Proof Load Formula for Highway Bridge Rating

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A proof load formula is proposed for highway bridge evaluation through proof load testing to determine target proof load and load rating. This formula is based on a target structural safety index β of 2.3, which is consistent with current bridge evaluation practice and also with an evaluation method of load and resistance factors under development. It is demonstrated that the proposed formula will ensure a relatively uniform level of bridge structural safety and that possible changes in input data and probability distribution assumptions in the reliability models will not affect the results obtained. This formula can be applied to highway bridge evaluation by proof load testing, and the resulting rating can be directly input to the current national bridge rating inventory. The formula may be included in specifications for highway bridge evaluation by proof testing.

According to FHWA, about 40 percent of this country's highway bridges are considered either structurally deficient or functionally obsolete. Some 68 percent of New York State's bridges fall into these categories, representing the highest percentage among the states. Funds necessary to replace and rehabilitate them will not be available in the foreseeable future. Major factors contributing to this serious situation are age of the infrastructure, increases in both volume and weight of vehicular loads, environmental contamination, and inadequate maintenance (*1*).

These statistics are based on current evaluation technology. For existing bridge structures, AASHTO's *Manual for Maintenance Inspection of Bridges* (*2*), referred to here as "the AASHTO manual," provides technical guidelines for routine analytical evaluation on the basis of data supplemented by field inspection. However, such an analytical evaluation often is not applicable because of inaccessibility of bridge structural components due to their locations or protection methods or lack of detailed information such as design plans of bridges, or both. When a bridge is evaluated by physical testing, many assumptions critical to analytical evaluation methods may be unnecessary. In addition, in many cases, physical testing may be the only way to obtain a reliable rating; it has proved effective in many parts of the world (*3–5*). The results have also demonstrated higher load-carrying capacity than predicted by conventional analytical methods. This is often attributed to (a) generally conservative analytical methods and (b) structural system effects not covered by simplified analytical methods that usually address only behavior of structural components. Despite these advantages of physical testing in bridge evaluation, the current AASHTO Manual does not include provisions for field testing to evaluate highway bridges.

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This paper presents partial results of a study sponsored by FHWA to develop and evaluate a proof load testing program for bridge evaluation. This study was undertaken based on recognition that proof load testing is one of the most effective approaches to examine structural load-carrying capacity. Development of a consistent method for determining both target proof load and load rating is a major focus here, based on a criterion of target structural reliability. The theory of structural reliability has been employed elsewhere to develop codes of structural design and evaluation (*6–9*). This theory has been recognized as an effective and realistic means to address unavoidable random variations of physical quantities used in structural engineering decision making. Recently, a load and resistance factor methodology for bridge evaluation, based on the same theory, has been adopted by AASHTO in guide specifications (*8*). This study attempts to be consistent with the concept used there in prescribing target proof load levels. The proposed proof load levels are intended to apply to evaluation of short- and medium-span highway bridges whose response is governed by vehicular loading.

PROOF LOAD FORMULA FOR BRIDGE RATING

A proof load formula is proposed as follows, in the load and resistance factor format,

$$\phi\, Y_p = \alpha_L L_n g_n I_n \tag{1}$$

where

Y_p = target proof load effect,
L_n = nominal static live load effect,
g_n = nominal load distribution factor,
I_n = impact factor accounting for dynamic effects of vehicular loading, and
ϕ, α_L = resistance reduction and live-load factors, respectively.

L_n, g_n, and I_n are specified by AASHTO (*8*) and are respectively based on the current AASHTO rating vehicles with a lane load, empirical estimations, and road surface roughness. Load and resistance factors are to be determined in this study based on a structural reliability criterion. In addition to determining target proof load, the proposed formula is also intended to be used for rating through proof load testing:

$$\text{rating factor} = \phi R_p/\alpha_L L_n g_n I_n = R_p/Y_p \tag{2}$$

where R_p is proved capacity for live load equaling or lower than the target value Y_p. This rating methodology is consistent

with the current rating method given by AASHTO in both concept and format (2). Only bending moment as load effect is considered in this paper, although Equations 1 and 2 are in general forms.

STRUCTURAL RELIABILITY MODELS FOR BRIDGE PROOF TESTING

Safety Index and Target Level

Consider a limit state function Z for a typical primary bridge member (e.g., a girder):

$$Z = R - D - L = R' - L \quad (3)$$

where R, D, and L are true values of resistance, dead load, and live load effects, respectively, and $R' = R - D$ is a resistance margin for live load. Considering uncertainties and random variation associated with these quantities, R' and L are modeled by independent random variables that are assumed to be of lognormal distribution. The uncertainties are attributed to such factors as fluctuation of vehicular load, variation of material properties and construction quality, and scatter caused by simplified analysis methods. The mean and standard deviation of R', $M_{R'}$, and $\sigma_{R'}$, are given by means and standard deviations of R and D:

$$M_{R'} = M_R - M_D$$
$$\sigma^2_{R'} = \sigma^2_R + \sigma^2_D \quad (4)$$

on the basis of an assumption that R and D are independent of one another. Z equaling or lower than 0 indicates failure of the member, and a value higher than 0 means survival. The live-load effect is further modeled by a combination of the following factors (7):

$$L = a\, HW_{.95} mgI \quad (5)$$

where all variables are modeled by independent lognormal random variables except a, which is a deterministic coefficient correlating truck weight to bending moment as load effect based on AASHTO rating vehicles (2). H is a factor accounting for multiple presence of vehicles on the bridge, and $W_{.95}$ is a characteristic value of the vehicle weight spectrum; their product is treated here as a single variable. m covers effect of vehicle configuration variation on the load effect, g is a lateral distribution factor, and I is an impact factor for dynamic effect. $HW_{.95}$ and m refer to characteristics of traffic load, and I addresses interaction of traffic and bridge structure. They may not be determined in a proof test with acceptable accuracy. On the other hand, g may be obtained by a proof test since it is largely a function of the structure. However, its accuracy depends very much on test procedures used and efforts affordable, which may vary considerably in practice. To be conservative, g is also modeled here by a random variable.

Structural reliability is often measured by its complement, failure probability P_f, of the component:

$$P_f = \text{probability } [Z \leq 0] \quad (6)$$

If Z were a normal random variable, which can be a linear combination of normal variables, then

$$P_f = 1 - \Phi(\beta) = 1 - \Phi(M_Z/\sigma_Z) \quad (7)$$

where $\Phi(\ )$ is the cumulative probability function of the standard normal variable, and β is called safety index. In this study Z defined in Equation 3 is not a linear combination of normal variables. However, it can be linearized (by a polynomial series expansion of first order) and variables R', m, $HW_{.95}$, g, and I transformed (equivalently in failure probability) to normal variables at a point known as the design point in the variable space. Equation 6 can then be used to calculate the safety index after linearization and transformation, about which the reader is referred to Ang and Tang (10) for more computation details.

It has been estimated that current bridge evaluation practice by the AASHTO Manual assures a reliability level of the safety index of about 2.3 for primary components (6,7). $\beta = 2.3$ is thus used here as the target safety level for this study to prescribe the target proof load level, because only redundant structures are addressed here. This criterion is consistent with that used in development of the AASHTO *Guide Specifications for Strength Evaluation of Existing Steel and Concrete Bridges* (8). The same target safety index also has been used for development of a permit overload checking method (11). The target value will not be hit exactly for every case of application, and thus certain variation in resulted β is expected.

Proof Load Testing with Analytical Rating

Proof load testing has an important application in verifying or enhancing an existing rating obtained by analytical methods. This need emerges when the existing rating factor RF is not satisfactory—namely, lower than the required 1.0. For this case, it is advantageous to use the existing rating for modeling resistance. Nominal resistance R_n related to the existing rating factor RF is obtained by an analytical evaluation

$$\phi\, R_n = \gamma_D\, D_n + \gamma_L\, L_n\, g_n\, I_n\, RF \quad (8)$$

where D_n is nominal dead load effect, and ϕ, γ_D, and γ_L, respectively, are resistance-reduction, dead-load, and live-load factors given by AASHTO (8). Resistance R is thus assumed to have a mean M_R related to its nominal value R_n by a bias B_R, as follows:

$$M_R = B_R R_n \quad (9)$$

A proof load test eliminates possibilities that the true resistance margin R' is lower than the applied proof load Y_p. This is shown in Figure 1 by truncating and then normalizing the probability density function of R' at Y_p. Thus the limit state function takes the following form:

$$Z = R' - a\, m\, HW_{.95}\, g\, I \quad (10)$$

where R' has a truncated lognormal distribution. A method developed by Fujino and Lind (12) is used here to calculate the safety index for this case. This method transforms R' to

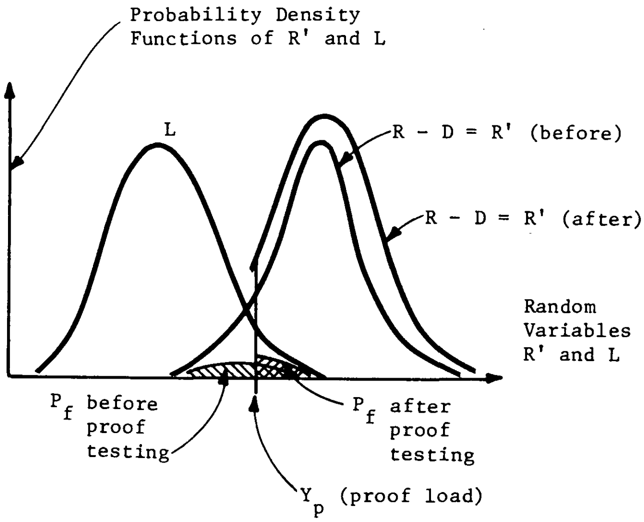

FIGURE 1 Structural reliability model for proof load testing with information on resistance *R*.

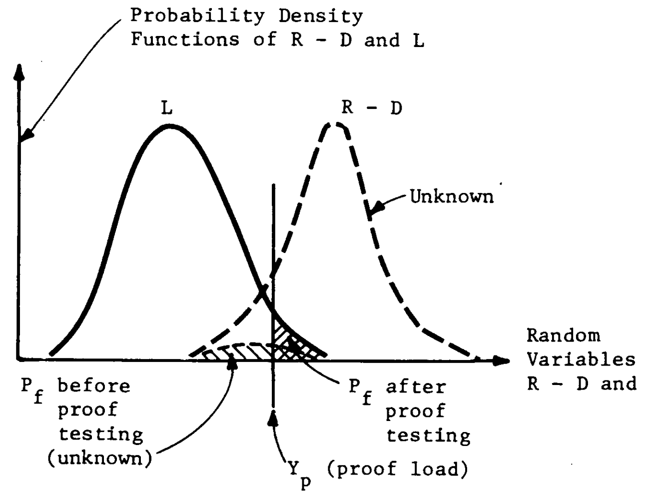

FIGURE 2 Structural reliability model for proof load testing without information on resistance *R*.

a standard normal variable by equivalence in probability. The limit function is transformed accordingly, providing a basis for calculating the safety index. This method has been compared with a direct integration method over a wide range of parameter variation for practical applications. Consistency has been observed in results obtained by the two methods (*13*).

Proof Load Testing Without Analytical Rating

Proof load testing is often desired also for bridge evaluation when a bridge is not suitable for rating by analytical methods. This occurs when necessary information on the bridge or reliable analysis methods are not available. R' is thus assumed to be equal to the applied proof load effect Y_p if the bridge survives the proof test, since no further information on R' is available. Therefore

$$Z = Y_p - L = Y_p - a\, m\, HW_{.95}\, g\, I \tag{11}$$

is used to calculate the safety index β for this case. The assumption $R' = Y_p$ underestimates the resistance conservatively, because it certainly can be higher than Y_p. A graphic demonstration of the proof testing effect on structural reliability for this case is shown in Figure 2. One can find a Y_p by satisfying a target structural reliability.

Statistical Data Base for Bridge Structural Reliability Models

Substantial statistical data collection has occurred for bridge structural reliability assessment (*7,14–18*). Table 1 contains a comprehensive data base used in this study as input to these reliability models, with information sources identified. It includes mean or bias (ratio of mean to nominal value), and coefficient of variation (COV, as ratio of standard deviation to mean). Three types of construction material are considered here: steel, reinforced concrete (RC), and prestressed concrete (PC), which covers a reasonably wide range of highway bridges in this country. The live-load parameters cover traffic load variation for a period of 2 years, to be consistent with the current maximal inspection interval. The four traffic conditions characterizing the live (vehicular) load are defined by AASHTO (*8*). This classification permits evaluation engineers to take site-specific loading conditions into account in rating bridges. The nominal dead load effect D_n used in Equation 8 is estimated by its empirical relations to live load effect L_{HS20} based on the HS-20 loading. These relations are also listed in Table 1 with sources identified. Note that the mean and COV of R in Table 1 are intended to cover minor deterioration of structural components caused by factors such as steel corrosion, concrete spalling, and prestress loss. They are used in β-calculation for the application case of proof testing only with the analytical rating, where it is usually desired to take deterioration into account for a more reliable rating by proof testing. They differ from those for components in good condition (*7,17*), to represent average strength decrease (by lower bias values) and uncertainty increase (by higher COV values) caused by deterioration. These values are selected here on the basis of subjective estimates, since no data are available. Implications of their use are examined in a sensitivity analysis presented later.

The data base in Table 1 is a summary of data collected by a variety of techniques, including field measurement for member dimensions, weigh-truck-in-motion for the real load spectrum, and empirical regression for a ratio of live to dead load. This data base is considered typical in covering the statistical variation of current practice and traffic loadings in the United States.

TABLE 1 Statistical Data Base for Structural Reliability Assessment

Random Variable[a]	Span Length (ft)	Mean	COV (%)
m	30	1.0	11.0
	40	1.0	11.0
	50	0.95	11.0
	60	0.92	11.0
	70	0.90	11.0
	80	0.91	8.2
	90	0.92	7.5
	100	0.93	5.7
	120	0.95	5.4
	140	0.95	4.6
	160	0.96	3.4
	180	0.97	3.9
	200	0.97	3.2

Random Variable[a]	Traffic Condition	Combinations, Singles	Combinations, Singles
$HW_{0.95}$	1	170 kips, 92 kips	5.0, 8.0
	2	180 kips, 100 kips	6.0, 8.0
	3	210 kips, 120 kips	10.0, 10.0
	4	225 kips, 125 kips	10.0, 10.0

Random Variable[a]	Surface Roughness	Mean	COV (%)
I	Smooth	1.1	10.0
	Medium	1.2	10.0
	Rough	1.3	10.0

	Bias			COV (%)		
Random Variable[a]	Steel	Reinforced Concrete	Prestressed Concrete	Steel	Reinforced Concrete	Prestressed Concrete
R	1.05[a]	1.05	1.0	16[a]	14[a]	11
D	1.0[a]	1.0	1.0[a]	10[a]	10[c]	10[a]
g	0.9[a]	0.97[b]	0.96[a]	13[a]	11[b]	8[a]

Notes: COV = standard deviation/mean, Bias = mean/nominal, SL = span length (ft)

$$D_n/(L_{HS20}\ I_n) = \begin{cases} 0.0132 \times SL \text{ (for steel, from Ref. 19)} \\ 0.6967 - 0.00762 \times SL + 0.0001554 \times SL \times SL \text{ (for reinforced concrete, from Ref. 17)} \\ 0.014 \times SL \text{ (for prestressed concrete, from Ref. 20)} \end{cases}$$

[a] From Ref. 7.
[b] From Ref. 18.
[c] From Ref. 17.

PROOF LOAD FACTORS BASED ON TARGET STRUCTURAL RELIABILITY

To be consistent with bridge evaluation practice by current analytical methods (*2*) and the recently developed method of load and resistance factors (*8*), the resistance reduction factor ϕ is proposed to be 0.95, 0.9, and 0.95, respectively, for steel, reinforced concrete, and prestressed concrete materials. Thus α_L is the only factor in the proof load formula (Equation 1), to be determined to reach the target safety index of 2.3. Given an α_L, Y_p determined by Equation 1 is used in limit state functions for Equations 10 and 11, respectively, for the two application cases of proof load testing. Their safety indexes are then calculated to be compared with the target value of 2.3. This mechanism allows selection of α_L to satisfy the requirement for structural reliability. For a given α_L, β varies with traffic loading condition, span length, and material type. Thus for each traffic loading condition, α_L is selected by minimizing β's variation as a result of other factors.

For application of proof load testing when an analytical rating exists, Figure 3 shows the relation of required α_L to reach uniformly the target safety index 2.3 and existing rating factor RF. The lower the original rating, the higher the proof load would have to be to reach the same target safety level. This is expected, since the higher proof load is needed to reduce the greater failure risk characterized by a lower rating factor. It is also seen in Figure 3 that when rating factor RF equals or is lower than 0.7, variation of α_L with the RF be-

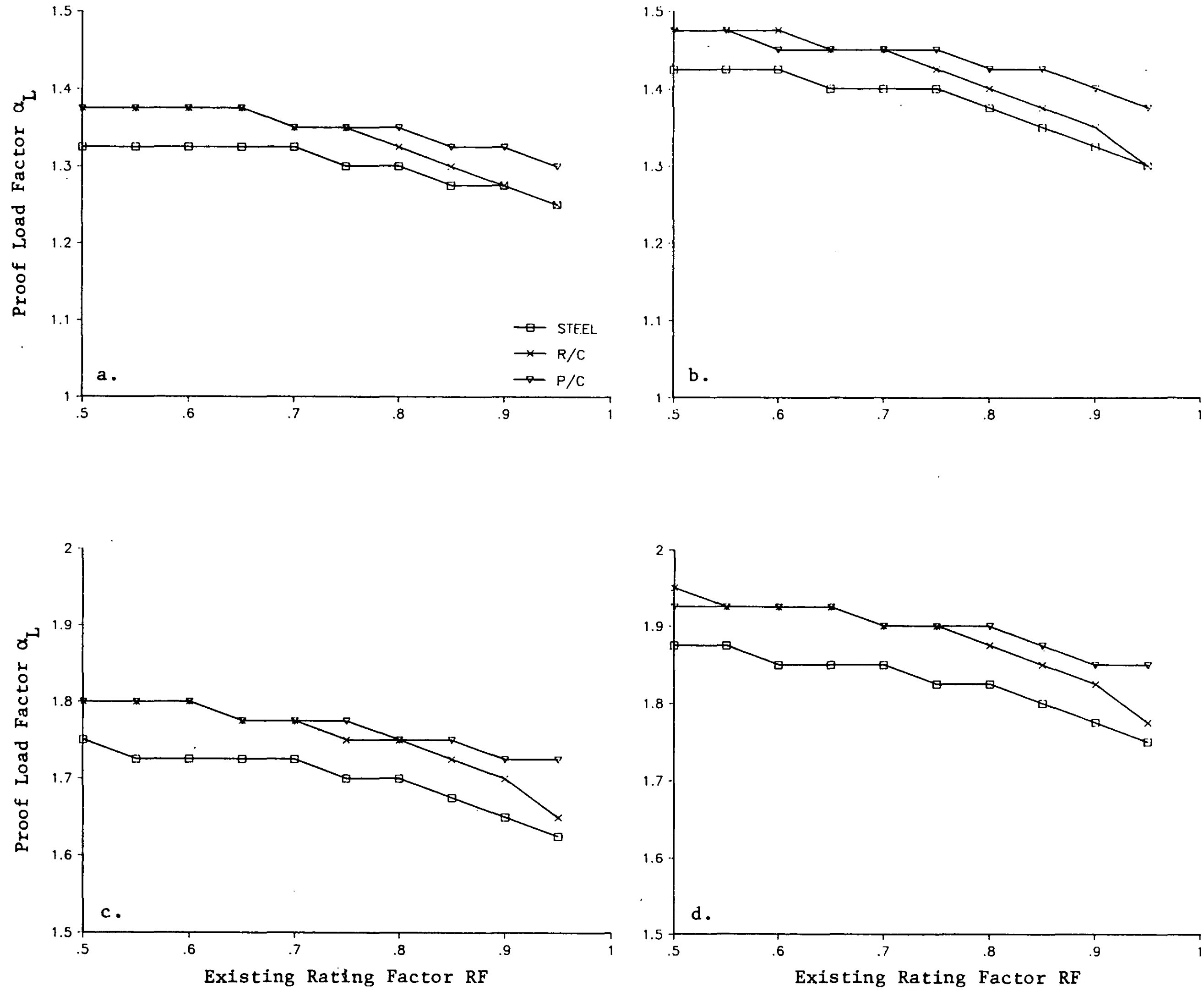

FIGURE 3 Required proof load factors α_L for existing rating factor RF: Traffic Conditions 1 (*a*), 2 (*b*), 3 (*c*), and 4 (*d*).

comes less significant, regardless of traffic loading conditions. Thus, RF equal to 0.7 is selected as a threshold whether to take into account the existing rating in determining target proof load. In other words, when an existing rating factor is higher than 0.7, it is considered an important piece of information to be included in selecting the target proof load level, but lower than 0.7, it is not worth being considered. By this criterion, the proof load factor α_L is proposed in Table 2 for the case of proof load testing with an analytical rating factor equaling or exceeding 0.7. Figure 4 shows safety index β using the proposed load and resistance factors for this case. As shown, they produce a relatively uniform reliability level of safety index equal to 2.3. Note that reinforced concrete bridges have significantly different ratios of live to dead loads than steel and prestressed concrete bridges. This is a major factor, causing safety indexes to be higher for reinforced concrete bridges than for the other two types of bridge, especially for longer spans. Its reliability assessment is not performed for spans longer than 100 ft, because the available empirical ratio of dead to live load is considered valid only up to this span length, and few RC highway bridges in the United States exceed this span length.

For the application case when a rating factor is not available, Table 3 contains a proposed proof load factor α_L for the four categories of live-load traffic. These factors are higher than those for the previous application case, because less information is required to reach the same target safety level. Figure 5 shows the safety index assured by the proposed proof load factor for this case. It is seen that a relatively uniform safety level 2.3 is realized with respect to span length. In this application case, differences in β for various materials are lower than those in the previous case. This is because the dead-load influence on β is eliminated, as it no longer appears in the limit function (Equation 11).

When an existing rating factor is lower than 0.7, the live-load factors in Table 3 can be used to determine required

TABLE 2 Proposed Live Load Factor α_L for Proof Testing with Existing Analytical Rating Factor RF ≥ 0.7

Traffic Condition	Live Load Category	Proposed α_L
1	Low volume roadways (ADTT less than 1000), reasonable enforcement and apparent control of overloads	1.35
2	Heavy volume roadways (ADTT greater than 1000), reasonable enforcement and apparent control of overloads	1.45
3	Low volume roadways (ADTT less than 1000), significant sources of overloads without effective enforcement	1.80
4	Heavy volume roadways (ADTT greater than 1000), significant sources of overloads without effective enforcement	1.90

Note: ADTT = Average Daily Truck Traffic

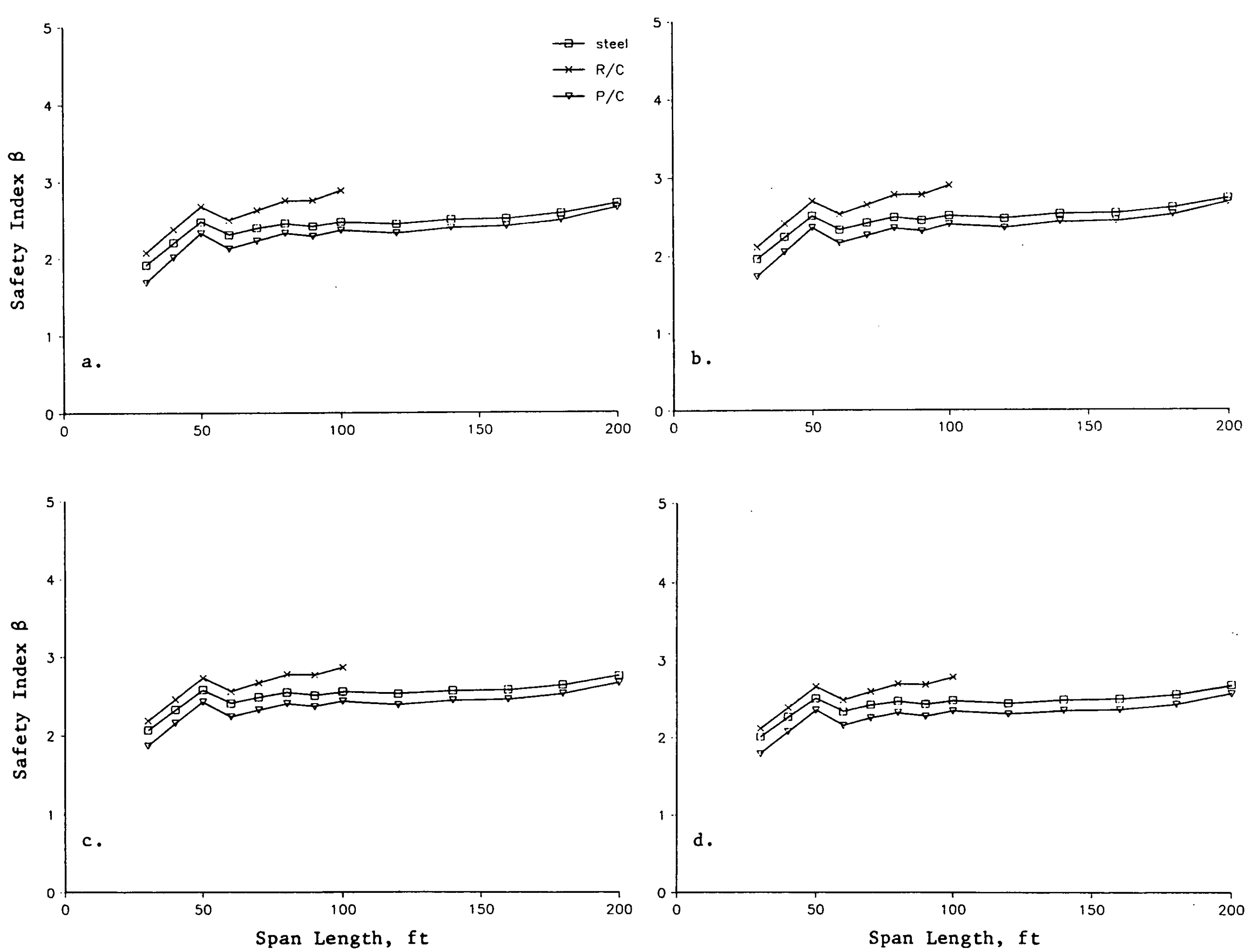

FIGURE 4 Structural reliability based on proposed proof load formula, with analytical rating: *a*, Traffic Condition 1, α_L = 1.35; *b*, Traffic Condition 2, α_L = 1.45; *c*, Traffic Condition 3, α_L = 1.80; *d*, Traffic Condition 4, α_L = 1.90.

TABLE 3 Proposed Live Load Factor α_L for Proof Testing Without Analytical Rating or Existing Rating Factor RF < 0.7

Traffic Condition	Live Load Category	Proposed α_L
1	Low volume roadways (ADTT less than 1000), reasonable enforcement and apparent control of overloads	1.45
2	Heavy volume roadways (ADTT greater than 1000), reasonable enforcement and apparent control of overloads	1.55
3	Low volume roadways (ADTT less than 1000), significant sources of overloads without effective enforcement	1.90
4	Heavy volume roadways (ADTT greater than 1000), significant sources of overloads without effective enforcement	2.00

Note: ADTT = Average Daily Truck Traffic

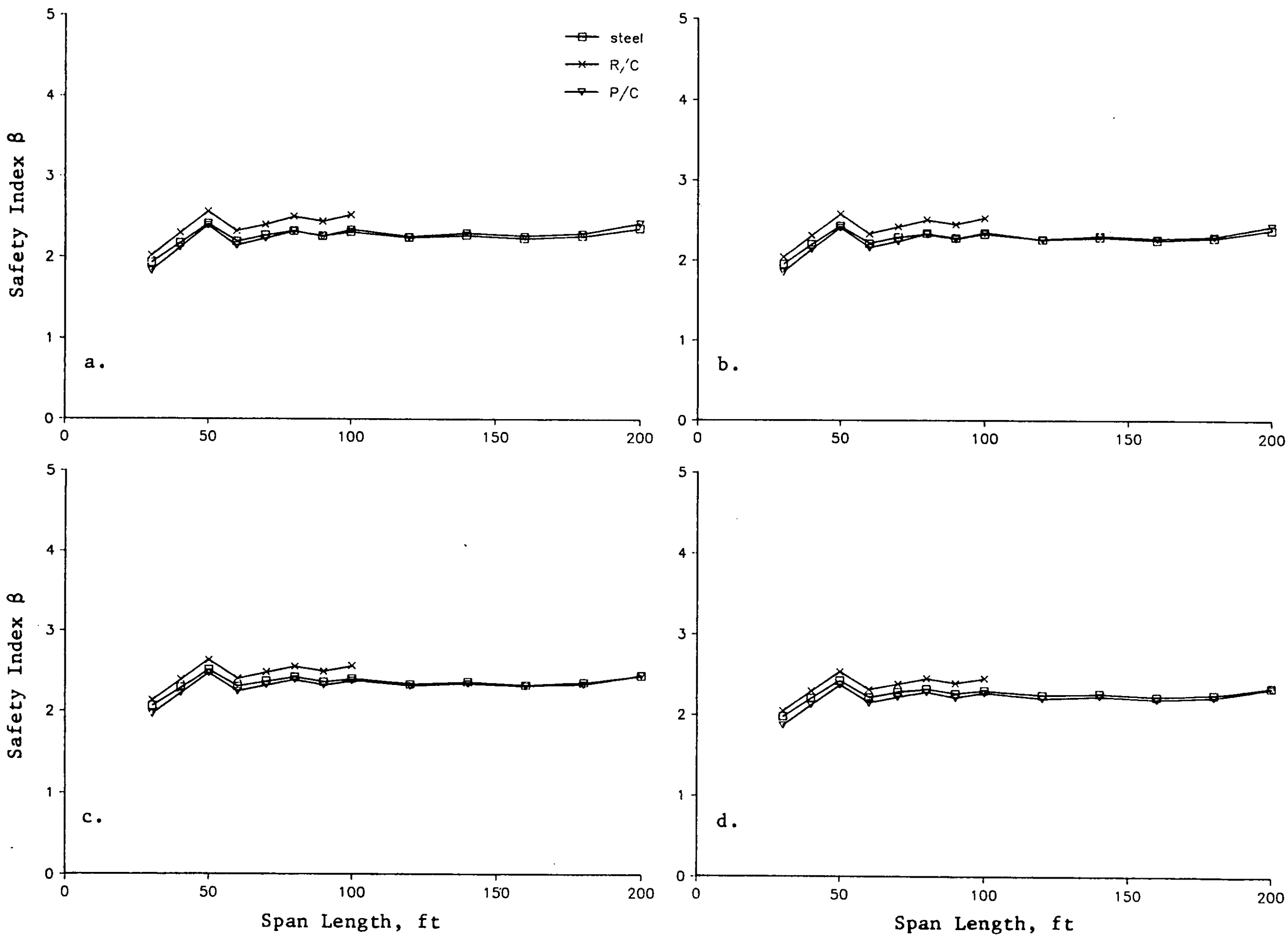

FIGURE 5 Structural reliability based on proposed proof load formula, without analytical rating: *a*, Traffic Condition 1, α_L = 1.45; *b*, Traffic Condition 2, α_L = 1.55; *c*, Traffic Condition 3, α_L = 1.90; *d*, Traffic Condition 4, α_L = 2.00.

target proof load and load rating by proof load testing. They are the maximum proof load levels needed for bridge rating to ensure the target reliability level and do not depend on any a priori information about the bridge's capacity. Other cases have also been checked to ensure the required safety level by the proposed proof load factors, such as nonredundant structures, continuous spans, and posting practice.

SENSITIVITY ANALYSIS

The input data and certain assumptions in modeling and calculation just described may influence the obtained safety index and, in turn, affect the proposed proof load factors. A sensitivity analysis thus is warranted in this exercise of code calibration based on structural reliability. Its purpose is to ensure that reasonable changes in input data and assumptions will not affect uniformity in reliability level and will satisfy appropriate target safety levels reached by the proposed proof load formula.

The assumption of random variable lognormal distribution is examined first. Figure 6 displays the safety index β for cases in which one of the random variables is modeled by a normal, instead of lognormal, variable for the case of steel bridges under Traffic Condition 1. It shows that a different probability distribution assumption has little influence on the safety index, and thus the assumption of lognormal distribution is not critical to the results obtained.

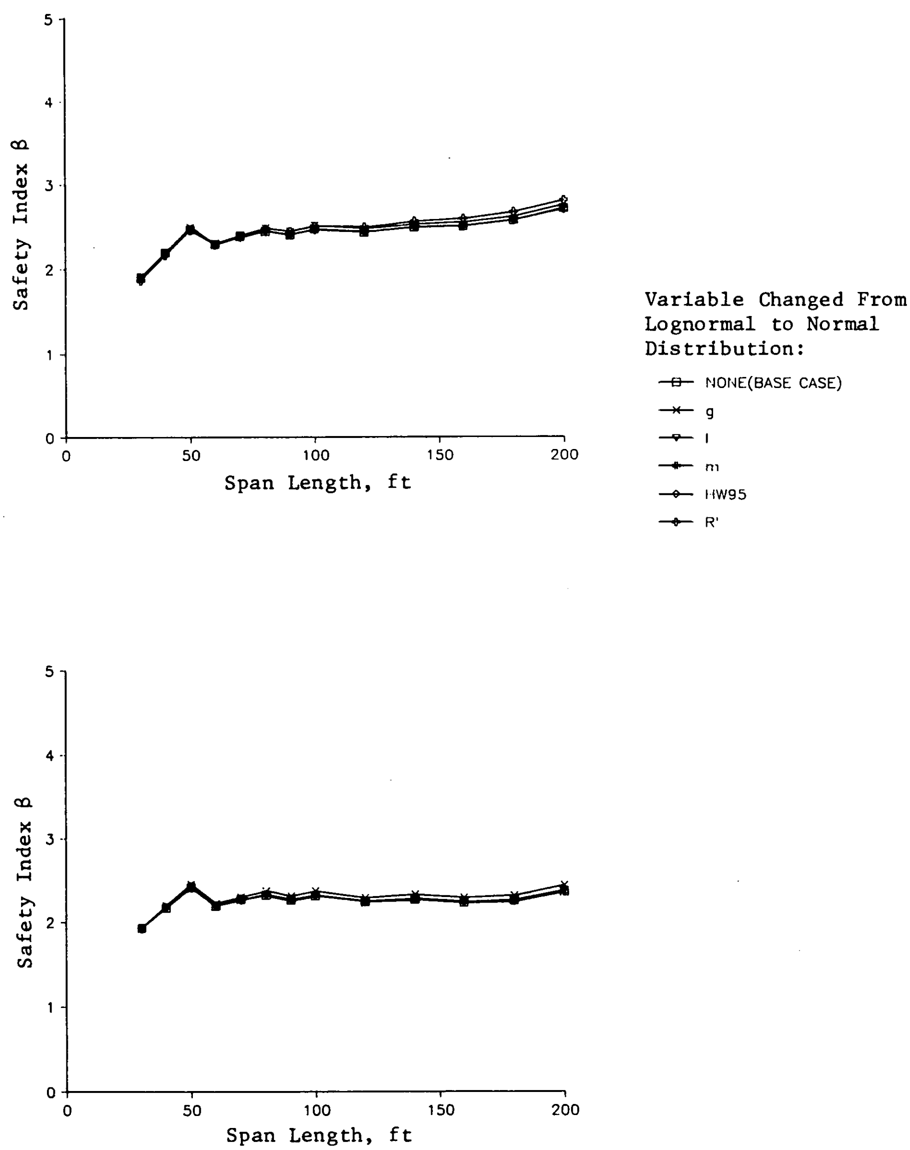

FIGURE 6 Sensitivity of β to probability distribution assumption (steel, Traffic Condition 1): *top*, with analytical rating; *bottom*, without analytical rating.

Figure 7 demonstrates sensitivity of the safety index to bias and COV of R (B_R and V_R) for the application case with analytical rating factor equaling or exceeding 0.7. It is seen in Figure 7 (*bottom*) that higher V_R leads to higher β, especially for shorter spans. This is because the higher scatter in R increases scatter of $R' = R - D$ for shorter spans where the dead-load effect is insignificant, and truncating the distribution of R' by proof testing is more effective to reduce failure risk. For longer spans, the dead-load effect is more dominant and thus higher scatter of R does not significantly increase scatter of R'. Figure 7 also shows that neither B_R nor V_R significantly affects the safety level. Figure 8 shows that the same conclusion applies to the bias and COV of dead-load effect D (B_D and V_D), since they have even lower influence on β than B_R and V_R, respectively. Note that parameters of R and D do not affect β at all in the second application case without analytical rating because information on them is not needed for β calculation using Equation 11.

The lateral distribution factor g has the highest influence on reliability index β among the factors in live-load effect L, because it has the highest COV for most of the cases considered. Thus sensitivity of β to g is discussed here. Figure 9 (*top* and *middle*) shows safety index for the two application cases of proof testing with bias of g (B_g) perturbed. As indicated in the figure, the change of B_g has little influence on the uniformity assured by the proposed proof load formula. On the other hand, this change does affect the level of absolute reliability. Figure 9 (*bottom*) exhibits β produced by

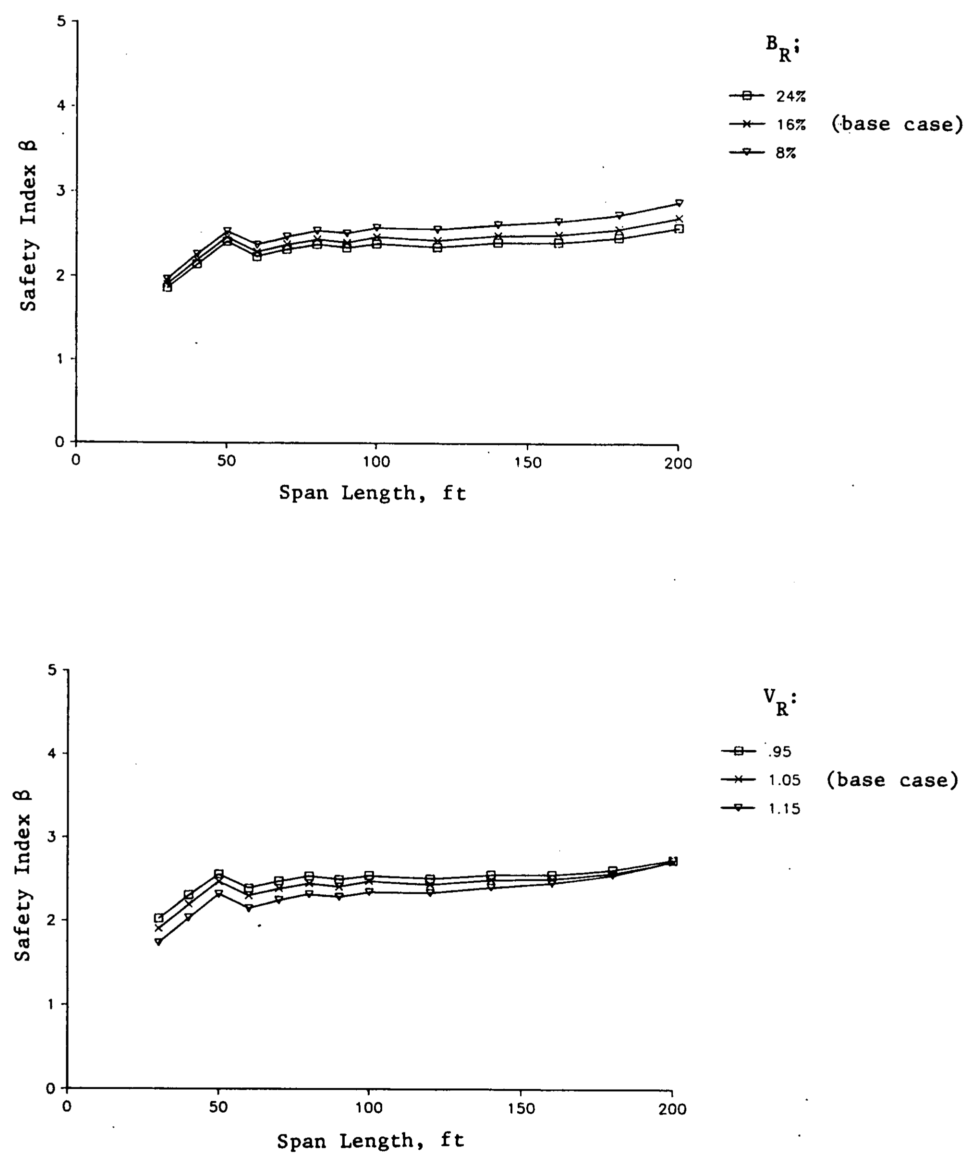

FIGURE 7 Sensitivity of β to bias of R (*top*) and COV of R (*bottom*) (steel, Traffic Condition 1).

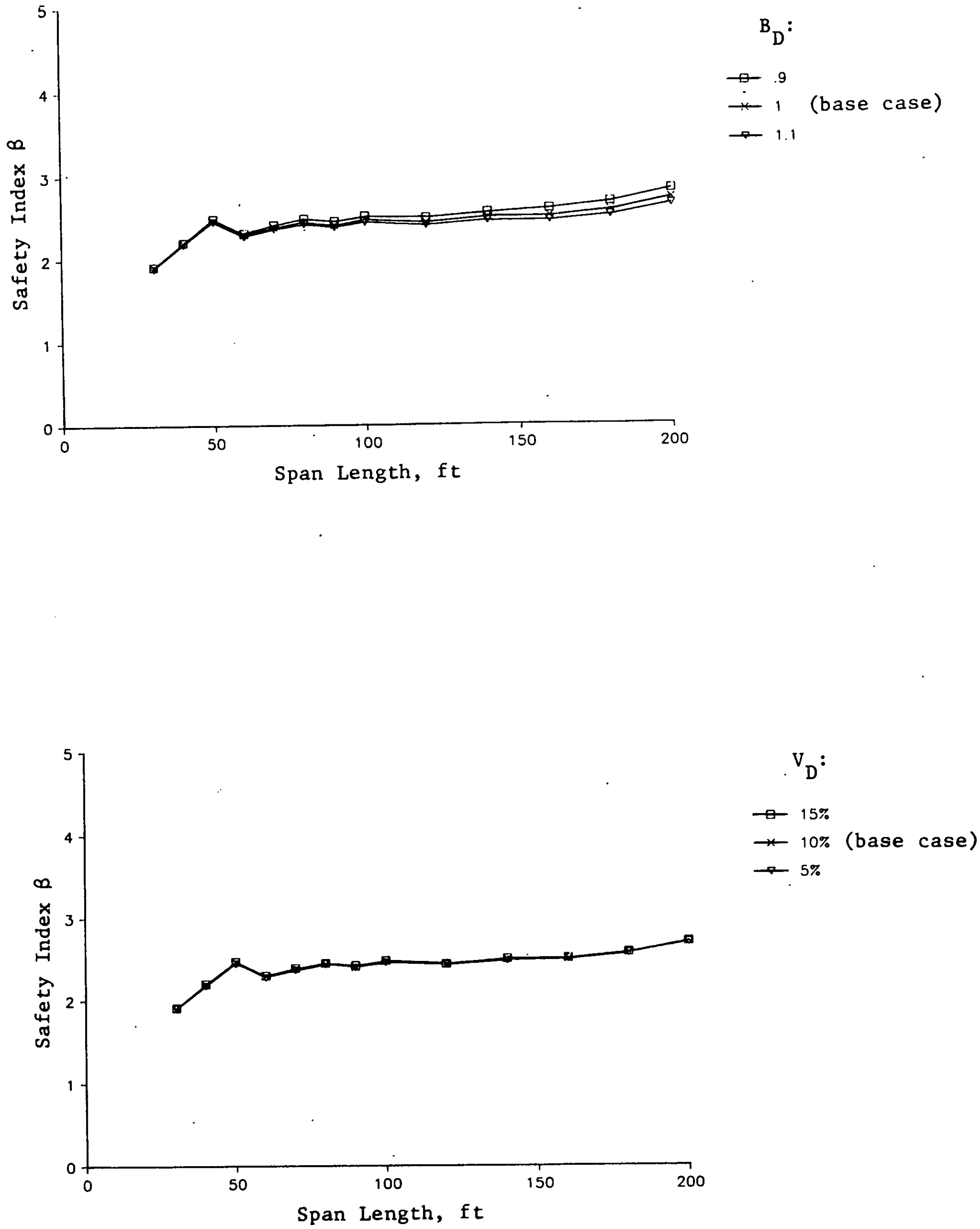

FIGURE 8 Sensitivity of β to bias of *D* (*top*) and COV of *D* (*bottom*) (steel, Traffic Condition 1).

the current working stress evaluation method at the operating level according to AASHTO (*2*). From Figure 9 (*bottom*) target β of 2.3, 2.0, and 1.7 can be recognized for cases of B_g equal to 0.8, 0.9, and 1.0, respectively. Figure 9 (*top* and *middle*) shows that these targets are correspondingly either reached or exceeded by the proposed formula. A similar sensitivity examination for COV of g (V_g) can be undertaken for the results shown in Figure 10. Uniformity of β still remains if V_g is changed for both application cases of proof testing, respectively shown in Figure 10 (*top* and *middle*). Reliability levels reached by the proposed formula are higher than those reached by the current working stress evaluation method at the operating level under the changed parameter. The current evaluation method produces lower reliability levels than those shown in Figures 9 (*bottom*) and 10 (*bottom*) for a more severe loading case (Traffic Condition 4). However, the proposed proof load formula will ensure a uniform target safety index, regardless of traffic conditions.

More cases of input data change have been examined in this sensitivity analysis but are not exhaustively presented here. However, the most predominant parameters and their typical cases have been discussed. It is concluded that possible

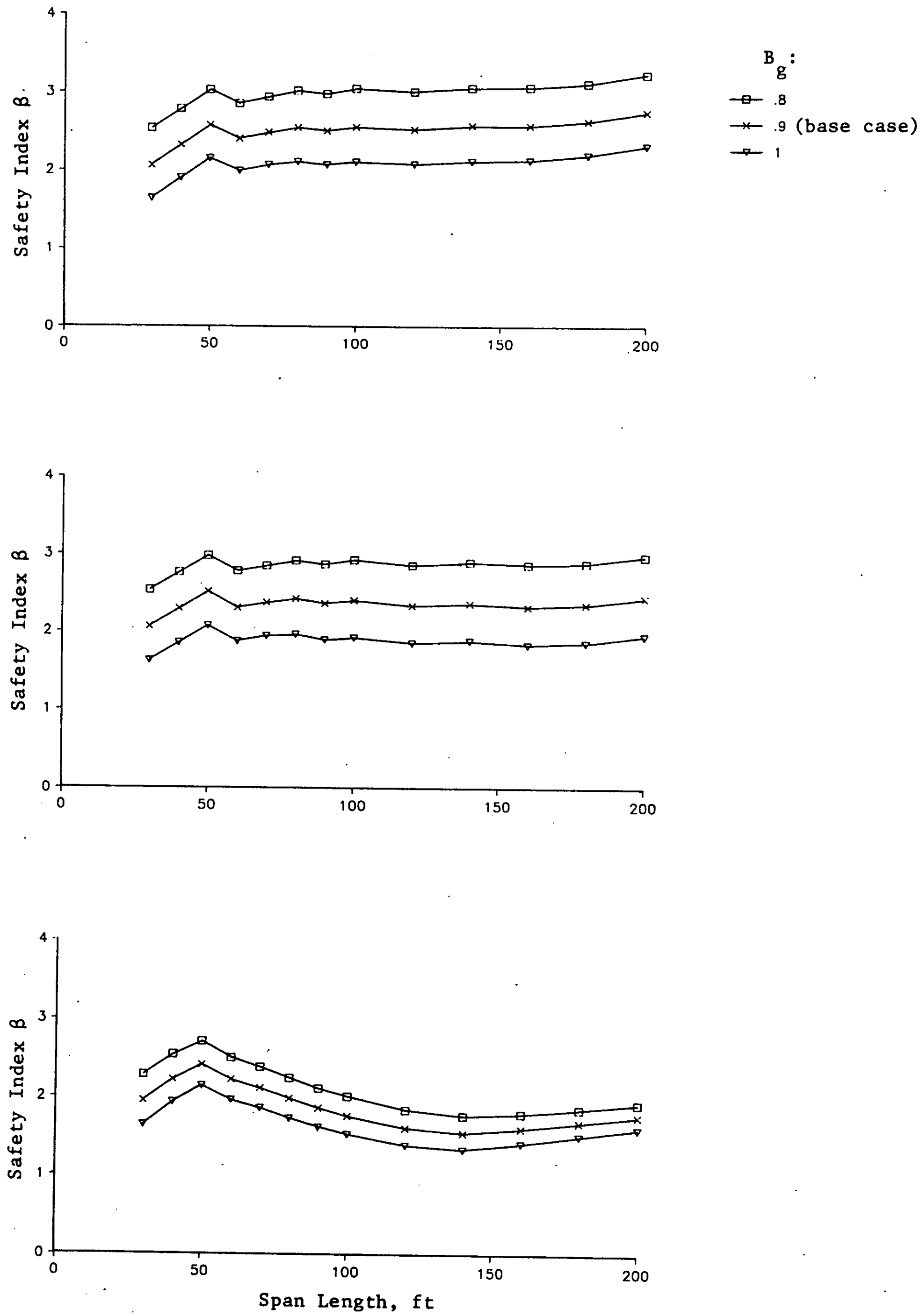

FIGURE 9 Sensitivity of β to bias of *g* (steel, Traffic Condition 3): *top*, with analytical rating; *middle*, without analytical rating; *bottom*, current working stress method at operating level.

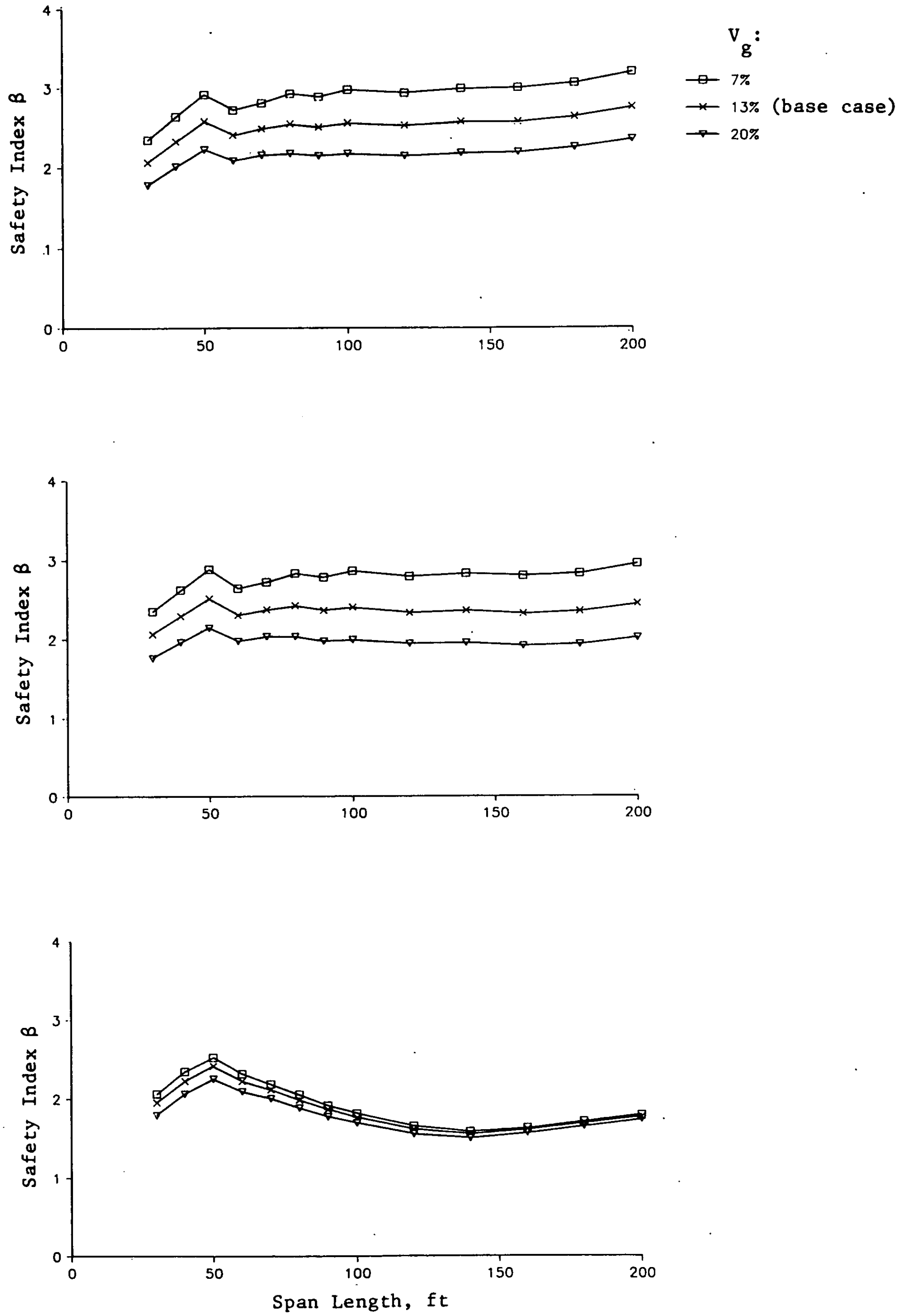

FIGURE 10 Sensitivity of β to COV of *g* (steel, Traffic Condition 3): *top*, with analytical rating; *middle*, without analytical rating; *bottom*, current working stress method at operating level.

changes of input data will not affect the proposed proof load formula, with respect to uniformity of β and satisfaction of target levels.

IMPLEMENTATION CONSIDERATIONS

Typical proof load testing of highway bridges for structural evaluation consists of three steps: planning, test execution, and rating based on analysis of test results. To apply the proposed proof load formula for successful results, factors other than those addressed here may have to be considered to make decisions in various stages of testing. In general, decisions should be made to minimize costs (such as possible bridge damage or failure by test loading, test operation, and penalties caused by improper test procedures) and maximize benefits (such as those resulting from potential reduction or removal of load restriction, deferral of bridge replacement, and savings on evaluating bridges by an alternative means). A thorough investigation of these factors is beyond the scope of this paper, because they often must be examined in consideration of local conditions, specifically site-specific bridge conditions, regional requirements on bridge capacity, and other factors. A procedure manual for proof load testing of highway bridges is under development in New York State to address the particular issues within that jurisdiction.

CONCLUSIONS

A proof load formula is proposed for bridge rating by proof testing. This formula can be used to determine target proof load and bridge load rating. The factors of the proposed formula are prescribed on the basis of a target safety index of 2.3, which is consistent with the current practice. Two cases of proof load testing application are covered: (a) an analytical rating is available but unsatisfactory and (b) no analytical rating can be obtained. A relatively uniform reliability level is produced by the proposed proof load formula for these cases over a practical range of span length, material type, and traffic conditions. A comprehensive sensitivity analysis has been performed to examine implications of the input data. Its results show that the proposed proof load formula is not sensitive to the input statistical parameters and probability distribution assumptions.

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