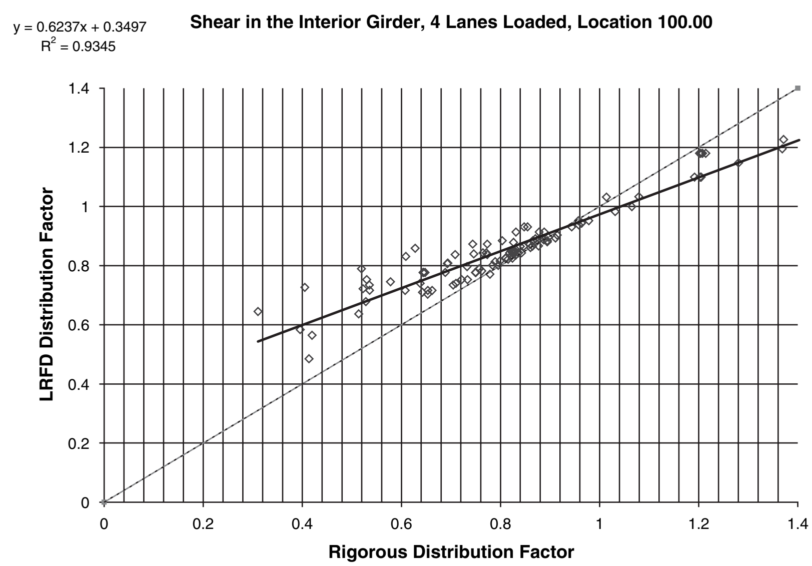


Figure 94. Slab-on-girder, shear, interior girder, four lanes loaded (example of a regression plot).

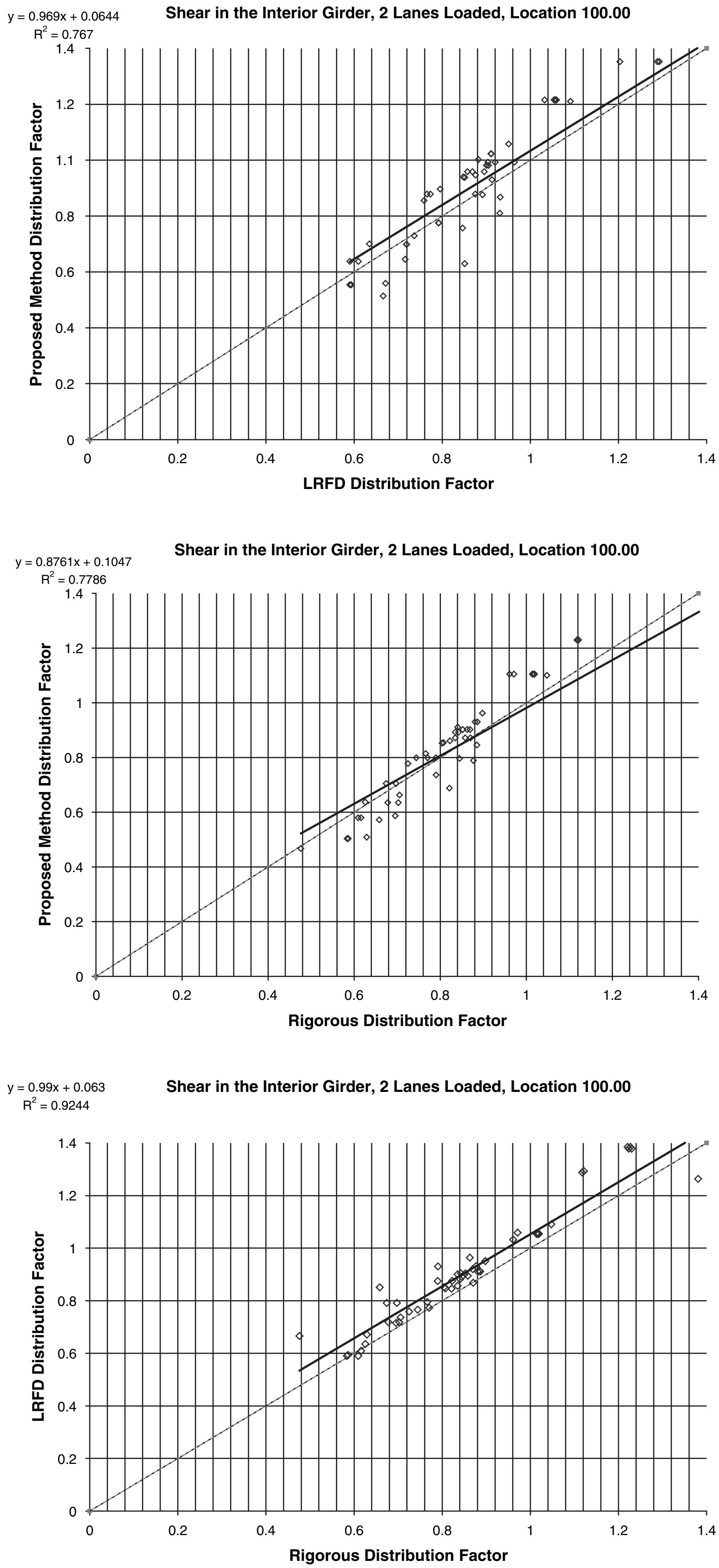


Figure 95. Spread box beam, shear, interior girder, two lanes loaded (example of a regression plot).

shows many of the data falling on a straight line, with some data points lying below the direct correlation. Investigation of the input data and intermediate calculations for these bridges shows that these are the cases with a small lever rule distribution factor. The small lever rule distribution factor is due to a combination of a short deck overhang and a wide curb width. Therefore, the LRFD rigid method value controls.

The middle plot in Figure 93 shows the proposed method compared to rigorous analysis. In this plot, the effect of calibrating the lever rule to match the rigorous results can clearly be seen, as the trend line for the proposed method lies close to the 1:1 baseline.

The bottom plot in Figure 93 shows the LRFD distribution factors, with the multiple presence factors included compared to the rigorous distribution factors. Because the multiple presence factor of 1.2 is included in these data, the LRFD results are generally conservative compared to the rigorous results, even though they are fairly close to the proposed method results in the first plot.

In many cases, the LRFD method uses curve-fitted equations and the proposed method employs the calibrated lever rule and the uniform distribution method. For these cases, the two procedures often compare well, with the expected variation in data (i.e., scatter). Finally, in cases where the LRFD is not a good predictor of the rigorous distribution and the proposed method is, significant scatter is expected in the specification-regression (i.e., top) plot.

As mentioned previously, the full set of regression plots and the associated plots with the rigorous distribution factors are available in Appendix K. There are two general trends from the full result set:

- For three and four lanes loaded, the proposed method is less conservative than the current LRFD method. This applies to all the bridge types studied. Except for a few cases, the results are below the 1:1 trend line, indicating that the proposed method distribution factor is smaller. This trend is expected because the two-lane loaded case typically controls, which means that the LRFD distribution factors are likely using a multiple presence factor of 1.0. In contrast, the other methods are using the three- and four-lane multiple presence factors of 0.85 and 0.65, respectively. For example, Figure 94 shows a case where the results correlate well, but the proposed method results are significantly lower than the current LRFD method results.
- For most one- and two-lane loaded cases, the methods compare fairly well, with around half the points above and half the points below the trend line. Figure 95 shows an example of such a case. However, there are a few exceptions where the proposed method is significantly less conservative.

The trends support the assumption that the two-lane loaded case typically controls over the three- and four-lane loaded case.

Flowcharts for the computation of distribution factors using the method recommended for the specifications and the alternative method for moments are shown in Figure 96 and Figure 97, respectively.

Recommended Specifications

The recommended specification language is presented in Appendix H. The proposed method formalized in the specification language was selected based primarily on simplicity and correlation with results from rigorous computation. Several concerns were addressed to simplify the distribution factor procedure. In general, the proposed method was selected based on the following simplifying qualities:

- The equations are simple and can be easily computed.
- The approach begins with either an equilibrium formulation (i.e., lever rule) or a kinematic assumption (i.e., uniform distribution method) and is adjusted according to the type of bridge.
- The same approach is used for nearly all bridge types. Only the adjustment constants in the equations are changed with the bridge type, girder location, and number of lanes loaded. In those cases, the constants were kept as consistent as possible.
- Multiple presence factors have been removed from the distribution factor computation. This gives the engineer a clear understanding of what factors are used, when, and why.
- The limits on the ranges of application from the current LRFD specifications have been largely removed.
- Lever rule equations are provided for convenience.
- The skew adjustment factor from the current LRFD specifications has been simplified. Computation of this factor requires only readily available geometric parameters.

As can be expected in the process of simplifying a complex, three-dimensional system into a set of equations that apply to several different bridge types, not all cases result in distribution factors as accurately as may be desired. Moment to the interior girder with one lane loaded is the one case that proved difficult for all simplified methods examined. The method proposed incorporates the best method for correlating this case while providing a consistency between bridge types. For the vast majority of the cases, the correlation

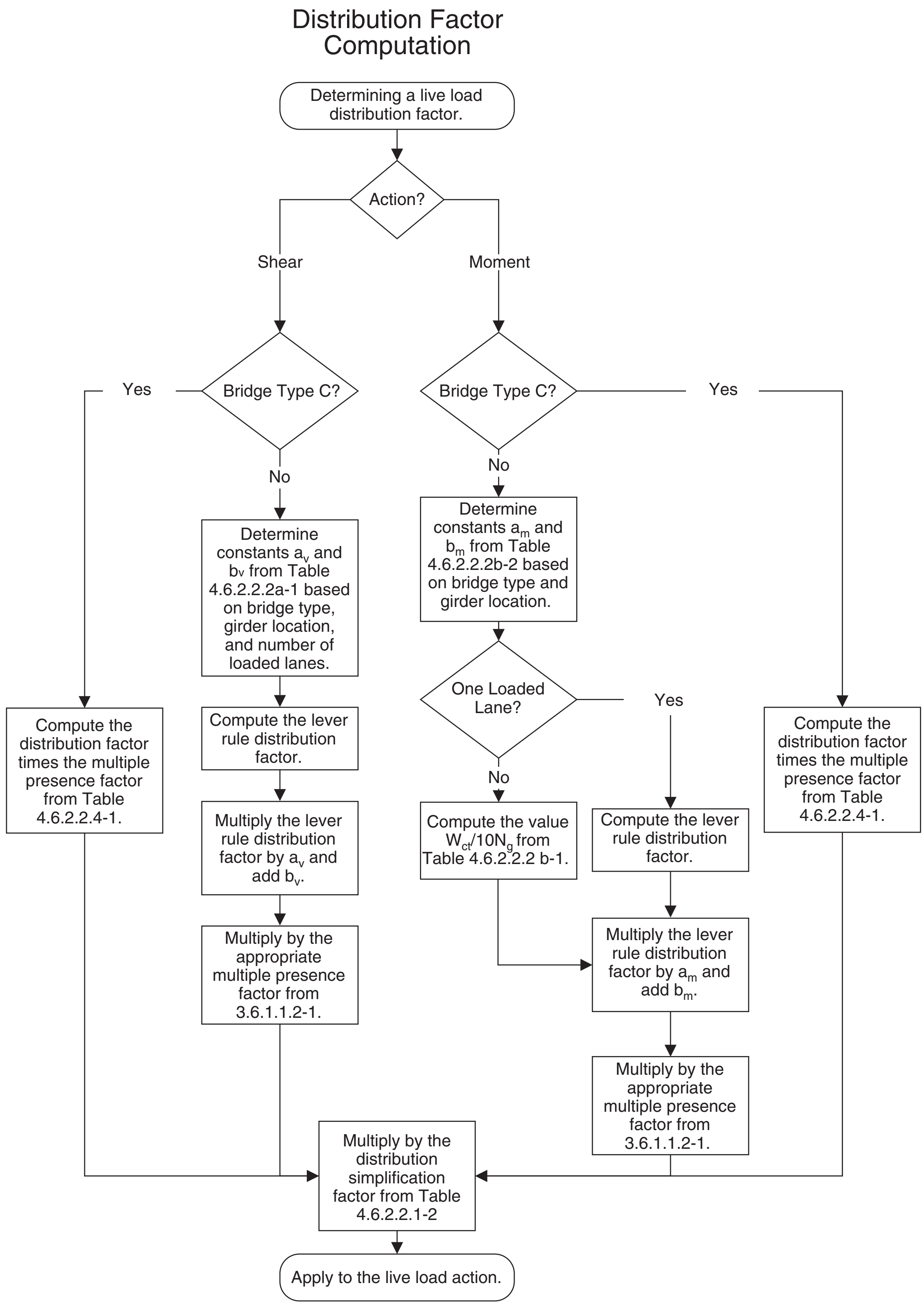


Figure 96. Flowchart for distribution factor computation based on 4.6.2.2.2.

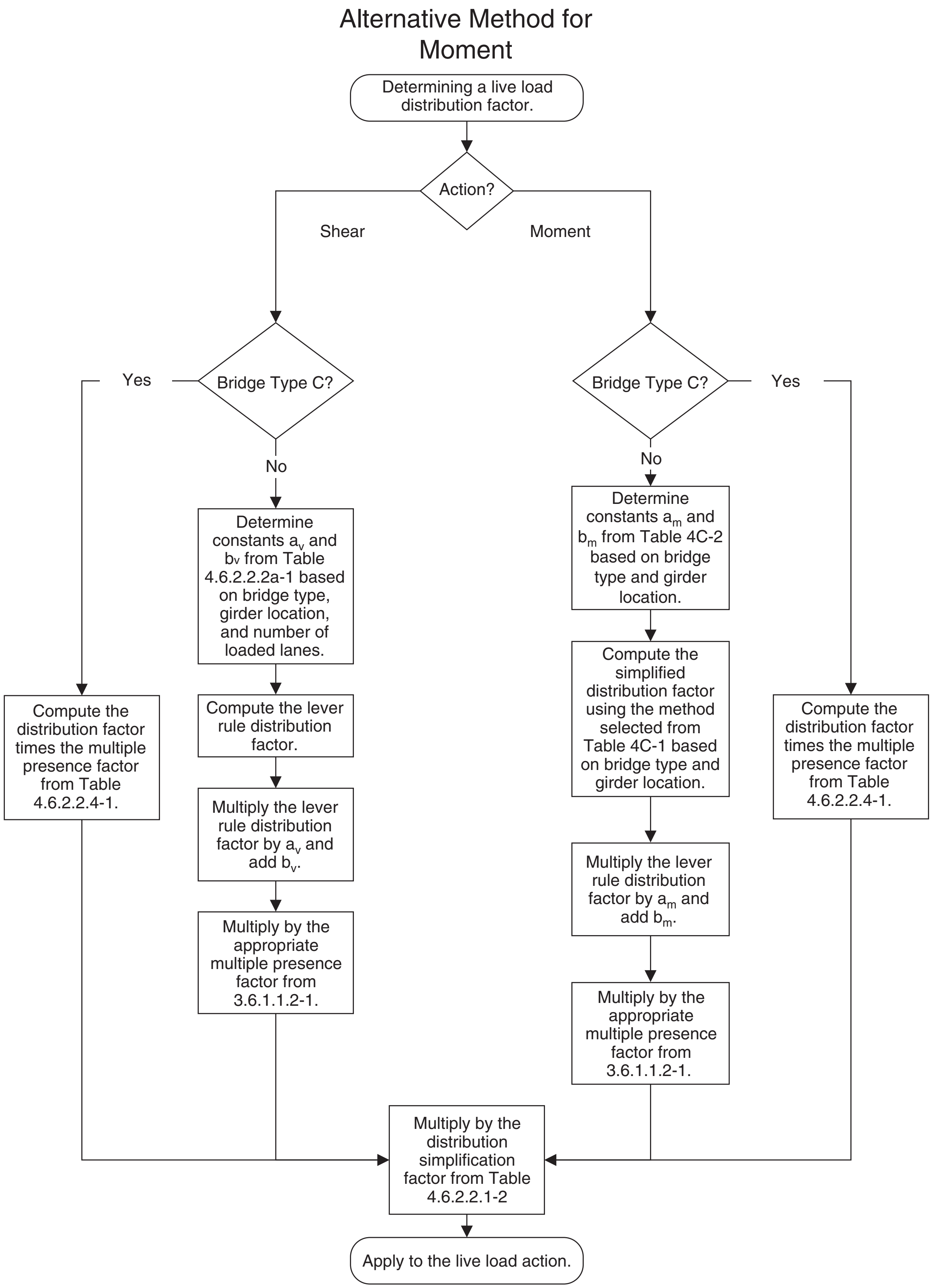


Figure 97. Flowchart for distribution factor computation based on the alternative method for moment, Appendix H, specification Appendix 4.

Table 28. Summary of recommended specification changes.

Specification Item	Modifications or Decision
Table of Contents	Updated per modifications
4.1 Scope	No change
4.2 Definitions	Several new definitions were added and some existing definitions were further clarified with additional text.
4.3 Notation	About 25 terms were deleted that were associated with articles that were modified. All article references were checked for 4.6.2.2 and 4.6.2.3. Other article references outside of the 12-62 scope were assumed to be correct.
4.4 Acceptable Methods of Structural Analysis	Article 4.4.1 contains the present information. Article 4.4.2 was added. This report and the commentary provide the rationale for 4.4.2. Additional tables were provided within the report for one-half and zero standard deviation offsets. The final offset and analysis factors should be debated and set by AASHTO.
4.5	No change
4.6 Static Analysis	Significant changes were made in Articles 4.6.1.3 and 4.6.2; commentary was changed in Article 4.6.3
4.6.1.3 Structures Skewed in Plan	Significant simplifications were made. All skew adjustment factors are now a function of bridge geometry that is readily available during preliminary design. Adjustments are made for shear for skew angles between 30 and 60°. These adjustments are optional from 0 to 30°. For angles greater than 60°, a rigorous analysis is necessary. Refinements suggested in report NCHRP 20-7/107 are referenced in the commentary, but these adjustments are not "simple." They were not recommended as part of specifications.
4.6.2.1 Decks	No modifications
4.6.2.2. Beam Slab and Box Beam Bridges	Significant modifications were made to the sections associated with these bridge types. These modifications are the primary results of this research. Existing language was either kept, moved to the appropriate article, or deleted. A list of actions are given below: • Multiple presence (m), calibration factors (a_v, b_v, a_m, b_m, F_L), and analysis factors (γ_a) are kept separate and explicit so that the designer may understand the method and the associated effects. Previous specifications (both standard and LRFD) combined these issues, sometimes to a point of confusion. • The method of combining a special (permit) vehicle with mixed traffic was kept fundamentally in place (4.6.2.7). Multiple presence factors (m) are now accounted for in an explicit manner. This is necessary due to the separation of m from other effects, such as calibration. • The types (and reference letters) of bridge cross section remain the same. • Three-girder bridges are treated the same as with the existing specifications. • The whole-bridge width design for box girders remains unchanged. • The term mg is used for the distribution factor that includes the effects of multiple presence (m), calibrations (a_v, b_v, a_m, b_m, F_L), and variability (γ_a). This notation has become commonplace in recent LRFD literature, example manuals, books, etc. • The live load distribution methods begin with either the lever rule or equal distribution, and then make adjustments from that basis. Both of these concepts approach live load distribution from well-accepted upper and lower bounds, respectively.

Table 28. (Continued).

	• The methodology unifies the live load distribution procedures for most bridge types. Only the coefficients change from bridge type to bridge type. • Where possible, bridge types with similar behavior were combined to use the same coefficients. • The research team decided that insufficient data was available to combine bridge type c (open steel boxes) with other cross sections of similar geometry and stiffness characteristics. The procedures for this type c remain unchanged. Note that the applicable equation is simple to apply and is based upon readily available geometry. Note that the multiple presence factors (*m*) are now explicitly applied, which is consistent throughout Article 4.6.2.2. • Live load distribution methods for wood beams remain unchanged. Note that the multiple presence factors (*m*) are now explicitly applied, which is consistent throughout Article 4.6.2.2. • Live load distribution methods for transverse floor beams remain unchanged. Note that the multiple presence factors (*m*) are now explicitly applied, which is consistent throughout Article 4.6.2.2.
4.6.3 Equivalent Strip Width for Slab-Type Bridges	The reason for the discontinuity at 15 feet is provided in the commentary.
General	Specifications were provided for the U.S. customary units. It should be a simple editorial change for the SI version once the articles are finalized by AASHTO. There are no difficult issues here, such as non-homogeneous units. The calibrated lever rule was not used for multiple-lane cases primarily because of the adjacent box systems, where the uniform method performed much better. The uniform method performs reasonably for other bridge cross sections. In order to unify and simplify, the uniform method was used for most multiple-lane cases. In a small number of cases (e.g., one lane loaded for moment to an interior girder), the variability is high. The research team recommends some additional work in this area.

coefficients between the proposed method and the rigorous analysis were greater than 0.8. In many cases, it was greater than 0.9.

For shear cases with multiple lanes loaded, the two-lane loaded case is assumed to control. This assumption is supported by the results of the regression testing discussed earlier. In any situation where the engineer feels that three or more lanes may control, it is a simple matter to compute the lever rule value for those cases and determine the controlling case. The three- and four-lane calibration constants apply; however, these were not codified because they typically do not control.

Summary of Recommended Specification Changes

The 12-62 research and the proposed modifications to the LRFD specifications in Section 4 involved the detailed work outlined in this report, as well as decisions made by the research team with the guidance of the research panel. Table 28 lists each section of the proposed specifications in Appendix H and provides a short discussion of the changes. Background information and guidance regarding the application are provided in the commentary.

CHAPTER 4

Limitations, Suggested Research, and Conclusion

Limitations

There are several notable limitations in the research:

- The proposed specifications were developed for use as design specifications, not for evaluation of existing structures. Therefore, direct application to evaluation is not recommended. Inherent in this work are simplifications that might not be appropriate for decisions associated with a bridge closure, retrofit/maintenance, or permit vehicle assessment. Conservatism is relatively inexpensive in new construction. A study on the implementation within LRFR is advised, specifically determining the appropriate DSF consistent with other aspects of reliability calibration with the LRFR.
- In cases where the variability is high (e.g., one lane loaded for moment to an interior girder), the DSFs are higher. This feature is not a limitation per se, but rather recognition that no simple method works well and that this issue must be addressed in a statistically based manner. Again, this could be an important issue with evaluation/rating. The alterative method (Section 4 of Appendix C) improves the one-lane loaded case with increased computational effort that is more complex than the methods contained within the body of the specifications.
- The number of actual bridges for cast-in-place tee beams and spread concrete box beams was lower than desirable for the study. However, this bridge type counts for only about 1% of new designs.
- Closed and open spread steel box beams and timber beams were not included in the study. In these cases, current specifications are recommended.

Suggested Research

Current research could be extended to include closed and open spread steel box beam bridges. Work is continuing in this area in order to extend the simplified methods to box girders. See Appendix Q.

Valuable data are contained in this work for several important side studies:

- LRFD distribution factors could be compared with standard specification distribution factors. This is an important issue in the adoption of the LRFR and is the primary reason for the significant scatter when comparing rating factors between the two methods.
- The main body of the specifications could be merged with one-lane loaded distribution factors for moment. These factors have already been improved with the proposed alternative method (see Section 4 of Appendix C).
- Distribution adjustment factors could be developed for fatigue for trucks traveling in or near the striped travel way. Data are available to develop the adjustment factors based upon strip-lane position (or other locations specified). The barrier stiffness could also be included for service limit and fatigue states. Currently, service limit states often control the design. A simple method could be developed to include the effect of the barrier.
- Nonstandard gage vehicles could be studied. Direct application of the specifications is not recommended for nonstandard gage vehicles.
- Similar procedures for evaluation/rating using LRFR could be developed. Such research should consider the DSF and the possibility of revising these values for different rating activities: NBI, posting, and permitting.

Conclusion

The project objectives have been met by providing a simple, reasonably accurate method for the computation of live load distribution factors. The research was conducted with a clear view of simplification and considered as many options as possible for as long as necessary. Several existing methods were selected for initial study. The calibrated lever rule and uniform distribution method were then selected for further study. The calibrated lever rule worked well for almost all cases except for adjacent box beams, for which the uniform method performed better for multiple lanes loaded for moment. For other bridge types, both methods performed approximately the same for multiple lanes loaded for moment. Therefore, the uniform method was selected for all multiple-lane loaded moment cases in the interest of simplification. The theoretical lower bound was imposed and is a stated limit in the recommended specifications.

In summary, the calibrated lever rule is recommended for shear and one lane loaded for moment, and the uniform distribution method (i.e., Henry's method) is recommended for multiple lanes loaded for moment. These methods were approximately calibrated to the mean of the rigorous method. To shift the codified results above the mean, DSFs were developed based upon the statistics associated with each method. An alternative method is available to better predict the distribution on live load for moment with one lane loaded.

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APPENDICES

The following appendices are not published herein, but are available online at http://trb.org/news/blurb_detail.asp?id= 7938:

- Appendix A: Bibliography
- Appendix B: Literature Review
- Appendix C: NBI Bridge Type Study
- Appendix D: Summary of Existing Simplified Methods
- Appendix E: Sample Calculations, Existing Simplified Methods
- Appendix F: Modeling Assumptions
- Appendix G: Modeling Verification
- Appendix H: Recommended Specification Language
- Appendix I: Sample Calculations, Recommended Simplified Method
- Appendix J: Recommended Simplified Method vs. Rigorous Analysis
- Appendix K: Recommended Simplified Method vs. Current LRFD
- Appendix L: Parameter Studies
- Appendix M: Lane Spacing Study
- Appendix N: All Simplified Methods vs. Rigorous Analysis
- Appendix O: Controlling Lanes Loaded Study
- Appendix P: Push the Limit Bridges
- Appendix Q: Steel Spread Box Girders

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation