NCHRP

REPORT 575

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Legal Truck Loads and AASHTO Legal Loads for Posting

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 575

Legal Truck Loads and AASHTO Legal Loads for Posting

Bala Sivakumar
LICHTENSTEIN CONSULTING ENGINEERS, INC.
Paramus, NJ

Fred Moses
Cranberry Township, PA

Gongkang Fu
WAYNE STATE UNIVERSITY
Detroit, MI

Michel Ghosn
CITY COLLEGE OF NEW YORK
New York, NY

Subject Areas
Bridges, Other Structures, and Hydraulics and Hydrology

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2007
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 575

Project 12-63
ISSN 0077-5614
ISBN 978-0-309-09881-6
Library of Congress Control Number 2007925827

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

The Transportation Research Board of the National Academies, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. William A. Wulf are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is a division of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation through research. In an objective and interdisciplinary setting, the Board facilitates the sharing of information on transportation practice and policy by researchers and practitioners; stimulates research and offers research management services that promote technical excellence; provides expert advice on transportation policy and programs; and disseminates research results broadly and encourages their implementation. The Board's varied activities annually engage more than 5,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR NCHRP REPORT 575

NCHRP PROJECT 12-63 PANEL
Field of Design—Area of Bridges

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 12-63 by Lichtenstein Consulting Engineers, Inc., Paramus, New Jersey, with subcontracting and consulting services provided by Drs. Fred Moses, Gongkang Fu, and Michel Ghosn. The Principal Investigator on this project and the primary author of this report was Bala Sivakumar from Lichtenstein Consulting Engineers, Inc. The calibration report was authored by Dr. Fred Moses. The weigh-in-motion data collection and analysis was performed by Dr. Gongkang Fu. The Principal Investigator wishes to acknowledge the advice and guidance of the NCHRP Project Panel, with Mr. Stan Woods as Chairman, and the Project Manager Mr. David Beal.

FOREWORD

By David B. Beal
Staff Officer
Transportation Research Board

This report contains the findings of research performed to develop recommended revisions to the legal loads for posting as depicted in the *Manual for Condition Evaluation of Bridges* and the *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges.* The report details the development of the new loads and includes recommended revisions to the manuals to incorporate these loads. The material in this report will be of immediate interest to bridge managers and load raters.

In the United States, trucks are typically allowed unrestricted operation and are generally considered "legal" provided they meet weight guidelines of Federal Bridge Formula B. Bridges are not usually posted if they have the capacity to carry the legal loads for posting described in the *Manual for Condition Evaluation of Bridges* or the *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges.*

During the past several years, the trucking industry has enhanced the load-carrying capacity of commercial vehicles by using a series of closely spaced axles. These axle configurations make it possible for shorter trucks to carry the maximum load of up to 80,000 pounds and still meet the requirements for Formula B. Nevertheless, these vehicles induce stresses in bridge structures that exceed the stresses induced by AASHTO Legal Loads for Posting. The result is that legally loaded trucks are overstressing some nonposted bridges.

The objective of this research was to reliably identify and quantify the types of short multi-axle legal vehicles operating on the public thoroughfares and the subset of these vehicles that cause overstressing. This information was used to develop new definitions for the AASHTO Legal Loads for Posting for use in the *Manual for Condition Evaluation of Bridges* and the *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges* such that bridges are more appropriately posted.

This research was performed by Lichtenstein Consulting Engineers, Inc., with contributions from Fred Moses, Gongkang Fu, and Michel Ghosn. The report fully documents the research leading to the recommended truck configurations and load factors.

C O N T E N T S

SUMMARY

Legal Truck Loads and AASHTO Legal Loads for Posting

Specialized hauling vehicles (SHVs) with short wheelbases have had difficulty complying with the Federal Bridge Formula B. The trucking industry has in recent years introduced SHVs with closely spaced multiple axles that make it possible for these short-wheelbase trucks to carry the maximum load of up to 80,000 lbs and still meet the Bridge Formula. Federal Bridge Formula B sets limits on gross vehicle weight and axle weight for vehicles operating on the Interstate System. The current AASHTO legal loads do not represent these newer axle configurations, and it is therefore considered likely that these specialized vehicles may be severely overstressing some non-posted bridges. The purpose of NCHRP Project 12-63 was to investigate the recent developments in specialized truck configurations and state legal loads and recommend revisions to the legal loads for posting as depicted in AASHTO's *Manual for Condition Evaluation of Bridges (MCE)* (*1*) and AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges* (*2*).

It was a requirement of Phase I of this project that the recommended posting loads reliably model all reasonable truck configurations meeting Formula B, particularly the subset of these trucks that cause overstressing in bridges. Vehicles considered representative of the newer Formula B configurations were investigated through the analysis of recent weigh-in-motion data and survey data of state legal loads obtained from the states. To document practices related to legal weight limits and posting vehicles used by the states and to obtain information on unusual axle configurations meeting the requirements of Federal Bridge Formula B, a survey of states was conducted. The responses show that various innovative arrangements of axles have evolved in the last two decades to increase load capacity within gross weight limits and not exceed axle limits. The Federal Bridge Formula allows more weight within a given length of truck if more axles are used. Trucks with multiple axles have difficulty turning and cornering. Industry has resolved this difficulty with the use of liftable axles. In several states, five-, six-, and seven-axle single-unit trucks with two to four lift axles are being used. Weigh-in-motion (WIM) data also served as another good source for obtaining unbiased information on unusual truck configurations in the traffic stream in various states. Recent WIM data covering 18 states were obtained and analyzed. Based on the survey responses and WIM data analyses, a suite of representative short-wheelbase single-unit multi-axle trucks with three to eight axles were identified as candidate legal load models for posting.

A key research objective was to identify a few vehicles among the candidate load models that could serve as envelope vehicles for load effects induced by the suite of legal trucks. A test suite of generic simple and continuous span bridges from 10 ft to 200 ft were assembled and used in the analysis of load effects. Bridges having transverse members were also included in the test suite assembled for this purpose. Floorbeam spacings from 10 ft to 30 ft were used in this study. Analytical studies have demonstrated that the shear and moment effects of these new Formula B SHVs are up to 50% over the same for the current family of AASHTO legal loads.

In summary, the studies performed in this project have shown the need to revise the present family of three AASHTO legal loads to better provide uniform safety for the new generation of Formula B truck configurations. Based on this study, a notional rating load (NRL) has been recommended as a single load model for load rating bridges for all likely Formula B multi-axle truck configurations. Bridges that rate for the NRL loading will have adequate load capacity for all legal Formula B truck configurations up to 80 Kips. Bridges that do not rate for the NRL loading representative of Formula B trucks should be investigated to determine posting needs using a suite of new single unit posting loads SU4, SU5, SU6, SU7 developed through this research. These SU trucks were developed to model the extreme loading effects of single unit SHVs with four or more axles. This series of loads affords the evaluator the flexibility of selecting only posting loads that model multi-axle Formula B trucks that operate in a particular state or jurisdiction.

Generalized live-load factors for the NRL rating load and posting loads for SHVs satisfying Formula B were determined in this project by reducing the target beta level from the design level of 3.5 to the corresponding operating level of 2.5. The live-load factors account for the multiple presence of two heavy trucks side-by-side on a multi-lane bridge as well as the probability that trucks may exceed the corresponding legal limits. Since there are typically fewer SHVs than routine commercial trucks in the traffic stream, the live-load factors for SHVs are appreciably smaller than the corresponding factors for routine commercial traffic represented by the three AASHTO legal loads. The load models and load factors developed in Phase I have been adopted by AASHTO in 2005 for rating and posting of bridges.

Before the adoption of the Federal Bridge Formula and weight limit requirements, the majority of states allowed vehicles with heavier axles or axle groups than would be permitted by the new requirements. These existing vehicle configurations were allowed to continue in use on the Interstate System under "grandfather rights." Additionally, vehicles operating on the state and local highway system are not subject to Federal Formula B limits. Therefore, a significant portion of the SHV population in states with grandfather rights belongs in this category, commonly referred to as "grandfather trucks." NCHRP Project 12-63 Phase II was initiated to develop calibrated load factors for posting analysis using states' legal single-unit trucks with gross vehicle weight less than or equal to 80,000 lbs that do not meet Federal Formula B axle weight and spacing limits. These factors are for inclusion in AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges (2)*. Currently, the states have no guidance on loads and load factors appropriate for posting computations for legal vehicles that do not meet Federal Formula B limits using the load and resistance factor rating (LRFR) methods being introduced.

Moments and shears for the generic spans were computed for a suite of single-unit non-Formula B legal truck models commonly seen in several state legal and posting loads to determine the governing force effects. Delaware's DE3 and Connecticut's T4 trucks were the most severe of the family of three- and four-axle grandfather loads. New single-unit trucks EX-3 and EX-4, based on the governing grandfather trucks, have been specified as two calibration trucks for deriving the LRFR load factors for the series of exclusion vehicles in use. Trucks EX-3 (three-axle) and EX-4 (four-axle) may be used as representative exclusion vehicles for load-rating bridges. The states can also use the calibrated load factors but apply a nominal loading based on their own exclusion vehicles. Since there are many variations to federal weight law exclusions among the states, some flexibility in substituting state-specific grandfathered legal loads is an important feature for national implementation of LRFR procedures for these vehicles.

In Phase II, the research team collected new WIM data with high-resolution time stamps at existing WIM sites to provide more accurate quantitative information on the occurrence of side-by-side truck loadings. In the LRFD calibration simultaneous occurrence assumptions for trucks were based on very limited statistical data. New WIM data collected in Phase II of this project provided the statistical information to make an independent assessment of multiple presence probabilities for use in calibration. The multiple presence probabilities determined for the three sites in Idaho, Michigan, and Ohio were quite low compared with past assumptions of 1/15 (= 6.7%) used in LRFD for an average daily truck traffic (ADTT) of 5,000. Field WIM data collected in this project validated the use of reduced multiple presence probabilities in LRFR for sites with less severe traffic conditions (<5,000) than that used in the LRFD calibration.

Generalized live-load factors suitable for use with the LRFR procedures have been calibrated for the EX-3 and EX-4 exclusion vehicles. The live-load factors were determined also for a beta index of 2.5. Since there are typically fewer exclusion vehicles than routine commercial trucks in the traffic stream, the live-load factors are appreciably smaller than the corresponding factors for routine commercial traffic. When the maximum legal exclusion load under state law exceeds the safe load capacity of a bridge, restrictive load posting may be required. The live load to be used for posting considerations could be a state's own exclusion vehicles or one of the exclusion vehicles provided herein. The live load factors given can be used with less severe grandfathered state loads or with grandfathered state loads that only moderately exceed the EX-3 and EX-4 load effects.

CHAPTER 1

Introduction

Problem Statement and Research Objective

In the United States, trucks are typically allowed unrestricted operation and are generally considered legal, provided they meet weight guidelines of Federal Bridge Formula (FBF) B. Specialized hauling vehicles (SHVs) such as dump trucks, ready-mix concrete trucks, construction vehicles, solid-waste trucks, and other hauling vehicles with short wheelbases have had difficulty complying with the FBF B. SHVs are a mainstay in many segments of the economy due to their maneuverability and operational safety considerations. The trucking industry has in recent years introduced SHVs with closely spaced multiple axles that make it possible for these short-wheelbase trucks to carry the maximum load of up to 80,000 lbs and still meet the FBF. In some cases, operators of SHVs have adopted artificial devices such as lift axles, dummy axles, and spread tandems to ensure technical compliance with the FBF.

These newer axle configurations (number, spacing, and weight) were not considered in the original development of the FBF. The current AASHTO legal loads selected at the time to closely match the FBF in the short-, medium-, and long-truck length ranges do not represent these newer axle configurations. Bridges are not usually posted if they have adequate capacity to carry the AASHTO legal loads for posting. It is therefore considered likely that these specialized vehicles may be overstressing some non-posted bridges. In response to changing truck configurations and their potential for overstressing shorter span bridges, several states have in recent years adopted a variety of short multi-axle vehicles as rating and posting loads.

NCHRP Project 12-63 (Phase I, Tasks 1–9) was initiated in July 2003 to investigate the recent developments in specialized truck configurations and state legal loads and to recommend revisions to the legal loads for posting as depicted in AASHTO's *Manual for Condition Evaluation of Bridges (MCE) (1)* and AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges (2)*. It was a requirement of Phase I of this project that the recommended posting loads reliably model all reasonable truck configurations meeting Formula B, particularly the subset of these trucks that cause overstressing in bridges. Phase I research was conducted over an 18-month period, from July 1, 2003 through December 31, 2004. The load models developed in Phase I were adopted by AASHTO in 2005 as new legal loads for rating and posting of bridges.

Federal Formula B sets limits on gross vehicle weight and axle weight for vehicles operating on the Interstate System. Before the adoption of the federal requirements, the majority of states allowed vehicles with heavier axles or axle groups than would be permitted by the new requirements. These existing vehicle configurations were allowed to continue in use on the Interstate System. Vehicles operating on the state and local highway system are not subject to Federal Formula B limits. A significant portion of the SHV population belongs in this category, commonly referred to as "grandfather trucks."

Many states exempt SHVs from the FBF under "grandfather rights." Over the years special exemptions to the federal weight limits have been enacted for individual states, sometimes applying only to the transportation of specific commodities that are important to the state economy. Because short-wheelbase trucks (non-conforming with respect to the bridge formula) were permitted in a number of states before the adoption of the FBF in 1975, their use has been grandfathered and they are exempt from the bridge formula up to the highest gross vehicle weight (GVW) allowed in 1975, typically 73,280 lbs.

NCHRP Project 12-63 (Phase II, Tasks 10–18) was initiated in January 2005 to develop load factors for posting analysis using states' legal single unit trucks with GVW of less than or equal to 80,000 pounds that do not meet Federal Formula B axle weight and spacing limits. These factors are for inclusion in AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges (2).*

In design, only a single live load that envelopes all possible truck configurations is considered. For posting, in contrast, specific vehicle configurations must be checked to ensure that posting decisions are not unnecessarily restrictive. The live-load factors used in the calculations must also be calibrated for the specific vehicle type to ensure uniform reliability. The assessment of safe posting loads must consider vehicle configurations typical of those operating in the state. Currently, the states have no guidance on loads and load factors appropriate for posting computations for legal vehicles that do not meet Federal Formula B limits using the load and resistance factor rating (LRFR) methods being introduced. Live-load factors calibrated specifically for these non-Formula B trucks are required to maintain the reliability targets adopted in the LRFR Manual (*2*) for Formula B trucks. In Phase II, calibration of live-load factors for non-Formula B trucks was carried out in a manner consistent with the calibration of the live-load factors in Phase I and the LRFR Manual. The project was completed in June 2006.

State rating and posting loads include a wide variety of vehicle configurations intended to meet the commercial and transportation needs of a particular state. These trucks could be broadly categorized into the following groups:

1. Trucks that meet Formula B for gross and axle group weights (outer- and inner-bridge limits) and have only minor variations from the AASHTO vehicles;
2. Short multi-axle trucks that meet Formula B for gross and axle group weights with configurations that differ significantly from the AASHTO vehicles;
3. Short multi-axle trucks that meet Formula B for gross weight but exceed axle group weight limits with configurations that differ significantly from the AASHTO vehicles; and
4. Trucks that do not meet Formula B limits for gross weight and for axle group weights (typically "grandfathered" trucks).

Trucks belonging to the first group are adequately covered by the current AASHTO family of trucks and are not of specific interest to this research. Phase I research focused on trucks belonging to Groups 2 and 3 that meet all or part of Formula B and have axle configurations that differ from the AASHTO vehicles. Phase II research was aimed at Group 4 trucks—grandfather trucks that exceed Formula B limits.

FBF B and Grandfather Rights

The FBF calculates the maximum allowable load (the total gross weight in pounds) that can legally be imposed on the bridge by any group of two or more consecutive axles on a vehicle or combination of vehicles. It provides for additional gross weight as the wheelbase lengthens and the number of axles increases.

The FBF B is given as follows:

$$W = 500\left[\frac{LN}{N-1} + 12N + 36\right] \tag{1}$$

where

W = the maximum weight in pounds that can be carried on a group of two or more axles to the nearest 500 lbs,
L = the distance in feet between the outer axles of any two or more consecutive axles, and
N = the number of axles being considered.

States historically had regulated the weights and dimensions of vehicles operating on state highways. The Federal-Aid Highway Act of 1956 placed limits on the weight of vehicles operating on the Interstate System to protect the substantial federal investment in its construction. A maximum gross weight limit of 73,200 pounds was established along with 18,000 pounds on single axles and 32,000 pounds on tandem axles. The allowable gross weight and axle weight limits were increased in 1975, in part to provide additional cargo carrying capacity to truckers faced with large fuel cost increases at the time, but Congress balanced this concession to productivity by enacting the FBF.

The Federal-Aid Highway Act of 1956 also contained a provision that allowed states to retain vehicle weight limits exceeding the federal limits if the state's higher weight limits were in effect in 1956. At least 30 states exercise their grandfather rights and permit exceptions to the Interstate System axle load limits or gross weight limits either with or without special permits. In the nearly 50 years since the enactment of the Federal-Aid Act of 1956, the extension of the grandfather rights to the states has grown more widespread and more controversial. At the state level, truck weight limits are influenced by three different grandfather rights provisions: the first was enacted in 1956 and deals primarily with axle weights, gross weights, and permit practices. The second was adopted in 1975 and applies to bridge formula and axle spacing tables. The third, enacted in 1991, ratifies state practices regarding longer combination vehicles (LCVs).

Adoption of the FBF in 1975 affected those segments of the trucking industry that use short-wheelbase hauling vehicles. These vehicles—SHVs—are commonly used in construction, waste management, bulk cargo, and commodities hauling industries. Users of these vehicles cannot simply lengthen the wheelbase to take advantage of the greater gross weight permitted under the FBF for longer vehicles. SHVs must be short enough to maneuver on city and residential streets. Construction vehicles need to be able to maneuver at off-road and construction sites.

Grandfather right states have differing standards on federal roads. Some states without grandfather rights have different standards on state roads than allowed on federal roads. Because of different weight requirements among the states, manufacturers, in essence, must develop different trucks to accommodate each state's regulations.

Research Approach

The research effort was organized and executed according to the 18 tasks given below. Phase I research to develop Formula B legal loads for posting encompassed Tasks 1 through 9. The Phase II research effort to develop the non-Formula B legal loads for posting was organized according to Tasks 10 through 18. Draft recommended revisions to the AASHTO manuals and the final report for both phases were integrated into Tasks 17 and 18.

Phase I Research—Formula B Legal Loads

Phase I research encompassed the following:

- **Task 1:** Document practices related to legal weight limits and posting vehicles used by the states and the criteria used to establish these practices. Information on unusual axle configurations (number, spacing, and weight) meeting the requirements of Federal Formula B is of interest.
- **Task 2:** Assemble a test suite of simple- and continuous-span bridges to be used to develop and verify the recommended revisions to the AASHTO legal loads for posting.
- **Task 3:** Propose acceptance criteria for a set of legal loads.
- **Task 4:** Develop an expanded work plan for analytical studies to develop recommendations for a set of legal loads for posting that reliably predict the forces induced in bridges by all reasonable truck configurations meeting Formula B. The work will identify the complete range of parametric values to be examined.
- **Task 5:** Submit an interim report that documents the results of Tasks 1 through 4. Following project panel review of the interim report, meet with the panel to discuss the interim report and the remaining tasks. NCHRP approval of the interim report will be required before proceeding with the remaining tasks.
- **Task 6:** Perform the work plan approved by NCHRP for developing legal loads for posting.
- **Task 7:** For the bridges in the test suite, compare the forces induced by the proposed legal loads for posting, the Federal Formula B configurations, and current legal loads for posting to the forces produced by HS20 loading.
- **Task 8:** Prepare a discussion of the possible effects of the recommended legal loads for posting on the calibration of the load factors provided in AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges*.
- **Task 9:** Prepare detailed examples of the application of the recommended legal loads for posting in bridge rating.

Phase II Research—Non-Formula B Legal Loads

Phase II research consisted of the following tasks:

- **Task 10:** Augment the information collected in Task 1 as needed to fully document practices related to legal weight limits and posting vehicles used by the states. Collect and analyze weigh-in-motion (WIM) data from existing sites with multiple presence and side-by-side occurrence statistics as necessary. Information on unusual axle configurations (number, spacing, and weight) operating legally is of particular interest.
- **Task 11:** Augment the test suite of simple- and continuous-span bridges developed in Task 2 as necessary to develop and verify the recommended revisions to the AASHTO Legal Loads for Posting.
- **Task 12:** Using the information assembled in Tasks 10 and 11 develop a set of vehicles representative of legal non-Federal Formula B vehicles operating in the States. At a minimum, the loads selected will envelop current practice.
- **Task 13**: Prepare an expanded work plan for developing load factors for application to bridge posting analysis of legal vehicles operating in the states that do not meet Federal Formula B limits.
- **Task 14:** Submit an interim report that documents the results of Tasks 1 through 4. Following project panel review of the interim report, meet with the panel to discuss the interim report and the remaining tasks. NCHRP approval of the interim report will be required before proceeding with the remaining tasks.
- **Task 15:** Perform the work plan approved by NCHRP for developing load factors for application to bridge posting analysis of non-Formula B vehicles operating legally in the states.
- **Task 16:** Prepare detailed examples of the application of the recommended load factors in screening and posting decisions.
- **Task 17:** Prepare draft recommended revisions to AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges* (Phases I and II).
- **Task 18:** Submit a final report documenting the entire research effort including recommended revisions to

AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges* (Phases I and II).

Introduction to the Final Report

The final report, prepared in accordance with Task 18 requirements for this project, documents the findings of Tasks 1 through 17. It contains four chapters and nine appendixes. The chapters are published herein; the appendixes are posted on the project website. Chapter 1 gives a review of the problem statement, Bridge Formula B requirements, and the research approach. Chapter 2 describes the findings of the literature search, survey of states, and the WIM data analyses. Chapter 3 provides the results of the development and calibration of live-load models that are representative of the Formula B and non-Formula B SHV configurations. Chapter 4 contains the conclusions, including the proposed load models and load factors, and recommendations for future research.

All appendixes for this report are available online at www.trb.org/news/blurb_detail.asp?id=7566. Appendix A contains the questionnaires used in the surveys and tabulated responses for Phases I and II. Appendix B includes spreadsheets documenting the results of WIM data from 18 states obtained and analyzed in this project, including state-by-state results of WIM data analyses. Results of the analyses of generic simple and continuous spans for load effects induced by candidate Formula B and non-Formula B SHVs are included in Appendixes C and D, respectively. A Monte Carlo simulation performed to estimate the expected maximum load effect for two side-by-side SHVs and validate the statistical projection approach used in this project is described in Appendix E. Appendix F contains the draft recommended revisions to the AASHTO MCE and LRFR manuals to allow the inclusion of the new legal load models developed in this project. Appendix G is the calibration report for this project documenting the live-load calibrations for Formula B and Non-Formula B trucks.

CHAPTER 2

Findings

This chapter summarizes the results of the literature search, state Department of Transportation (DOT) surveys, and the WIM data collection program. The objective was to document practices related to legal weight limits and posting vehicles used by the states and to obtain information on unusual axle configurations and truck types in the traffic stream. The WIM data were also used to investigate the overload and multiple-presence probabilities for SHVs.

Literature Review

A search, assembly, and review of technical documents and research reports were performed. Transportation Research Information Services (TRIS) and Internet search engines were used to identify many useful source documents. Full-text versions of technical publications relevant to this research were obtained and reviewed. The area of truck loads in the United States is a vast topic with numerous published references; however, the narrow research focus of this project requires a very careful review of this information to identify those publications that are of value to this project. Fortunately, much of the available information on this topic is summarized in recent TRB and FHWA truck studies and reports. The following reports were found to be among the most useful:

- AASHTO (1987). *Guide for Maximum Dimensions and Weights of Motor Vehicles and for the Operation of Non-Divisible Load Oversize and Overweight Vehicles (3).*
- FHWA (1999). *Truck Characteristics Analysis (4).*
- Fancher Jr., P.S., and T.D. Gillespie (1997). *NCHRP Synthesis of Highway Practice 241*: *Truck Operating Characteristics (5).*
- Fu, G., et al. (2003). *NCHRP Report 495: Effect of Truck Weight on Bridge Network Costs (6).*
- Nix, F., and M. Boucher (1990). *Economics and Liftable Axles on Heavy Trucks (7).*
- TRB (2002). *TRB Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles (8).*
- TRB (1990). *TRB Special Report 225: Truck Weight Limits: Issues and Options (9).*
- TRB (1990). *TRB Special Report 227: New Trucks for Greater Productivity and Less Road Wear (10).*
- USDOT (2000). *Comprehensive Truck Size and Weight Study (11):*
  - *Volume I: Summary Report,*
  - *Volume II: Issues and Background,* and
  - *Volume III: Scenario Analysis.*
- Washington State Transportation Center (1994). *An Evaluation of the Lift Axle Regulation (WAC 468.38.280) in Washington (12).*

The research team contacted several major manufacturers of heavy trucks for information on their short-axle work trucks used in construction and heavy hauling operations. Brochures were received from Mack, Volvo, Freightliner, Western Star, and Peterbilt on their lines of heavy-duty trucks. Information was also gathered by visiting the websites of these and other companies and component manufacturers. The information received was helpful in a general sense in understanding the capabilities of each line of trucks, in the range of available options, and in the choices available to the customers of these work trucks. The truck manufacturers typically provide a wide range of engine and component options for each truck, including components made by other manufacturers. For instance, Hendrickson Auxiliary Axle Systems, located in Ohio, is one of the leading producers of liftable suspension systems for heavy-duty trucks and trailers. Hendrickson manufactures a complete line of air and spring-leaf lift axles for a wide range of trucks that are offered by most truck manufacturers as an option. These lift axles have gained increased use on vocational trucks and trailers since the FBF was enacted because it forced by law many heavy operators to add lift axles to truck bodies to optimize payload.

The information in the product literature typically highlighted the following items and options:

- Engine horsepower and torque ranges;
- Transmission options;
- Front axle ratings;
- Rear axle ratings;
- Suspension options, including capacity and axle spacing options for tandems;
- Lift axle options;
- Body and axle configurations; and
- Trailer options.

The data were not useful in determining precise axle configurations and weights because these are often customized to fit customer needs either by the manufacturer or after-market vendors. The literature notes that each customer is different and the operational requirements for each truck are unique. A big selling point is that these heavy-duty trucks can be custom tailored to the customer's exact specifications. For instance, Mack's Granite model of trucks offers front axle ratings from 12,000 to 20,000 lbs and tandem rear axles from 38,000 to 65,000 lbs. Mack also offers a Granite Bridge Formula model that maximizes the payload (minimize tare weight) while fully complying with the FBF. The axle spacing and weight distribution are optimized for maximum efficiency and lower operating costs.

Federal Bridge Formula B

There are four basic federal weight limits:

1. 20,000 lbs for single axles,
2. 34,000 lbs for tandem axles,
3. A maximum GVW of 80,000 lbs, and
4. Application of the FBF B for each axle group up to the maximum GVW.

The FBF calculates the maximum allowable load (the total gross weight in pounds) that legally can be imposed on the bridge by any group of two or more consecutive axles on a vehicle or combination of vehicles. If a vehicle conforms to the FBF, then it most likely will not cause bridge structure stresses, strains, or deflections to exceed those critical values calculated using the standard HS20-44 design vehicle. In effect, the formula helps to ensure bridges are not "overstressed" due to the almost infinite number of truck-axle configurations and weights. The FBF reflects the fact that loads concentrated over a short distance are generally more damaging to bridges than loads spread over a longer distance. It provides for additional gross weight as the wheelbase lengthens and the number of axles increases. The result is that motor vehicles may be loaded to the maximum weight only if each group of axles on the vehicle and their spacing also satisfy the requirements of the Formula. This is to prevent the vehicle from overstressing bridges.

The FBF is based on assumptions about the amount by which the design loading can be exceeded for different bridge designs. Older bridges (prior to the 1940s) were usually designed to H-15 or H-20 standards. The formula was specifically designed to avoid overstressing HS-20 bridges (simple spans) by more than 5% and H-15 bridges (simple spans) by more than 30%. The rationale for the 5% overstress criterion for HS-20 bridges was that a majority of the heavier loads would travel on the Interstate and primary systems and that this criterion will minimize the fatigue attributable to repetitive loads. Although a level of up to 30% is considered a safe level for overstressing an H-15 bridge in good condition (operating level stress), the fatigue life of these structures may be shortened by repeated loadings at this level.

The Federal Bridge Formula B is given as follows:

$$W = 500\left[\frac{LN}{N-1} + 12N + 36\right] \tag{1}$$

where

W = the maximum weight in pounds that can be carried on a group of two or more axles to the nearest 500 lbs,
L = the distance in feet between the outer axles of any two or more consecutive axles, and
N = the number of axles being considered.

Allowable weight depends on the number of axles a vehicle has and the distance between those axles. However, the single- or tandem-axle weight limits supersede the formula limits for all axles not more than 96 in. apart.

Federal law provides that any two or more consecutive axles may not exceed the weight computed by the FBF even though single axles, tandem axles, and gross weight are within legal limits. In other words, the axle group that includes the entire truck, sometimes called the "outer bridge" group, must comply with the formula. Interior combinations of axles, called the "inner bridge" group, must also be in compliance with weights computed by the formula.

An example of a calculation for a five-axle truck is as follows:

- One single axle (steering axle) – 51 ft separation from steering axle to rear portion of back tandem,
- Two tandem axles (34 ft separation for tandems), and
- Each set centered 4 ft apart.

$$W = 500\left[\frac{5(51)}{5-1} + 12(5) + 36\right] = 80{,}000 \text{ lbs}$$

(for the group of axles – steering to rear tandem).

Some definitions are needed to use the FBF correctly:

- **Gross Weight**—the weight of a vehicle or vehicle combination and any load thereon. The federal gross weight limit on the Interstate System is 80,000 lbs.
- **Single-Axle Weight**—the total weight on one or more axles whose centers are not more than 40 in. apart. The federal single-axle weight limit on the Interstate System is 20,000 lbs.
- **Tandem-Axle Weight**—the total weight on two or more consecutive axles more than 40 in. but not more than 96 in. apart. The federal tandem-axle weight limit on the Interstate System is 34,000 lbs.

Table 1 was derived using FBF B for various *N* and *L* values. As seen in the table, there is a greater gain in allowable load by adding an axle than by increasing the distance between axles. Increasing the number axles in an axle group without increasing the overall length of the group has very little effect in reducing bridge load effects. The effect of axle weight is more significant to pavement than bridges. Bridge stress is affected more by the total amount of load (GVW) than by the number of axles and should not have been made part of the formula. The FBF encourages the addition of more axles to obtain more payload even though the underlying bridge stress criteria may be exceeded. At other times, the formula may be restricting allowable loads for short trucks below that allowed by the stress criteria themselves. Irrespective of the derivation criteria and perceived shortcomings, it is FBF B that was adopted by Congress as the standard for truck weights and axle configurations nationwide and is the federal law that industry has to comply with.

State Legal Loads and Weight Limits

Truck loads are considered legal in a given state if the gross load, axle load, axle configuration, length, and width are within the current weight and size laws or rules. Many states allow loads that exceed the federal weight limits. When the Interstate System axle and gross weight limits were adopted in 1956, states were allowed to keep or "grandfather" those that were higher. In 1975, states were also allowed to keep "grandfathered" bridge formula limits that were higher than those established for the Interstate System.

Although the federal weight limits generally apply both on and off the Interstate system, only seven states apply the federal limits statewide without modification or "grandfather right" adjustment. Four states have grandfather rights to exceed 80,000 lbs on the Interstate (see Table 2). On non-Interstate Highways, 18 states have GVW limits higher than 80,000 lbs. Fifteen states have tandem axle limits greater than the federal limit of 34,000 lbs on the Interstate. On the non-Interstate system, 21 states have limits greater than 34,000 lbs, and 2 states are below the federal limit. These include states that allow heavier tandem axle loads only on trucks with a GVW of 73.28K or less (grandfather rights). When taken together, the 50 states and the District of Columbia have created 40 different combinations of these limits (*11*).

The USDOT study reports the following (*11*):

- States that allow tandem axle loads greater than the federal limit on Interstate highways are Alaska, Colorado, Connecticut, Georgia, Hawaii, Maryland, Massachusetts, New Hampshire, New Mexico, New York, North Carolina, Pennsylvania, Rhode Island, South Carolina, and Wyoming;
- States such as Pennsylvania, South Carolina, and Florida do not apply the FBF to trucks weighing 73.28K or less on Interstate highways;
- A modified bridge formula is used by California, Maine, New Mexico, North Carolina, New York, Oregon, Texas, and Wisconsin on Interstate highways; and
- Many more states either do not apply FBF or use a modified bridge formula to non-Interstate highways (see Table 2).

Equipment Characteristics

The most general distinction among truck configurations is whether they are single-unit trucks whose cargo carrying units are mounted on the same chassis as the engine, or whether they are combination vehicles that have separate cargo-carrying trailers or semi-trailers that are pulled by a truck or truck-tractor. Nationally the distribution of the trucking fleet by configuration is approximately as follows (*11*):

- Single-unit trucks: 68%;
- Truck-trailer combinations: 4%;
- Tractor-semi trailer combinations: 26%;

Table 1. Maximum weight allowed under FBF in Kips.

Wheelbase (ft)	3-Axles	4-Axles	5-Axles
20	51.0	55.5	60.5
24	54.0	58.0	63.0
28	57.0	60.5	65.5
32	60.0	63.5	68.0
36		66.0	70.5
40		68.5	73.0

Table 2. State vehicle weight limits (*11*)*.

State	Gross Vehicle Limit		FBF Limit	
	Interstate	Other Highways	Interstate	Other Highways
Alabama	80	84	Yes	No-WT
Alaska	—	90	—	Yes
Arizona	80	80	Yes	No-WT
Arkansas	80	80	Yes	Yes
California	80	80	Yes-mod	Yes-mod
Colorado	80	85	Yes	No
Connecticut	80	80	Yes	Yes
Delaware	80	80	Yes	No-WT
D.C.	80	80	Yes-mod	Yes-mod
Florida	80	80	Yes **	No-WT
Georgia	80	80	Yes	Yes
Hawaii	80.8	88	Yes	No
Idaho	80	105.5	Yes	Yes
Illinois	80	80	Yes	Yes
Indiana	80	80	Yes	Yes
Iowa	80	80	Yes	Yes
Kansas	80	85.5	Yes	Yes
Kentucky	80	80	Yes	Yes
Louisiana	80	80	Yes	No
Maine	80	80	Yes-mod	No
Maryland	80	80	Yes	Yes
Massachusetts	80	80	Yes	Yes
Michigan*	80	80	Yes	Yes
Minnesota	80	80	Yes	Yes-mod
Mississippi	80	80	Yes	Yes
Missouri	80	80	Yes	Yes
Montana	80	80	Yes	Yes
Nebraska	80	95	Yes	Yes
Nevada	80	129	Yes	Yes
New Hampshire	80	80	Yes	No
New Jersey	80	80	Yes	No
New Mexico	86.4	86.4	Yes-mod	Yes-mod
New York	80	80	Yes-mod	Yes-mod
North Carolina	80	80	Yes-mod	Yes-mod
North Dakota	80	105.5	Yes	Yes
Ohio	80	80	Yes	Yes
Oklahoma	80	90	Yes	Yes
Oregon	80	80	Yes-mod	Yes-mod
Pennsylvania	80	80	Yes (2)	Yes (2)
Rhode Island	80	80	Yes-mod	Yes-mod
South Carolina	80	80	Yes (2)	No
South Dakota	80	129	Yes	Yes
Tennessee	80	80	Yes	Yes
Texas	80	80	Yes-mod	Yes-mod
Utah	80	80	Yes	Yes
Vermont	80	80	Yes	Yes
Virginia	80	80	Yes	Yes
Washington	80	105.5	Yes	Yes
West Virginia	80	80	Yes	Yes
Wisconsin	80	80	Yes-mod	Yes-mod
Wyoming	117	117	Yes	No

*Michigan: Federal axle, gross, and bridge formula limits apply to 5 axle combinations if the GVW is 80K or less. For other vehicles and GVWs over 80K, other limits apply. State law sets axle weight controls, which allow vehicles of legal overall length to gross a maximum of 164K.
**If the GVW exceeds 73.28K, FBF applies.

- Double-trailer combinations: 2%; and
- Triple-trailer combinations: 1%.

The most common single-unit trucks in the commercial fleet with three or more axles are dump trucks, transit mixers, tank trucks, and trash trucks. These trucks are designed to provide specialized services and are commonly referred to as “specialized hauling vehicles” or SHVs. SHVs represent approximately 46% of the single-unit trucks operating with three or more axles (*11*). They are typically used in local and intrastate, short-haul operations. The most common commodities that they haul are construction materials, gravel, ready-mix concrete, grain, petroleum products, milk, and garbage or waste (see Figures 1 and 2).

Most trucks and combinations operate at or below the GVW limits as they do not reach their weight limit because the available space in the truck becomes filled first—that is, it “cubes out.” Tank trucks and hauling trucks that operate at average load levels reach their maximum weight limit and “weigh out” over 80% of the time. This occurs less than 20% of the time for enclosed van trailers used to transport commodities that have low density.

The 1975 FBF mandate led to a variety of vehicle configurations and characteristics not initially envisioned. The new configurations are typically directed at increasing the potential payload. Examples of such “bridge formula” trucks are (1) four-axle tractors with lift axles; (2) very long “tongues” on truck-trailer and double-trailer configurations (to increase axle spacing and, therefore, allow a higher gross weight limit); and (3) split tandem axles, now a common feature of five-axle tractor–semi trailers carrying heavy commodities.

The FBF specifies the maximum gross weight given a vehicle’s wheelbase and the number of axles it has. The federal provision also has a maximum GVW of 80,000 lbs. Consequently, various innovative arrangements of axles and tires have evolved in the last two decades to increase load capacity within GVW limit and not to exceed axle limits. Two of these innovative arrangements are split tandem axles and lift axles (within three- and four-axle groups—tridems and quadrems). Single-unit trucks and semi-trailer combinations with tridem axles are operating in all states. Lift axles are routinely used on single-unit trucks such as dump trucks and cement mixers as well as on semi-trailers. Lift axles are used on more than 70% of all four-axle single-unit trucks (*11*). In several states, five-, six-, and seven-axle single-unit trucks with two to four lift axles are used. Federal and most state laws do not address the use of lift axles. Generally a truck operates with the lift axle down when loaded to increase its weight limit and up when empty to improve vehicle maneuverability and handling.

Figure 1. Single-unit multi-axle SHV.

Figure 2. SHVs used in construction.

A split tandem axle is created by increasing the spacing between the two axles in a tandem axle group from a typical standard of approximately 4 ft up to 8 ft, 9 ft, or even 10 ft.

Split tandem axles are an increasingly common feature of trucking throughout the United States. The operational advantages are that they increase GVW within the allowable limit and provide flexibility in load distribution. By increasing the spacing, the split tandem—rather than being considered a tandem axle with an axle weight limit of 34,000 lbs—is considered as two single axles with a total allowable weight governed by the FBF. The combined weights allowed on a split tandem axle are 38,000 lbs for a spread of more than 8 ft, 39,000 lbs for 9 ft, and 40,000 lbs for 10 ft or more.

The truck types that are most likely to have lift axles are basic platforms, dump trucks, and concrete mixers (*4*). The dump truck is the most likely truck type among vehicles with one lift axle. Two lift axles are commonly found on the basic platform. Lift axles are also an important regulatory issue since they are used on heavy vehicles that are more prone to overweight violations. The lift axles themselves are sometimes subject to misuse, further increasing the risk of damage to pavements and bridges. The combination of overweight trucks and lift axles not properly deployed could pose a significant risk to bridge safety. These are compliance issues outside the scope of this project.

Lift Axles

The FBF allows more weight within a given length of truck if more axles are used. Trucks with multiple axles have difficulty turning and cornering. Industry has resolved this difficulty with the use of liftable axles. A lift axle is a non-fixed axle located on a tractor, semi-trailer, or trailer that can be retracted or lifted from contact with the road. The purpose of a lift axle is to provide additional support when a truck is carrying a load that is heavier than was originally intended for the vehicle configuration.

Lift axles allow the trucker to carry substantially higher payloads for a small increase in vehicle cost. Haulers of heavy dense freight most commonly use liftable axles. Lift axles can be raised when the load is sufficiently light or the truck is empty, allowing the trucker to conserve fuel and reduce tire wear and tear. Lift axles when lowered can produce additional traction on slippery roads or inclines. Additionally, lift axles reduce pavement damage by distributing the truck loads across the pavement surface. Lift axles and suspensions are available in pusher or tag configurations, steerable or non-steerable capacity from 10,000 lbs to 22,000 lbs (see Figures 3 and 4). The most common use of the lift axle is in dump trucks preceding a tandem axle, thus forming a tridem axle. In concrete mixers, two lift axles are common: one following the steering axle and one at the extreme rear of the truck. In most states, the load and spacing of lift axles are governed by the same bridge formula that governs fixed axles.

Common drawbacks of lift-axle trucks are as follows (*12*):

- Lift axles, when deployed, reduce the turning capabilities of the truck and may cause the truck to jackknife on slippery roads. If the axles are raised through the turn the truck's stability is compromised and the chance of rollover is increased.
- The proportion of the load carried by the lift axle is often controlled by the driver. If the axle is deployed too far, it may carry too much of the load. If the axle is not deployed far enough, the other axles may be overloaded.
- Enforcing compliance with lift axle regulations is very difficult. Lowering retractable axles when approaching a weigh facility and then raising the lift axles after clearing the weigh facility is not uncommon. Regulatory agencies sometimes require the controls for raising and lowering the lift axles to be located outside the cab to inhibit this practice. Some states have banned the use of lift (or retractable) axles for the reasons cited above.

The lift axles are deployed and retracted with hydraulic-cylinder or air-bag technology. In both cases, a change in pressure (hydraulic pressure or air pressure) loads and unloads the liftable axles. Controls for raising and lowering the lift axle or regulating the proportion of the load carried

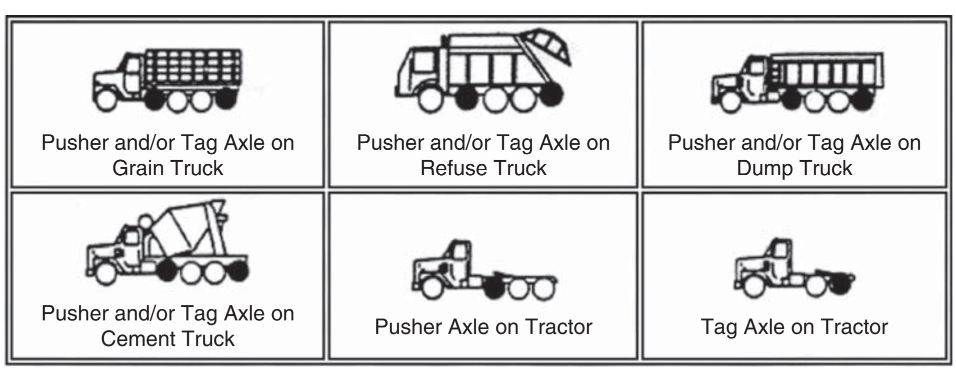

Figure 3. Common applications of lift axles.

Figure 4. SHVs with liftable axles.

by the lift axle can be installed in a number of ways. They can be both inside the cab and outside the cab or the controls for raising and lowering can be inside the cab with the regulating switch outside the cab. Lift axles may be self-steering, controlled steering, or non-steering. Non-steerable axles suffer the greatest resistance as the vehicle turns. They may encourage the practice of lifting the retractable axles around corners. Self-steering axles have wheels that articulate under forces developed between the tire and the road surface. Steerable axles are controlled by a hydraulic steering mechanism coupled to the front axle steering mechanism. Lift axle guidelines set forth by AASHTO recommend self-steering axles.

Criteria for lift-axle design and operation are contained in AASHTO's *Guide for Maximum Dimensions and Weights of Motor Vehicles and for the Operation of Non-Divisible Load Oversize and Overweight Vehicles* (*3*). Several states have adopted the AASHTO guidelines as regulations. These AASHTO guidelines specify the following criteria for vehicles serving in regular operations (*3*):

2.07.6 Retractable or Variable Load Suspension (VLS) Axles

In computation of gross vehicle or axle weight limits for highway legal vehicles not requiring oversize/overweight permits, no allowance will be made for any retractable or variable load suspension meeting the following criteria:

1. All controls must be located outside of and be inaccessible from the driver's compartment.
2. The gross axle rating of the VLS devices must conform to the expected loading of the suspension and shall in no case be less than 9000 pounds.
3. Axles of all retractable or VLS devices manufactured or mounted on a vehicle after January 1, 1990 shall be engineered to be self-steering in a manner that will guide or direct the VLS mounted wheels through a turning movement without the tire scrubbing or pavement scuffing.
4. Tires in use on all such axles shall conform in load capacity with relevant State regulations or with Federal Motor Vehicle Safety (FMVS) standards or with both as is deemed appropriate.

2.07.7 Weight Distribution Within Axle Groups:

All axle group suspension systems shall at all times distribute the loads equally among all axles of the group in order to be allowed the upper weight limits specified in Section 2.07, without the necessity for downward adjustment due to imbalance. "Equally" for the purposes of this subsection means no more than +/— 10 percent variation from the theoretical maximum average axle load of the group.

Many western states have adopted the AASHTO guidelines as regulation. The Washington state regulation governing lift axles is "A retractable axle carrying weight shall have a manufacturer's rating of at least 10,000 pounds, shall be self-steering, and shall have the capacity to be activated from a location out of reach of the driver's compartment." California DOT's (Caltrans') permits policy states that lift axles are acceptable for extralegal weight if they meet two simple tests: (1) the lift-axle loading group must have common suspension and (2) all axles in the loading group must meet the +/— 10% equal weight distribution requirement. The lift-axle controls must also be located outside the cab and inaccessible to the driver while driving.

Posting Loads

Posting loads are a subset of the state or federal legal loads used for implementing bridge weight restrictions. Many load models, actual or notional, may be used for load rating, but load posting—when represented by truck symbols with associated weight limits—is based on trucks representative of actual truck traffic. AASHTO's *Manual for Condition Evaluation of Bridges* (*MCE*) (*1*) Section 6.7.2 specifies the HS20 truck or lane load as the rating live load to be used in the basic load-rating equation. The inventory and operating ratings for HS20 are reported to FHWA for inclusion in the National Bridge Inventory and the Structure Inventory and Appraisal sheet. Bridges that do not pass the HS20 ratings with a rating factor of 1.0 or higher are subjected to a posting analysis to determine the need for weight-limit posting. In the recently adopted AASHTO LRFR guide manual (*2*), the HL-93 design loading performs the same screening and reporting function as HS20. In both manuals, the live load used in the rating equation for posting considerations is any of the three AASHTO legal loads—Type 3, Type 3S2, and Type 3-3—or state legal loads. Therefore, the three AASHTO trucks—Type3, Type 3S2, and Type 3-3—are the AASHTO posting loads. In LRFR, only state legal loads that have minor variations from the AASHTO legal loads may be included in the posting analysis. Grandfathered state legal loads that induce load effects significantly greater than the AASHTO trucks have not been included in the reliability-based LRFR calibrations of live-load factors. There are no such limitations on state legal loads in load factor rating and allowable stress rating as their load factors and safety factors were not statistically based.

The AASHTO trucks were developed in the 1970s to be sufficiently representative of commercial truck configurations at the time, and they also model the FBF in the short-, medium-, and longer-span ranges. In recent years, to increase load-carrying capacity and maximize productivity, the trucking industry has introduced SHVs with closely spaced multiple axles that exceed the load effects induced by the AASHTO legal loads, yet meet the requirement of the FBF. In response to the changing truck configurations, several states have adopted a variety of short multi-axle vehicles as state legal loads for rating and posting purposes. The current AASHTO legal loads selected at the time to match closely the FBF do not represent these newer axle configurations.

Non-Formula B Posting Loads

A significant portion of the SHV population belongs in this category, commonly referred to as "grandfather trucks." They exceed FBF gross weight limits (≤ 80 K) and limits for axle groups. Many more states either do not apply FBF or use a modified bridge formula to non-Interstate highways. The most common grandfathered truck seen in many states is the tri-axle dump truck that can weigh up to 75,000 lbs with a total wheelbase of less than 20 ft. They are legal under state law in some states with grandfather rights and are free to operate unrestricted, except as limited by bridge posting. Weight-limit posting for these vehicles seems to be the only safeguard the states have to protect their bridges from overstress or failure. Due to their widespread use and concerns about their adverse impact on bridge safety, several states have adopted a non-Formula B version of the four-axle dump truck and other common truck configurations as rating and posting vehicles.

Posting Practices

Bridge posting involves a consideration of safety, economy, and the public interest. Statutory law governs the maximum weight of vehicles legally allowed on bridges without special overload permits. The federal government became involved in weight-limit posting in 1968 with the creation of the National Bridge Inspection Standards (NBIS) (*13*). Weight limits were required for bridges found to be structurally inadequate. The NBIS require that every bridge be rated for its safe load-carrying capacity in accordance with the AASHTO Manual. According to the NBIS: "If it is determined under this rating procedure that the maximum legal load under State law exceeds the load permitted under the Operating Rating, the bridge must be posted in conformity with the AASHTO Manual or in accordance with State law" (23 CFR Part 650, Subpart C).

Posting regulations vary widely among agencies including the criteria for initiating a posting action, methodology for setting the allowable truck weight limit, and techniques for how the limits should be represented on highway signage. The NBIS provide limited guidance on evaluating and posting weight limits on bridges; considerable engineering judgment is required to fill the gaps. This leads to differences in posting criteria in different jurisdictions that reflect different rating and evaluation philosophies, different jurisdictional needs, different bridge inventories, and different traffic conditions. For instance, the bridge posting level may be set at the operating level, at the inventory level, or somewhere in between, depending upon factors such as bridge type, condition rating, redundancy, fatigue sensitive details, average daily truck traffic (ADTT), inspection frequency, enforcement, and so forth. There is considerable leeway in the way bridges are currently posted because most of these factors are selected intuitively. The recently adopted LRFR procedures will provide only a single load rating for use on load posting through a more systematic consideration of these factors in the rating process and therefore will encourage more uniform posting practices.

States may not have the statutory authority to post locally and privately owned bridges. The state may perform engineering calculations to determine the safe-load capacity of any given bridge and send the rating report to the local agency. Because the responsibility for posting locally and privately owned bridges rests with the local bridge owners, it follows that the procedure for posting these bridges may also be different. Problems with the lack of compliance with posting regulations are also more common at the local level.

Survey of States

Tasks 1 and 10 required the research team to obtain information and document practices on issues central to this research, such as state legal loads different from the AASHTO vehicles and how these vehicles are used in load rating and in implementing load postings, how weight limits are shown on posting signs, information on other unusual truck configurations that are common in a given state but not used as legal loads, information on lift-axle regulations and industry compliance, enforcement of lift-axle regulations, and specific concerns the states may have with regard to load rating and posting for SHVs. As part of these tasks, two surveys were conducted of state DOTs. The first survey done under Phase I data collection focused on vehicles that meet Formula B requirements. The second survey for Phase II researched the use of grandfather vehicles that do not comply with Formula B as state legal loads. Copies of the questionnaires and responses are included in the Appendix A to this report. The first questionnaire on Formula B trucks consisted of the following five sections:

1. State Bridge Load Rating and Posting Documents,
2. State Legal Loads,
3. Load Posting,
4. Lift-Axle Truck Regulations, and
5. Weigh-in-Motion Truck Weight Data.

Completed questionnaires were received from 45 states. A large number of state legal loads having unusual axle configurations different from the AASHTO loads were obtained from the survey responses.

The second questionnaire on non-Formula B trucks consisted of the following four sections:

1. Vehicle Weight Limits,
2. Exempt Vehicles,
3. Non-Formula B State Legal Loads for Posting, and
4. "Routine" Permit Limits.

Forty states responded to the questionnaire. A large number of state legal loads that deviate from the AASHTO loads and exceed federal weight limits were obtained from the survey responses. Tabulated responses to all survey questions are contained in Appendix A. The significant findings are as follows.

Summary of Surveys

The survey questionnaire sought information on state legal loads, specifically those loads that differ from the AASHTO vehicles. Only 11 of the 45 states that responded to the first survey questionnaire use the AASHTO legal/posting loads exclusively. Half the states report that they use only state legal loads. The remaining states use a combination of AASHTO and state legal loads. The following is a summary of the state of the practice with respect to legal loads, based on the survey responses from 45 states:

Question 2.1: Which of the following best describes the legal vehicles in your state?

- AASHTO loads only (11 states): Arizona, California, Indiana, Kansas, Massachusetts, Nebraska, Nevada, Oregon, South Carolina, West Virginia, and Wyoming.
- State loads only (23 states): Alabama, Alaska, Arkansas, Delaware, Florida, Georgia, Idaho, Illinois, Kentucky, Michigan, Minnesota, Missouri, New Hampshire, New York, North Carolina, North Dakota, Ohio, Pennsylvania, South Dakota, Tennessee, Texas, Virginia, and Wisconsin.
- Both (11 states): Colorado, Connecticut, Hawaii, Iowa, Louisiana, Mississippi, New Jersey, New Mexico, Oklahoma, Rhode Island, and Washington.

A large number of state legal load configurations currently in use were obtained from the states that use state legal loads only or a combination of state and AASHTO legal loads. They included both single-unit and combination trucks. They were a combination of Formula B and non-Formula B trucks as revealed through further analysis and discussed in this report. As the purview of this research is short multi-axle SHVs, only single-unit trucks under 35 ft long and within the 80,000-lb weight limit were extracted for further review and analysis. A seven-axle, 35-ft-long SHV is allowed a gross weight of 80,500 lbs under FBF requirements, slightly over the maximum under federal weight laws and the 80,000-lb gross weight limit. Therefore, any increase of length would not lead to increased gross weight. It was also felt that this length limit would adequately encompass the SHVs in operation and at the same time leave out the longer combination vehicles. There was no consideration given to the type of vehicle or the number of axles in preparing this shortlist of state legal loads. Some states identify the type of vehicle being modeled by a state legal load, whereas in other cases it may only be a schematic axle configuration with all data needed for bridge rating and posting. Figures 5 through 11 present schematic axle configurations of state legal loads used for load rating and posting by the various states identified and are also sufficiently different from the AASHTO legal load models.

Michigan uses 28 truck models as legal loads that are divided into three levels: normal, designated, and special designated. The special designated loading applies to Interstate highways and meets applicable federal weight laws.

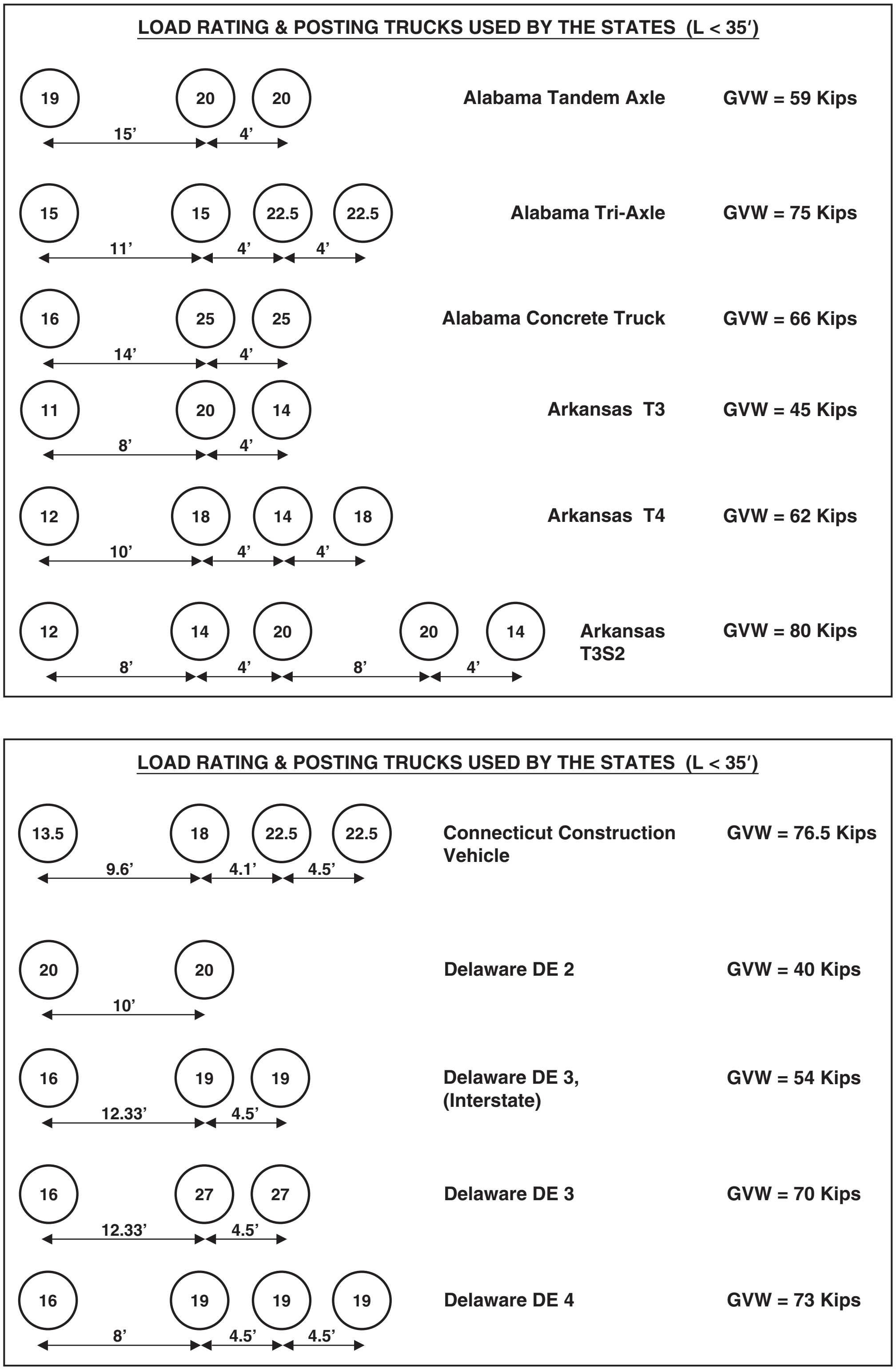

Figure 5. State posting loads (axle load in Kips).

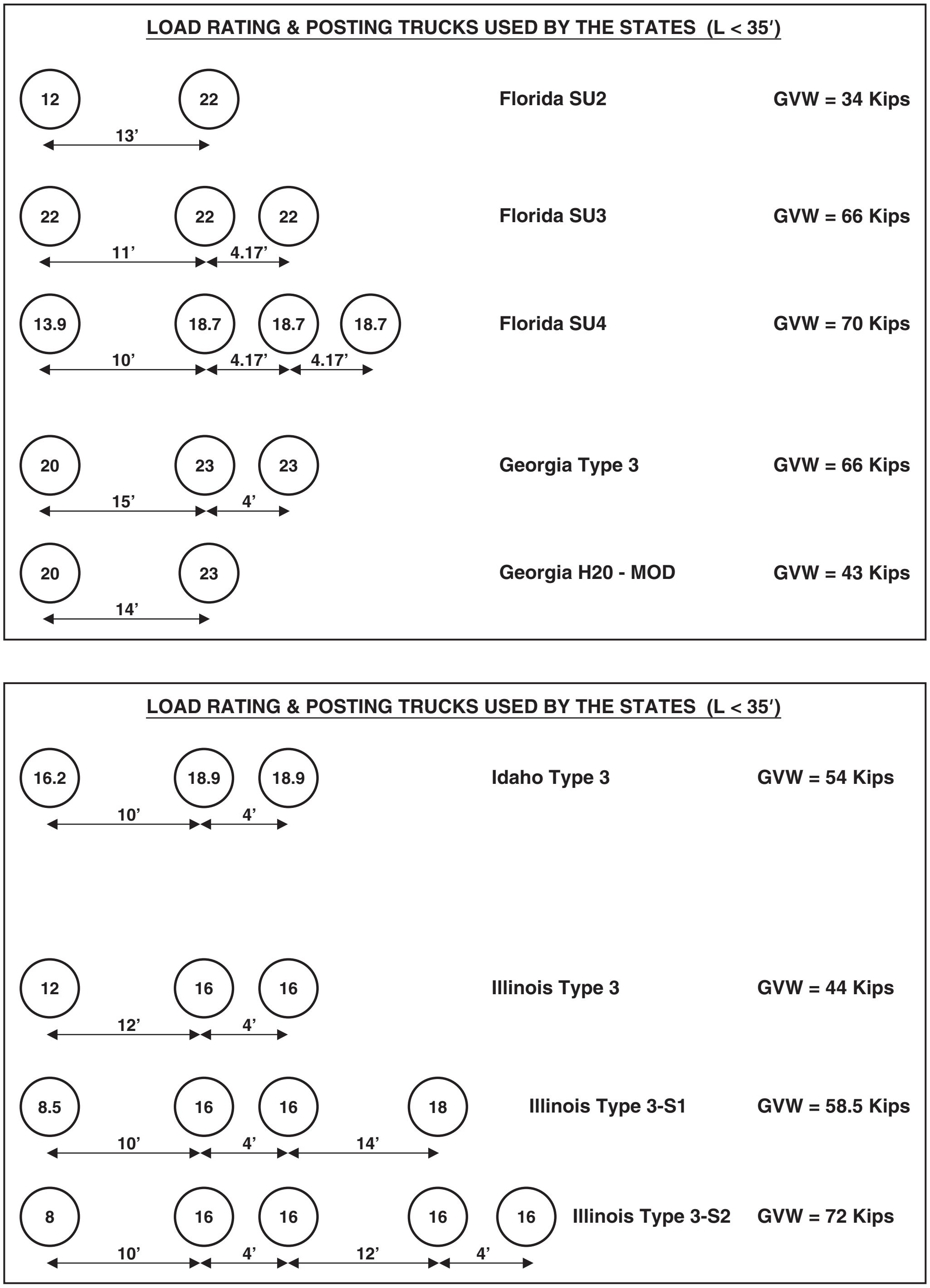

Figure 6. State posting loads (axle load in Kips).

The normal loading defines the maximum loading for all Michigan roads. For the normal and designated loading there is no direct maximum for the total GVW. There is an indirect maximum caused by the length of vehicle and the number and spacing of axles. Michigan allows up to 11 axles for legal vehicles. Michigan trucks meeting the selection criteria are shown in Figures 8 and 9. North Carolina uses eight single-unit trucks having up to seven axles and five combination trucks as state legal loads. Different axle and gross weights are allowed for Interstate and non-Interstate bridges (higher for non-Interstate, see Figures 10 and 11). They were defined as state legal loads based upon a statewide traffic study in 1995 and by closely matching the Formula B gross weight requirements. Under grandfather rights, trucks are allowed to exceed the federal limit for tandem axles by up to 10% (maximum tandem axle weight of 38 K, gross weight not to exceed 80 Kips). Pennsylvania truck TK527 (see Figure 8) was developed in 2001 to envelope an entire group

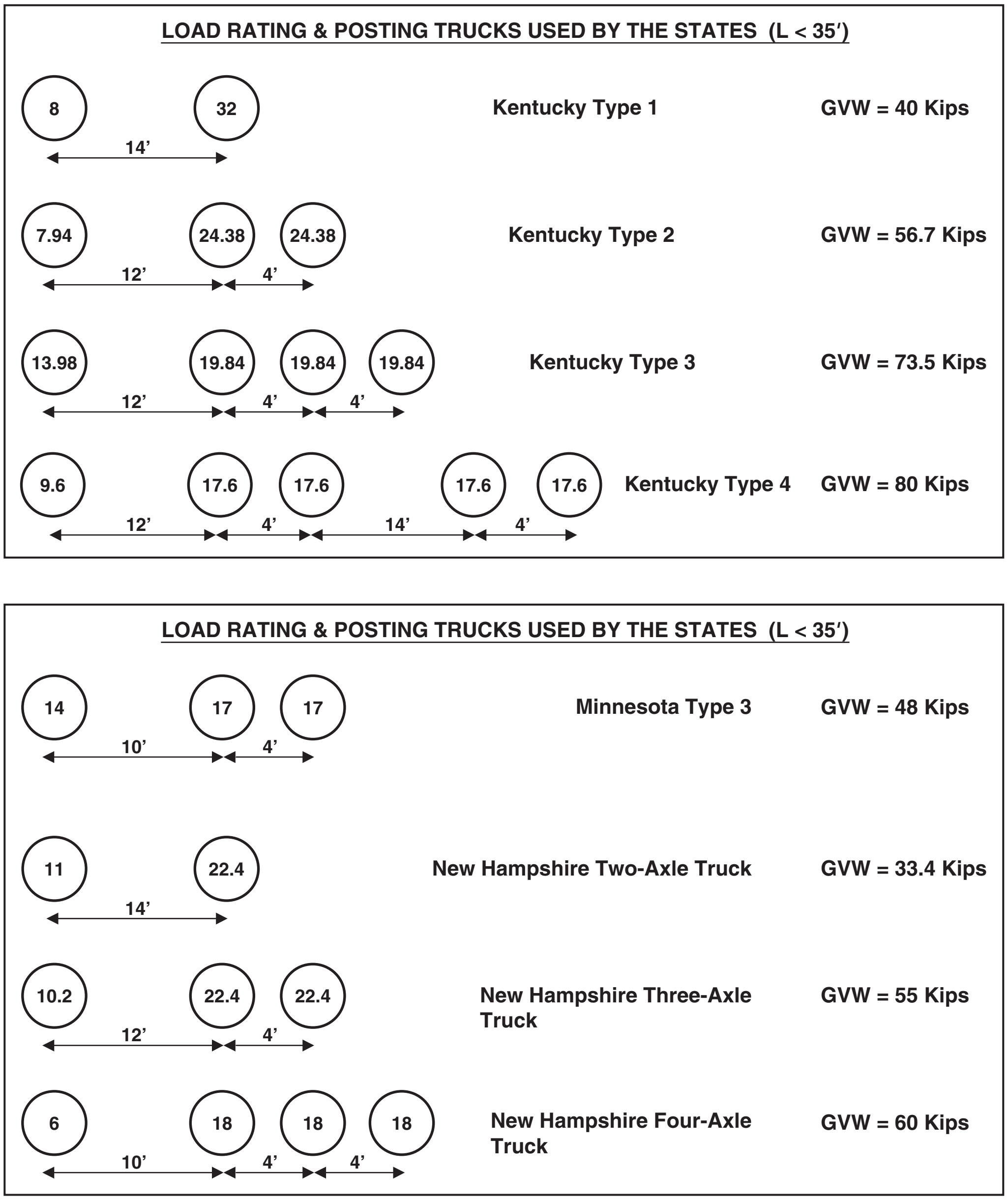

Figure 7. State posting loads (axle load in Kips).

of five- to seven-axle trucks that are legal in Pennsylvania. The seven-axle truck with two consecutive axles carrying 41.2 Kips (grandfather rights) produces moments and shears in excess of the five- and six-axle vehicles allowed under Pennsylvania law. It serves as a notional posting vehicle to represent this series of vehicles. For easy identification the truck was designated “TK527.” Of the six consecutive rear axles, the first four are lift axles, each carrying 8.24 Kips. Studies have shown that the TK527 vehicle exceeds the HS20 and ML80 load effects in the span range of 80 to 175 ft.

Several states (Delaware, Florida, Georgia, Kentucky, New Hampshire, Ohio, Michigan, Texas, and North Carolina) use a short two-axle truck 9 ft to 17 ft long as a posting load. The tri-axle dump truck with a tridem axle in the rear is a common posting load in many states (Alabama, Arkansas, Connecticut, Delaware, Florida, Kentucky, Michigan, New Hampshire, North Carolina, Pennsylvania, and Tennessee). In some states, these short heavy trucks are allowed to operate under the grandfather exemptions for non-conforming vehicles less than 73.28 Kips—a fact that is reflected in the legal load used for posting. Ohio uses a tri-axle dump that meets FBF requirements. Certain state legal loads are variations of the H, HS, AASHTO Type 3, Type 3S2, and Type 3-3. Georgia uses a modified H20 truck, and Mississippi uses a short version of the HS truck weighing 80 Kips. Many states have a three-axle Type 3 truck that is often a shorter version of the AASHTO Type 3, typically in the 14–16 ft range. In Alabama, Mississippi, and Texas, the three-axle truck models a concrete truck.

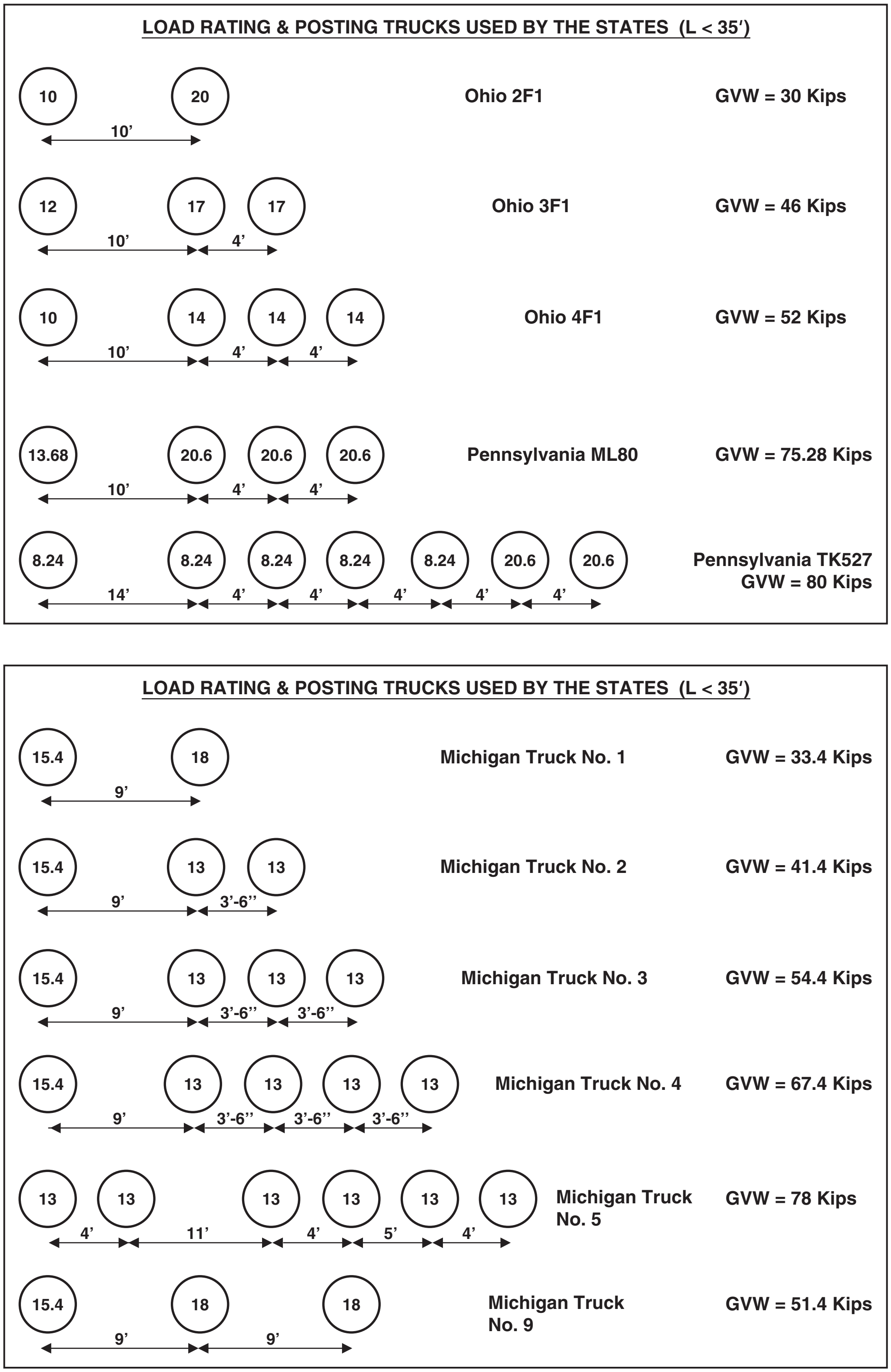

Figure 8. State posting loads (axle load in Kips).

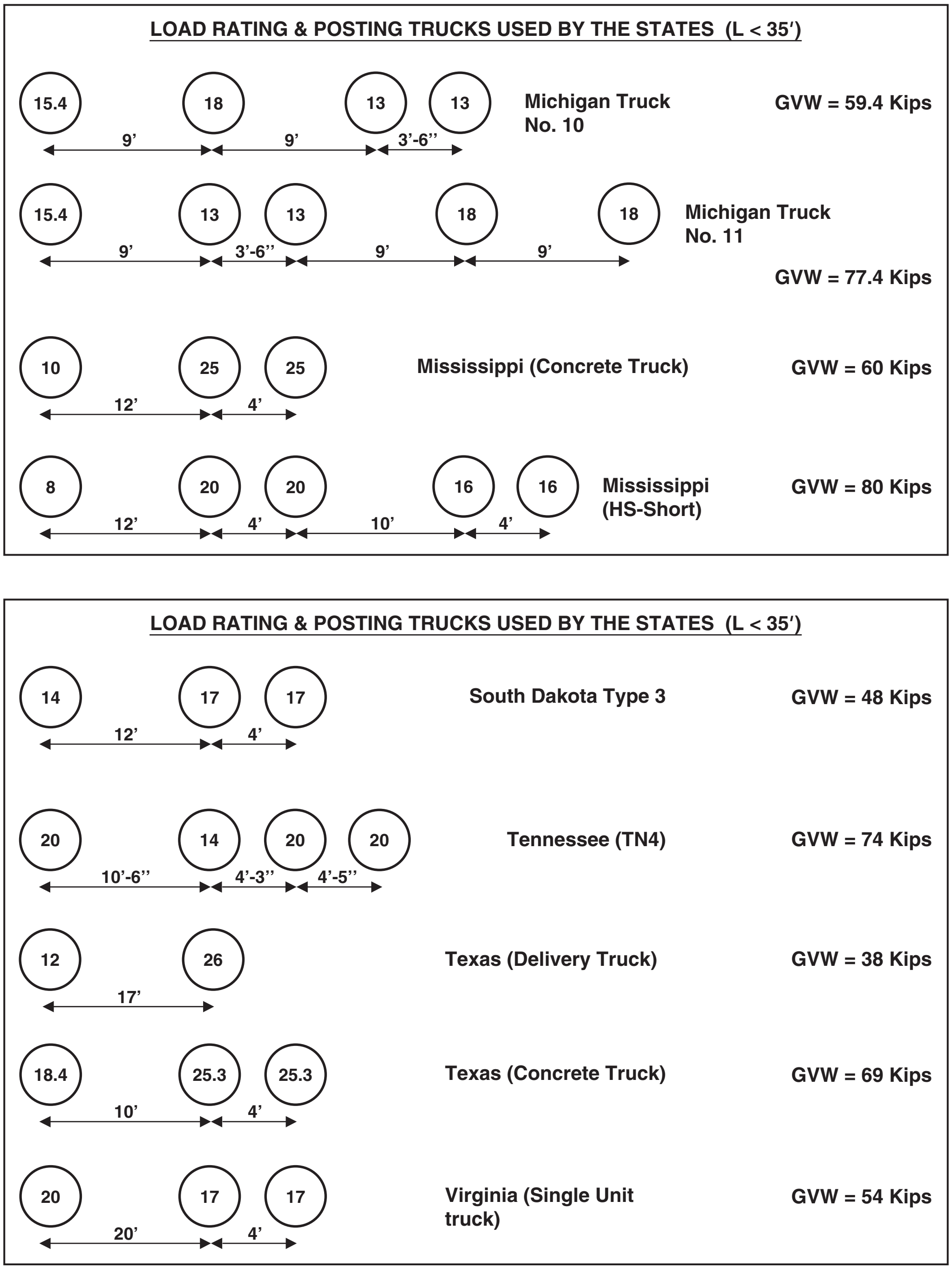

Figure 9. State posting loads (axle load in Kips).

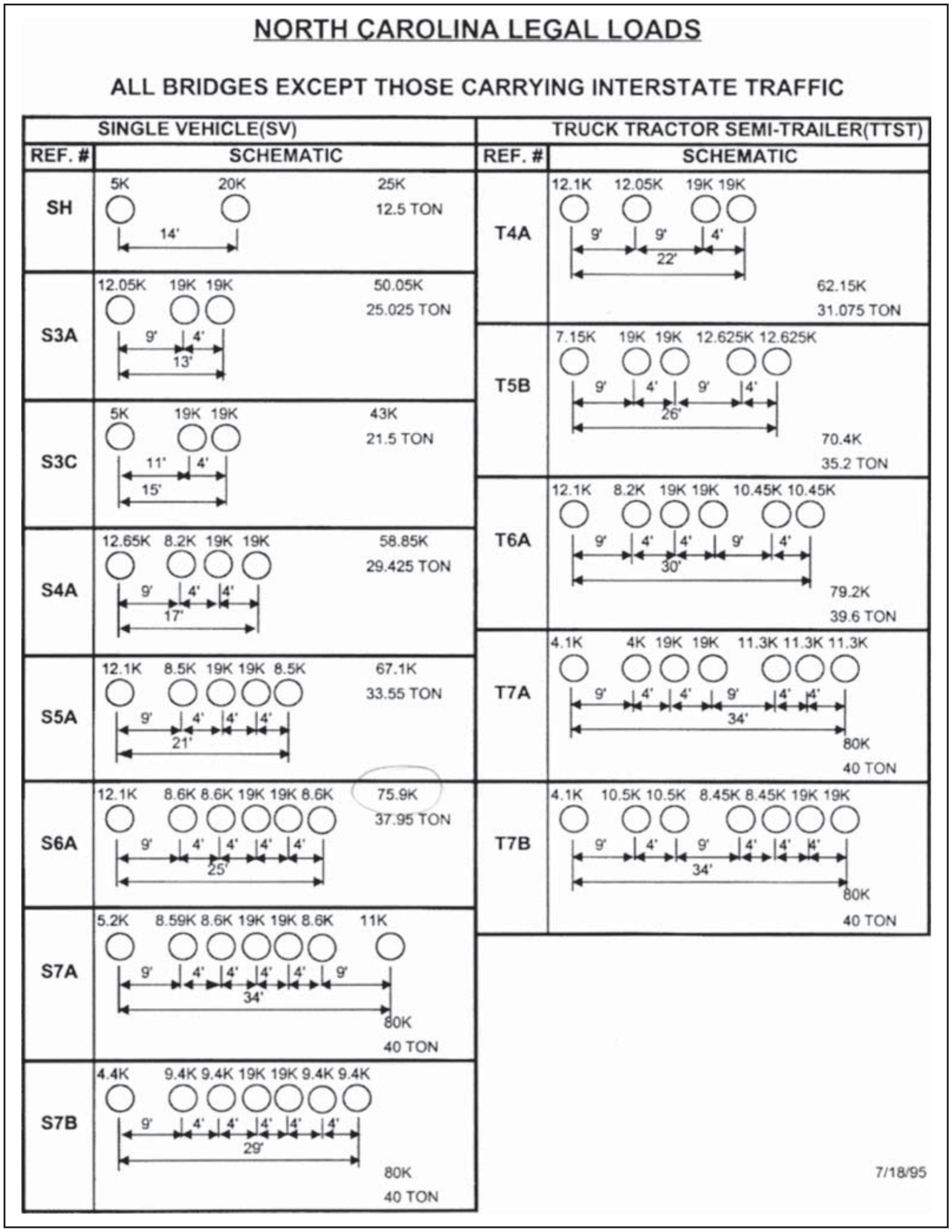

Figure 10. State posting loads (axle load in Kips).

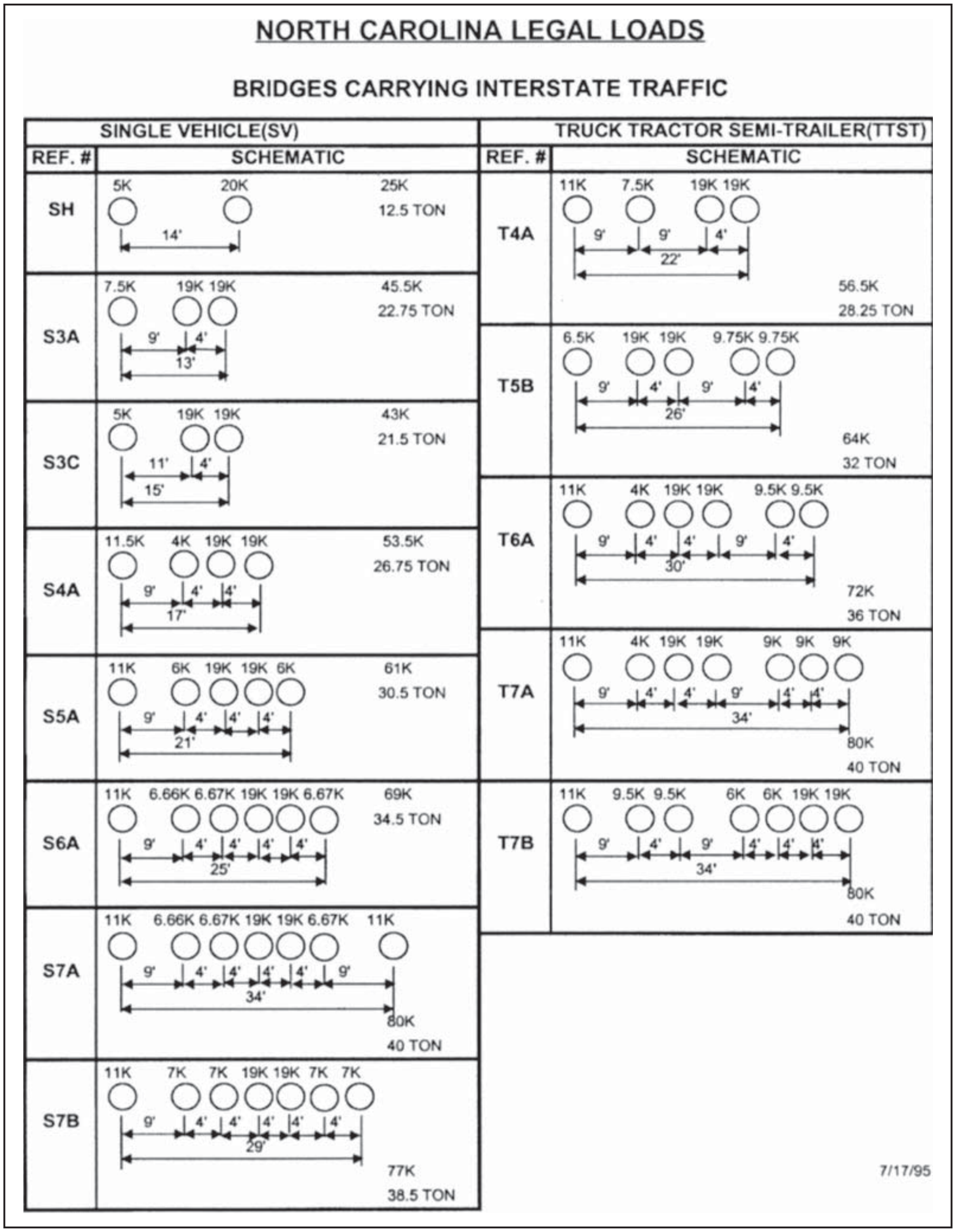

Figure 11. State posting loads (axle load in Kips).

Table 3 presents the results of the survey on axle weight limits for this project, NCHRP Project 12-63. The intent was to ascertain state practices with respect to tandem, tridem, and quadrem axles, which are becoming increasingly common on commercial trucks. Responses indicate a combination of FBF limits, weight table limits, or higher grandfathered limits being allowed on these multi-axle groups. Several states have indicated that they have no specific criteria for tridem and quadrem axles—FBF or other bridge formula limits for axle groups apply.

States were surveyed on SHV exemptions to federal laws. Of the respondents, 19 states allowed exemptions, 18 states did not, and 7 were not sure.

Question 2.4: Does your state exempt certain Specialized Hauling Vehicles (SHVs) from federal weight laws (limits)?

- Yes (19 states): Arkansas, Idaho, Illinois, Iowa, Kansas, Maine, Massachusetts, Minnesota, Mississippi, Nebraska, New Jersey, North Carolina, North Dakota, Ohio, Oklahoma, Tennessee, Texas, Washington, and Wisconsin.

Table 3. State axle weight limits from DOT survey.*

State Axle Weight Limits (in Kips) from DOT Survey Question 2.3								
State	Single		Tandem		Tridem (3-Axle)		Quadrem (4-Axle)	
	Inter-state	State Highways	Inter-state	State Highways	Interstate	State Highways	Interstate	State Highways
Alabama	20	20+10%	34	36+10%	42	42+10%	50	50+10%
Alaska	20	20	38	38	42	42	50	50
Arizona	20	20	34	34	FBF	FBF	FBF	FBF
Arkansas	20	20	34	34	50	50	68	68
California	20	20	34	34	WT	WT	WT	WT
Colorado	20	20	36	40	54	54	N/S	N/S
Connecticut	22.4	22.4	36	36	54	54	N/S	N/S
Delaware	20	20	FBF	FBF	FBF	FBF	FBF	FBF
Florida	22	22	44 (WT)	44(WT)	WT	WT	WT	WT
Georgia	20	23	34	46	34	46	N/A	46
Hawaii	22.5	22.5	34	34	42	43.2	50	50
Idaho	20	20	34	34	42	42	50	50
Illinois	20	18	34	32	WT	WT	WT	WT
Indiana	20	20	34	34	42	42	42	42
Iowa	20	20	34	34	FBF	FBF	FBF	FBF
Kansas	20	20	34	34	42 to 43.5	42 to 43.5	50	50
Kentucky	20	20	34	34	48	48	—	—
Louisiana	20	22	34	37	42	45	50	53
Maine	22	24.2	34	46	42	54	N/S	N/S
Maryland	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Massachusetts	24	24	34	34	36	36	N/S	N/S
Michigan	18	18	WT	WT	WT	WT	WT	WT
Minnesota	20	20	34	34	42	42	50	50
Mississippi	20	20	34	34	42.5	FBF	FBF	FBF
Missouri	20	20	40	40	60	60	60	60
Montana	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Nebraska	20	20	34	34	42	42	50	50
Nevada	20	20	34	34	42	42	—	—
New Hampshire	20	22.4	36/34	44.8	FBF	54/ 60	FBF	N/S
New Jersey	22.4	22.4	34	34	FBF	—	FBF	—
New Mexico	20	21.6	34	34.3	34	48	50	52
New York	22.4	22.4	36	36	FBF	FBF	FBF	FBF
North Carolina	20	20	38	38	FBF	FBF	FBF	FBF
North Dakota	20	20	34	34	FBF	48	FBF	48
Ohio	20	20	34	34	—	—	—	—
Oklahoma	20	20	34	34	FBF	FBF	FBF	FBF
Oregon	20	20	34	34	WT	WT	WT	WT
Pennsylvania	22.4	22.4	38	38	58.4	58.4	73.28	73.28
Rhode Island	22.4	22.4	44.8	44.8	67.2	67.2	89.6	89.6
South Carolina	20	20	40	40	60	60	—	—
South Dakota	20	20	34	34	42	42	—	—
Tennessee	20	20	34	34	FBF	FBF	FBF	FBF
Texas	20	20	34	34	—	—	—	—
Utah	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Vermont	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R
Virginia	20	20	WT	WT	WT	WT	WT	WT
Washington	20	20	34	34	FBF	FBF	FBF	FBF
West Virginia	20	20	34	34	FBF	FBF	FBF	FBF
Wisconsin	20	20	34	34	42	42	50	50
Wyoming	20	20	36	36	42	42	FBF	FBF

*N/S = Not specified; WT = Weight table; N/R = No response.

- No (19 states): Alabama, Arizona, California, Colorado, Connecticut, Delaware, Georgia, Hawaii, Kentucky, Louisiana, Missouri, New Hampshire, New Mexico, New York, South Carolina, South Dakota, Virginia, West Virginia, and Wyoming.
- Not sure (7 states): Alaska, Florida, Indiana, Michigan, Nevada, Pennsylvania, and Rhode Island.

States were also questioned on the types of exemptions they grant to SHVs. The results are shown on Table 4. Relief from FBF requirements appears to be the most common type of exemption granted (12 states), followed by increased tandem axle allowables (11 states). In Section 4 of the survey, other related questions on lift-axle issues were included. The results are summarized in Table 5.

Table 4. SHV exemptions from federal weight laws.

Question 2.5: For these SHVs, specify below how your agency grants exemptions from certain federal weight limits.												
DOT	**Single Axle**			**Tandem Axle**			**Federal Limit B Formula**			**Gross Weight (80 Kips)**		
	Yes	No	If yes, up to (Kips)	Yes	No	If yes, up to (Kips)	Yes	No	If yes, specify	Yes	No	If yes, up to (Kips)
Arkansas		X		X		36.5	X		36.5		X	
Idaho		X		X		37.8	X		Exceeds FBF by up to 26% for certain axle comb		X	
Illinois		X			X			X			X	
Iowa		X		X			X		Up to 20 kips per axle	X		
Kansas	X			X			X			X		85.5
Minnesota		X			X		X				X	
Mississippi		X			X			X			X	
New Jersey	X		No Limit	X		No limit	X		Limit is applied only on GVW and tire pressure	X		
New Mexico	X		21.6	X		34.3		X			X	
North Carolina	X		23.5	X		44	X			X		90
North Dakota		X			X		—	—	Allow 3 or 4 axle group to 51000#	—	—	—
Ohio	X		10%	X		10%	X		10%	X		10%
Oklahoma		X			X		X				X	
Texas		X		X		46	X				X	
Washington	X		24	X		43	X			—	—	
Wisconsin		X		X		45	X			X		155
Total	**6**	**10**		**11**	**5**		**12**	**3**		**6**	**8**	

Table 5. Survey questions on lift axles.

Survey Questions on Lift Axles	*DOT Responses*		
	Yes	No	Not Sure
Question 4.1: Does your agency permit the use of liftable axles on heavy trucks?	41	3	
Question 4.2: Do any of the state legal loads used by your agency represent trucks with liftable axles?	14	28	
Question 4.3: Does your agency or state monitor the weight carried by the liftable axles to ensure compliance with state regulations?	21	5	5
Question 4.4: When performing load ratings for trucks with liftable axles, are ratings checked with the axles in the raised position under full load?	3	15	

Posting Loads that Meet Formula B Requirements

Formula B checks were performed on state legal loads obtained from the survey responses. Table 6 outlines the key parameters and FBF limits for state posting loads having axle configurations different from the AASHTO vehicles. The main consideration in selecting these vehicles is the significance of the differences in axle configurations on the induced load effects. Shorter axle spacings and heavier axles usually signify higher moments and shears when comparing two trucks of the same type. For reasons discussed previously, only trucks having total axle spacing "*L*"—less than 35 ft—are included. Schematic diagrams for these state legal loads that show the axle configuration (number, spacing, and load) are given in Figures 5 through 11.

There were several posting loads that satisfied FBF gross weight limits but violated the FBF limit for axle groups or the federal 20-Kip limit for a single axle. Federal law states that any two or more consecutive axles may not exceed the weight computed by the bridge formula. For an axle spacing of 4 ft, the FBF allows the following maximum loads for consecutive axles spaced at 4 ft:

- 2-Axle: 34 Kips;
- 3-Axle: 42 Kips; and
- 4-Axle: 50 Kips.

Table 6. Formula B checks for state posting loads.

DOT	Truck Designation	Total Axle Spacing *L* (ft.)	No. of Axles *N*	GVW (Kips)	FBF Gross Weight Limit (Kips)	Satisfies FBF Gross Weight Limit?	Satisfies FBF Axle Weight Limit?
Alabama	Tandem Axle	19	3	59.0	50.3	No	No
	Tri-Axle	19	4	75.0	54.7	No	No
	Concrete Truck	18	3	66.0	49.5	No	No
Arkansas	T3	12	3	45.0	45.0	Yes	Yes
	T4	18	4	62.0	52.7	No	No
	T3S2	24	5	80.0	63.0	No	Yes
Connecticut	Construction Vehicle	18.2	4	76.5	54.1	No	No
Delaware	DE 2	10	2	40.0	40.0	Yes	Yes
	DE 3 Inter-State	16.83	3	54.0	48.6	No	No
	DE 3	16.83	3	70.0	48.6	No	No
	DE 4	17	4	73.0	52.9	No	No
Florida	SU2	13	2	34.0	43.0	Yes	No
	SU3	15.17	3	66.0	47.4	No	No
	SU4	18.34	4	70.0	53.7	No	No
	C3	30	3	56.0	58.5	Yes	No
Georgia	H20-MOD	14	2	43.0	44.0	Yes	No
	Type 3	19	3	66.0	50.3	No	No
Idaho	Type 3	14	3	54.0	46.5	No	No
Illinois	Type 3	16	3	44.0	48.0	Yes	Yes
	Type 3-S1	28	4	58.5	60.8	Yes	Yes
	Type 3-S2	30	5	72.0	66.8	No	Yes
Kentucky	Type 1	14	2	40.0	44.0	Yes	No
	Type 2	16	3	56.7	48.0	No	No
	Type 3	20	4	73.5	55.3	No	No
	Type 4	34	5	80.0	69.3	No	No
Michigan	No 1	9	2	33.4	39.0	Yes	Yes
	No.2	12.6	3	41.4	45.4	Yes	Yes
	No.3	16	4	54.4	52.7	No	Yes
	No.4	19.6	5	67.4	60.2	No	No
	No.5	28	6	78.0	70.8	No	No
	No.9	18	3	51.4	49.5	No	Yes
	No. 10	21.6	4	59.4	56.3	No	Yes
	No.11	30.6	5	77.4	67.1	No	Yes
Minnesota	Type 3	14	3	48.0	46.5	No	Yes
Mississippi	Concrete Truck	16	3	60.0	48.0	No	No
	HS-Short	30	5	80.0	66.8	No	No

Table 6. (Continued).

DOT	Truck Designation	Total Axle Spacing *L* (ft.)	No. of Axles *N*	GVW (Kips)	FBF Gross Weight Limit (Kips)	Satisfies FBF Gross Weight Limit?	Satisfies FBF Axle Weight Limit?
New Hampshire	Two-Axle Truck	14	2	33.4	44.0	Yes	No
	Three-Axle Truck	16	3	55.0	48.0	No	No
	Four-Axle Truck	18	4	60.0	54.0	No	No
North Carolina (Interstate Traffic)	SH	14	2	25.0	44.0	Yes	No
	S3A	13	3	45.5	45.8	Yes	No
	S3C	15	3	43.0	47.3	Yes	No
	S4A	17	4	53.5	53.3	Yes	No
	S5A	21	5	61.0	61.1	Yes	No
	S6A	25	6	69.0	69.0	Yes	No
	S7A	34	7	80.0	79.8	Yes	No
	S7B	29	7	77.0	76.9	Yes	No
	T4A	22	4	56.5	56.7	Yes	No
	T5B	26	5	64.0	64.3	Yes	No
	T6A	30	6	72.0	72.0	Yes	No
	T7A	34	7	80.0	79.8	Yes	No
	T7B	34	7	80.0	79.8	Yes	No
North Carolina (Except Interstate Traffic)	SH	14	2	25.0	44.0	Yes	No
	S3A	13	3	50.1	45.8	No	No
	S3C	15	3	43.0	47.3	No	No
	S4A	17	4	58.9	53.3	No	No
	S5A	21	5	67.1	61.1	No	No
	S6A	25	6	75.9	69.0	No	No
	S7A	34	7	80.0	79.8	No	No
	S7B	29	7	80.0	76.9	No	No
	T4A	22	4	62.2	56.7	No	No
	T5B	26	5	70.4	64.3	No	No
	T6A	30	6	79.2	72.0	No	No
	T7A	34	7	80.0	79.8	No	No
	T7B	34	7	80.0	79.8	No	No
Ohio	2F1	10	2	30.0	40.0	Yes	Yes
	3F1	14	3	46.0	46.5	Yes	Yes
	4F1	18	4	52.0	54.0	Yes	Yes
Pennsylvania	ML80	18	4	73.3	54.0	No	No
	TK527	34	7	80.0	80.0	Yes	No
South Dakota	Type 3	16	3	48.0	48.0	Yes	Yes
Tennessee	TN4	19.17	4	74.0	54.8	No	No
Texas	Single Delivery Truck	17	2	38.0	47.0	Yes	No
	Concrete Truck	14	3	69.0	51.0	No	No
Virginia	Single-Unit Truck	24	3	54.0	51.8	No	Yes

North Carolina's Interstate loads and Pennsylvania's TK527 truck fall into this group. North Carolina trucks carry up to 38 Kips on two consecutive axles (at 4-ft spacing). North Carolina has grandfather rights to exceed the federal weight limit of 34 Kips on Interstate and other highways (15 states have similar rights). Pennsylvania truck TK527 has a total load of 41.2 Kips on two consecutive axles of the rear axle group, also at 4-ft spacing. TK527 serves as a notional posting vehicle to envelop a series of multi-axle trucks.

Non-Formula B Posting Loads

Many states either do not apply FBF or use a modified bridge formula to non-Interstate highways. The most common grandfathered truck seen in many states is the tri-axle dump truck, which can weigh up to 75,000 lbs with a total wheelbase of less than 20 ft. They are legal under state law in some states with grandfather rights and are free to operate unrestricted, except as limited by bridge posting. Weight-limit posting for these vehicles seems to be the only safeguard the states have to protect their bridges from overstress or failure.

Due to the widespread use of triaxle-dump trucks and concerns about their adverse impact on bridge safety, several states have adopted a non-Formula B version of the 4-axle dump truck and other common truck configurations as rating and posting vehicles (see Table 7). Alabama, Arkansas, Connecticut, Delaware, Florida, Kentucky, Michigan, New Hampshire, North Carolina, Pennsylvania, and Tennessee use a heavy 4-axle vehicle as one posting load. Table 7 shows the load in excess of the FBF gross weight limit for various three-, four-, five-, and six-axle state posting loads. Figures 12 through 14

Table 7. State posting loads that exceed Formula B gross weight limits.

DOT	Truck Designation	No. of Axles	Total Spacing	Truck Weight (Kips)	FBF Limit for Gross Wt (K)	Excess over FBF Limit (K)
Alabama	Tandem Axle	3	19.00	59.00	50.30	8.70
	Concrete Truck	3	18.00	66.00	49.50	16.50
Delaware	DE 3 Interstate	3	16.83	54.00	48.60	5.40
	DE 3	3	16.83	70.00	48.60	21.40
Florida	SU3	3	15.17	66.00	47.40	18.60
Georgia	Type 3	3	19.00	66.00	50.30	15.70
Idaho	Type3	3	14.00	54.00	46.50	7.50
Kentucky	Type 2	3	16.00	56.70	48.00	8.70
Michigan	No. 9	3	18.00	51.40	49.50	1.90
Mississippi	Concrete Truck	3	16.00	60.00	48.00	12.00
New Hampshire	Three-Axle Truck	3	16.00	55.00	48.00	7.00
Texas	Concrete Truck	3	14.00	69.00	51.00	18.00
Virginia	Single-Unit Truck	3	24.00	54.00	51.80	2.20
Alabama	Tri-Axle	4	19.00	75.00	54.70	20.30
Arkansas	T4	4	18.00	62.00	52.70	9.30
Connecticut	Construction Vehicle	4	18.20	76.50	54.10	22.40
Delaware	DE 4	4	17.00	73.00	52.90	20.10
Florida	SU4	4	18.34	70.00	53.70	16.30
Kentucky	Type 3	4	20.00	73.50	55.30	18.20
Michigan	No. 3	4	16.00	54.40	52.70	1.70
	No. 10	4	21.50	59.40	56.30	3.10
New Hampshire	Four-Axle Truck	4	18.00	60.00	54.00	6.00
North Carolina	S4A	4	17.00	58.85	53.30	5.55
Pennsylvania	ML80	4	18.00	73.30	54.00	19.28
Tennessee	TN4	4	19.17	74.00	54.80	19.20
Arkansas	T3S2	5	24.00	80.00	63.00	17.00
Illinois	3-S2	5	30.00	72.00	66.80	5.20
Kentucky	Type 4	5	34.00	80.00	69.30	10.70
Michigan	No. 4	5	19.50	67.40	60.20	7.20
	No. 11	5	30.50	77.40	67.10	10.30
Mississippi	HS-Short	5	30.00	80.00	66.80	13.20
North Carolina	S5A	5	21.00	67.10	61.10	6.00
Michigan	Concrete Truck No. 5	6	28.00	78.00	70.80	7.20
North Carolina	S6A	6	25.00	75.90	69.00	6.90

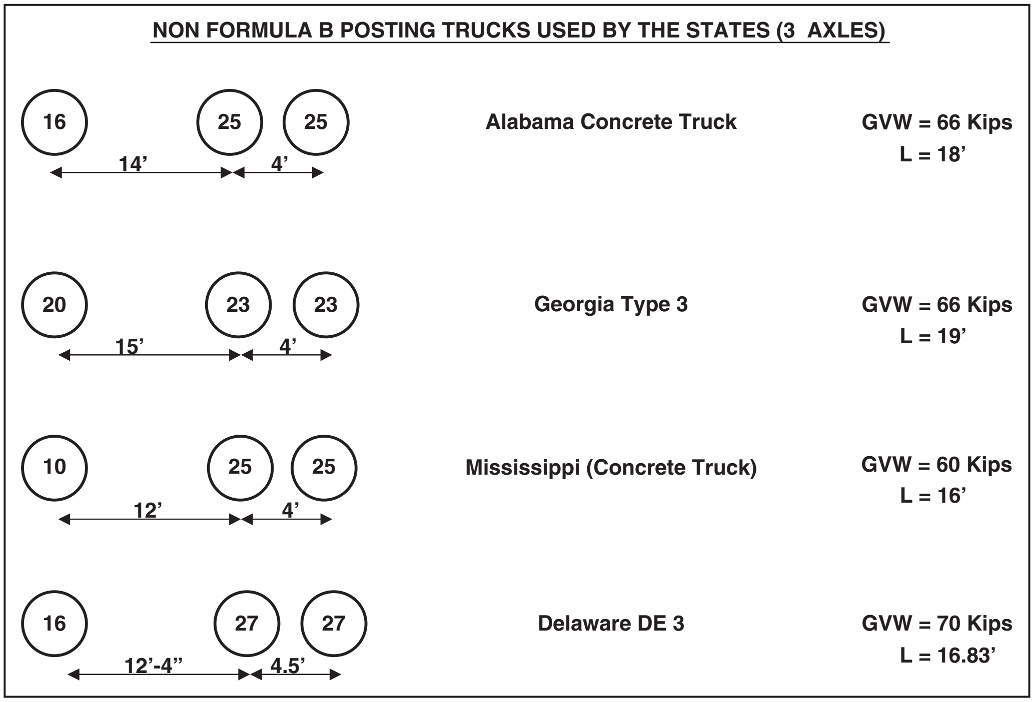

Figure 12. Non-Formula B state legal and posting vehicles.

present axle configurations of state posting loads that do not satisfy Bridge Formula B.

WIM Data Collection and Review

Collection and Review of Existing WIM Data, Phase I

DOT surveys yielded extensive information on unusual legal truck configurations and DOT rating and posting practices with respect to SHVs. WIM data served as another good source for obtaining information on unusual truck configurations in the traffic stream in various states. Short heavy trucks less than 80,000 lbs that satisfy the FBF observed in the WIM data were identified for further investigation and possible consideration as new legal load models. Short heavy trucks are defined here as those that are legal (according to the FBF), but that induce a load effect exceeding the maximum load effect of the three AASHTO legal rating vehicles. Trucks with a total wheelbase in excess of 35 ft were eliminated because the Formula B gross weight limit for multi-axle trucks with lengths in excess of 35 ft will start to exceed the federal weight limit of 80,000 lbs, which will govern. To reiterate, the intent of Phase I of this project was to investigate short multi-axle trucks at or under 80,000 lbs that also satisfy Formula B.

Recent WIM data obtained from FHWA, covering the following 18 states, were analyzed: Ohio, Kansas, Nebraska, Rhode Island, Minnesota, Virginia, Connecticut, Alabama, Arkansas, Washington, Kentucky, Pennsylvania, California, Idaho, Missouri, Michigan, North Carolina, and Montana. Most of the WIM data were obtained over a time period from 2001 to 2003 (see Table 8). Three states had WIM data from 1997. Each data set pertained to a specific month and year for a given state. The data in a dataset may have been obtained from various WIM sites within the state during that month.

The purpose of the WIM studies was to obtain information on unusual truck configurations by analyzing actual truck data. The truck data used for this analysis were obtained at remote WIM sites and not at weigh stations, which are usually bypassed by some heavier vehicles. The data have served as a valuable source of up-to-date information on unusual truck configurations meeting Formula B and the prevalence of such trucks in the various states. The other source of information on such trucks is the rating and posting loads provided by the states and discussed in the previous chapter. The numbers of truck configurations in the traffic stream are too numerous to be considered separately in bridge analyses. Rating and posting loads aim to use a limited number of truck models to represent the most severe loadings of classes of vehicles that operate in a state. WIM data are an important and essential adjunct to truck information provided by the states. States such as North Carolina have used WIM data to validate their state posting load models and to calibrate axle loads. Recent advances in WIM technologies have reduced data collection costs, improved the quality and reliability of the data, and resulted in significant increases in WIM being collected by the states.

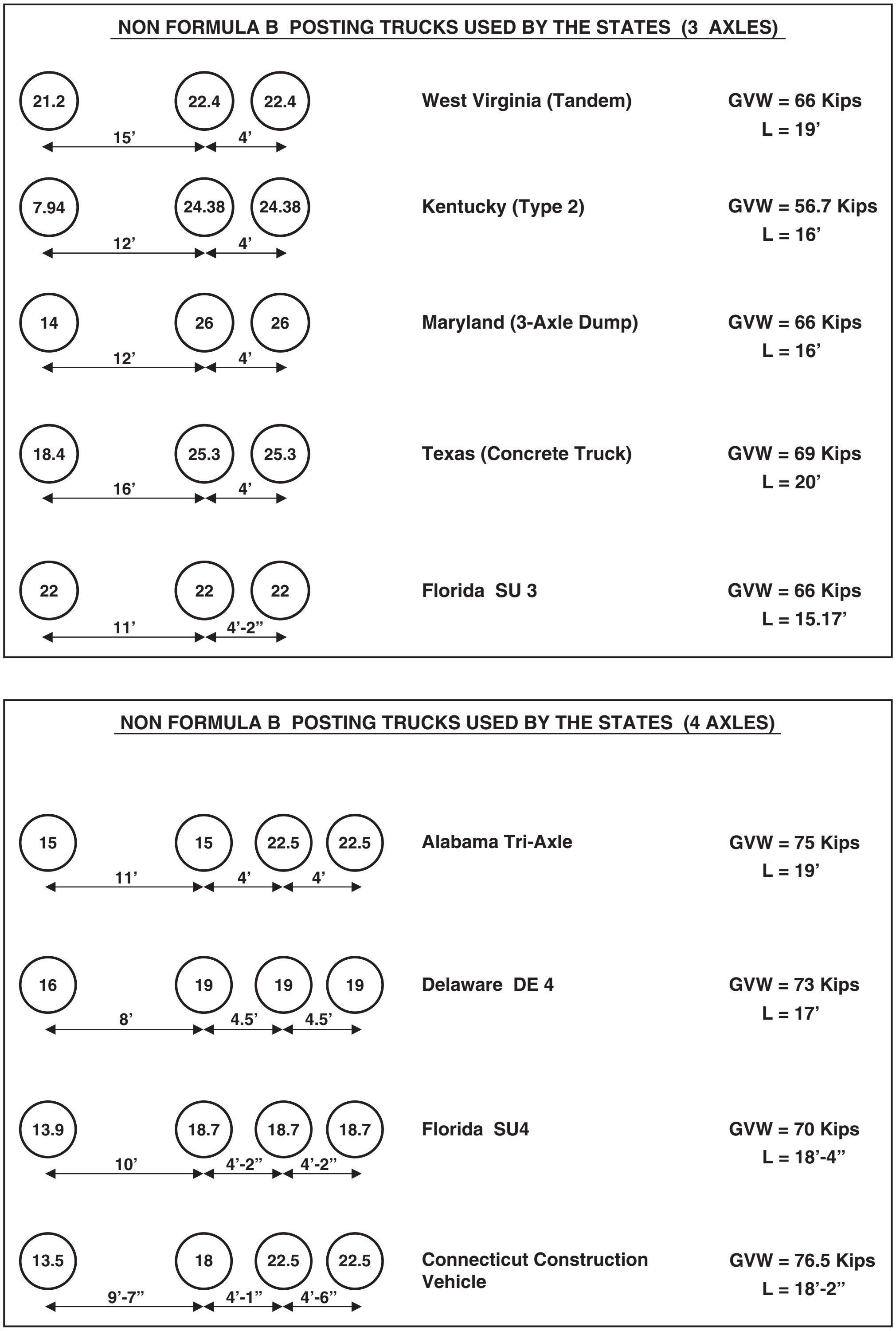

Figure 13. Non-Formula B state legal and posting vehicles.

Table 8 provides an overview of the WIM data used on this project. Eighteen states were included in the analysis. The states were selected for the quality and quantity of WIM data available and the mix of heavy vehicles observed in the traffic stream. States having short trucks with five or more axles were of particular interest. The states were also selected to ensure that different regions of the country were represented in the data set, to the extent possible in this limited study.

Analysis of Existing WIM Data

For each truck in the available WIM data set, an automated procedure was used to identify the short heavy vehicles of

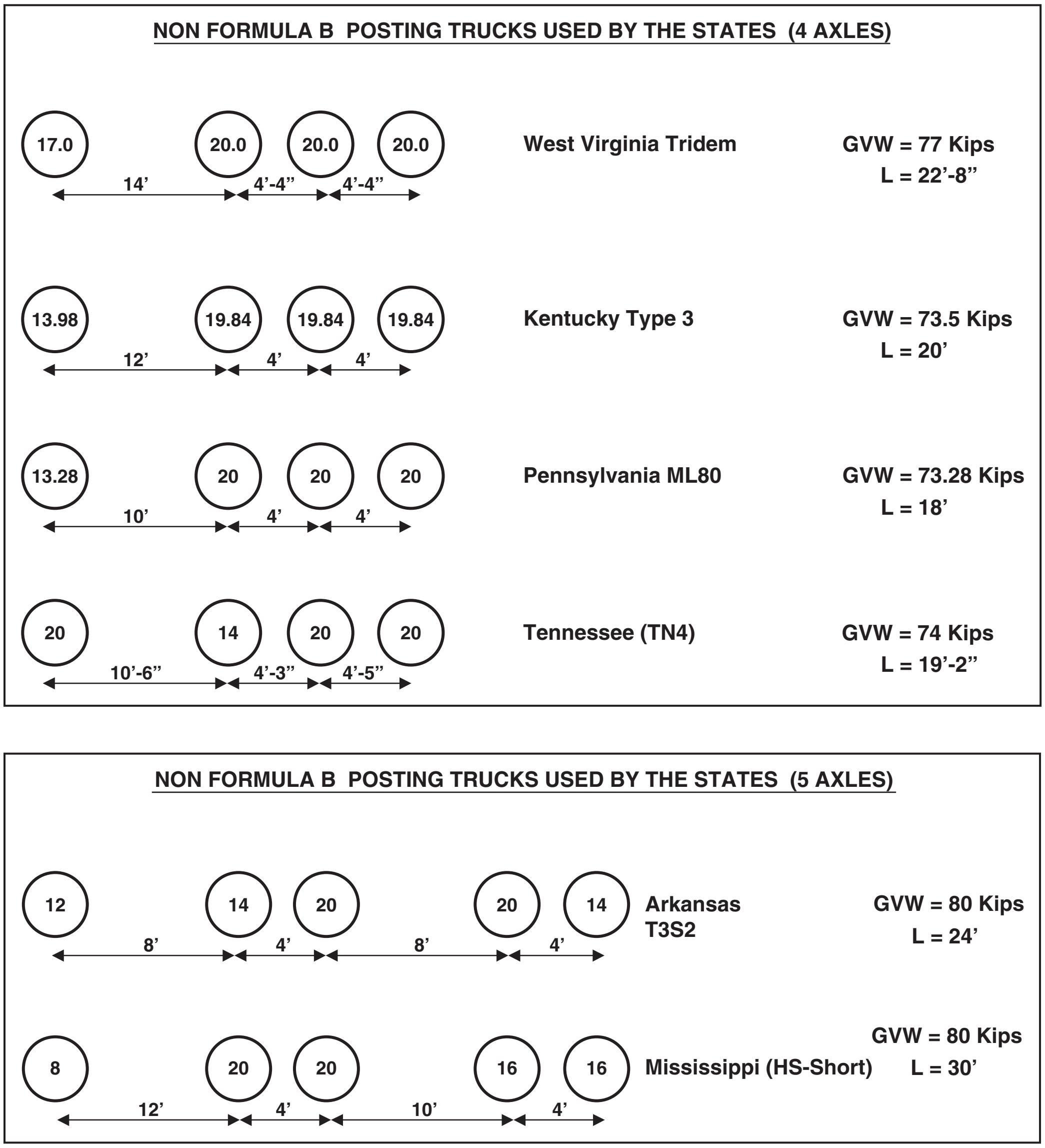

Figure 14. Non-Formula B state legal and posting vehicles.

interest, which were then subjected to further manual screening and sorting prior to inclusion in the list of trucks making the shortlist for each WIM dataset. An automated procedure that implemented the following procedure for selection was developed:

- Check whether the truck exceeds a total wheelbase of 35 ft. If it does not, the truck will be subjected to the next check. If it does, it is excluded from further checks. The objective is to identify short multi-axle trucks (and to exclude longer combination vehicles).
- Check whether the truck meets the FBF and federal weight limits. This step includes a check for axle weight limit (20 Kips). Note that the tandem axle weight limit (34 Kips at 4-ft spacing) is included in Formula B and thus is also checked. Formula B is checked for all possible combinations of any two or more axles. If the truck meets Formula B (i.e., it is legal), it is subjected to the next check. If it does not, it is then excluded from further consideration.
- Check whether the truck induces a load effect that exceeds the maximum of the three AASHTO legal rating vehicles. Both moment and shear load effects are considered. Eleven simple spans having the following span increments were used for this check: 10, 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 ft. The moment effect is at the mid-span section and the shear is at a support.

Axle configurations for trucks with three to eight axles were obtained from the screening of the WIM data. Detailed results of WIM data analyses is contained in Appendix B. Table 9 summarizes the mean axle spacings for the single-unit trucks observed in the WIM data.

Table 8. WIM data summary.

State	Time Period for WIM Data Collection	Number of Trucks Weighed	Axle Configurations Detected (# of Axles per Truck)
Alabama	Apr-2001	169,495	3,4
	Jun-2001	246,768	4
Arkansas	Jan-2002	1,682,611	3,4,5
	Jul-2002	2,525,640	3,4,5
California	Jan-2002	2,514,788	3,4
	Feb-2002	235,622	3,4
Connecticut	Oct-2002	78,699	4
	Dec-2002	37,133	4
Idaho	Sept-2001	1,330,465	3,4,5,6
	Oct-2001	1,715,647	3,4,5,6,7
Kansas	Aug-2001	17,356	4,5
Kentucky	Feb-2002	437,519	3,4,5,6,7
	Sept-2002	321,829	3,4,5,6,7
Michigan	Sept-2001	1,245,080	3,4,5,6,7,8
Minnesota	Jan-1997	274,872	3,4,5,6,7
	Nov-1997	509,036	3,4,5,6,7
Missouri	Jan-2002	908,674	3,4,5
Montana	Jan-2003	582,068	3,4,5,6,7
	May-2003	630,794	3,4,5,6,7
North Carolina	Jan-2001	538,857	3,4,5,6,7
	June-2001	659,678	4,5,6,7
Nebraska	June 2002	40,659	4
	July-2002	41,345	4
Ohio	Jan-1997	913,900	3,4,5,6,7
	Feb-1997	176,604	3,4,5,6
Pennsylvania	Jan-2001	80,603	4
	Apr-2001	137,535	4
Rhode Island	May-2001	57,329	3,4
	Oct-2001	39,635	3,4
Virginia	Jan-1997	52,643	4,5,6,7
	Apr-1997	58,161	4,5
Washington	July-2001	492,807	4,5,6,7
	Oct-2001	674,919	4,5,6

The principal difference among trucks with the same number of axles lies in the arrangement of the rear axles, which are

1. All in one axle group;
2. One split rear axle, the rest in one axle group; or
3. Distributed among two axle groups.

These axle configurations combined with the results of the DOT survey formed the basis for the development of a suite candidate legal load models to represent the newer Formula B truck configurations, which are discussed in Chapter 3.

Collection and Review of New WIM Data, Phase II

Statistics on truck overloads and multiple presence probabilities are central to the calibration of live-load factors to satisfy the target reliability index. When extending the calibration to a new application, in this case non-Formula B SHV vehicles, the consistency of the load data and truck weight statistics should be examined with data representative of the new application. The WIM data collected and evaluated in Phase I was focused on identifying truck configurations and axle combinations meeting Formula B. In Phase I, as in the load and resistance factor design (LRFD) and LRFR calibrations, assumptions were used for the number of side-by-side events with two heavy trucks simultaneously on the bridge. Truck weight data, including overload percentages, could not be accurately established as the truck weight measurement errors inherent in the FHWA data obtained from the various states is unknown.

In many spans, the maximum lifetime truck loading event is the result of more than one vehicle on the bridge at a time. An important step in defining nominal load models for evaluation is the modeling of multiple-presence probabilities.

Table 9. Summary of mean axle spacings from WIM data.

Truck Type	Operating in States	Mean Spacings of Axles (ft.)						
		Sp. 1–2	Sp. 2–3	Sp. 3–4	Sp. 4–5	Sp. 5–6	Sp. 6–7	Sp. 7–8
3-Axle	OH, RI, MN, AL, AR, KY, CA, ID, MO, MI, NC, MT	8.93’ to 14.10’	3.74’to 4.7’					
4-Axle	OH, KS, NE, RI, MN, VA, CT, AL, AR, WA, KY, PA, CA, ID, MO, MI, NC, MT	10.69’ to 14.12’	3.83’ to 4.98’	4.07’ to 4.68’				
5-Axle (1)	OH, KS, MN, VA, AR, WA, KY, ID, MO, NC, MT	8.72’ to 12.23’	3.48’ to 5.25’	3.58’ to 4.75’	3.98’ to 4.65’			
5-Axle (2)	MI	10.18’	5.23’	7.65’	5.34’			
6-Axle (1)	KY, OH, NC	8.56’to 10.03’	3.28’ to 3.85’	3.28’ to 4.37’	3.68’ to 4.11’	4.04’ to 5.70’		
6-Axle (2)	MN, VA, MI	9.38’ to 12.79’	4.20’ to 4.82’	6.53’ to 9.49	4.07’ to 4.70’	3.93’ to 4.83’		
6-Axle (3)	OH, WA, ID	6.62’ to 9.29’	3.50’ to 4.55’	3.66’ to 4.41’	4.21’ to 4.44’	7.96’ to 12.75’		
7-Axle (1)	OH	11.59’ to 11.76’	3.93’ to 3.97’	5.93’ to 6.35	3.67’ to 3.75	3.67’ to 3.83’	3.91’ to 3.97’	
7-Axle (2)	MN	9.26’	3.53’	8.44’	4.18’	3.53’	9.84’	
7-Axle (3)	MN, WA	5.13’ to 5.96’	8.02’ to 8.15’	3.66’ to 3.67’	4.04’ to 4.15’	4.30’ to 4.48’	5.48’ to 7.10’	
7-Axle (4)	VA	9.51’	3.61’	4.26’	8.20’	3.93’	3.93’	
7-Axle (5)	MI, KY, NC	8.15’ to 12.18’	3.39’ to 4.29’	3.5’ to 4.54’	3.37’ to 5.07’	3.61’ to 4.35’	3.91’ to 4.59’	
7-Axle (6)	ID, MT	6.51’ to 6.59’	4.36’ to 4.81’	3.61’ to 3.82’	4.26’ to 4.59’	4.01’ to 4.26’	8.55’ to 8.85’	
8-Axle	MI	8.22’	3.89’	3.92’	3.86’	3.86’	3.90’	3.88’

NOTE: Among the five-, six-, and seven-axle trucks, a few variations in axle configurations were observed:

- 5-Axle (1) having four closely spaced rear axles at approximately 4 ft.
- 5-Axle (2) having two rear tandem axle groups spaced at approximately 8 ft.
- 6-Axle (1) having five closely spaced rear axles at approximately 4 ft.
- 6-Axle (2) having a tandem and tridem axle groups in the rear spaced at approximately 8 ft.
- 6-Axle (3) having four closely spaced rear axles at approximately 4 ft and a split rear axle.
- 7-Axle (1) having a tandem and quadrem axle groups in the rear spaced at approximately 6 ft.
- 7-Axle (2) having tandem and tridem axle groups in the rear and a split rear axle.
- 7-Axle (3) likely having two front axles, a quadrem axle group in the rear and a split rear axle.
- 7-Axle (4) having two tridem axle groups in the rear spaced at approximately 8 ft.
- 7-Axle (5) having six closely spaced rear axles at approximately 4 ft.
- 7-Axle (6) having five closely spaced rear axles at approximately 4 ft and a split rear axle.

In the LRFD development, it was assumed that side-by-side vehicle crossings occur as follows (see study by Nowak [*14*]):

- One out of every five trucks is a heavy truck, which describe the Ontario statistical parameters (site ADTT of 5,000).
- One out of every 15 heavy truck crossings occurs with two trucks side-by-side.
- Of these multiple-truck events on the span, 1 out of 30 occurrences has completely correlated weights.
- Using the product of 1/15 and 1/30 means that approximately 1/450 crossings of a heavy truck occurs with two identical heavy vehicles alongside each other.
- With the above assumptions and a 75-year exposure period, the expected maximum lifetime loading corresponds to two heavy trucks side-by-side, each with a weight equal to the maximum expected truck in a 2-month interval. It clarifies where the 2-month interval comes from: $(75 \times 12)(1/15)(1/30) = 2$ months.
- No field data on multiple-presence probabilities and truck weight correlation were provided in the study by Nowak (*14*) to support these truck-crossing assumptions.

It is important to reevaluate the multiple-crossing probabilities because in evaluation there are many other types of situations, including lower-volume roads and overload permit crossings. The 1/15 probability of side-by-side truck events is considered conservative for a more common range of truck volumes on U.S. highways (*15*). WIM data from U.S. sites indicated multiple-presence factors of only 1% to 2%, even for Interstate sites with ADTT of above 2,000. Conservative truck traffic and multiple-presence assumptions may not cause a major cost impact in the design of new bridges, but these assumptions have a significant impact on bridge evaluation as most bridges see a less extreme loading in terms of truck weights and volume.

The data presented in the LRFD calibration report (*14*) are in the form of cumulative frequency distributions of bending moments for simple spans of different lengths based on the largest 20% of the vehicle population. The original truck weight data taken at a site in Ontario are not presented in the report. Thus, for purposes of calibration of the LRFR manual (published as *NCHRP Report 454* [*16*]), the following procedures and assumptions were used:

- The Ontario truck weight data (upper 20% moments of different spans) were reasonably matched (fit to a normal distribution) by a 3S2 truck with a mean of 68 Kips and a standard deviation of 18 Kips.
- The 3S2 truck has a legal weight of 72 Kips; thus, the upper fifth of the truck weight distribution can be described with a normal distribution with a mean = 0.95 × legal load limit and a coefficient of variation (COV) = 0.25. This suggests that about 8% of trucks are overloaded (72 Kips is 0.222 standard deviations above the mean, this corresponds to 42% of the upper 20% trucks over the legal limit or 8.4% of all trucks over the legal limit.)
- For ADTT equal to 5,000, a 1/15 side-by-side probability was used to maintain consistency with the LRFD calibrations.
- For ADTT equal to 1,000, a multiple-presence probability value was set equal to 1% (*15*). This value was also verified using a simple traffic model to estimate side-by-side presence (*16*).
- For ADTT equal to 100, the multiple-presence probability was set equal to 0.001, consistent with field observations and traffic model predictions.

In Phase I of this project, the same approach was applied for selecting a single-unit calibration truck for SHV load models. The equivalent statistical parameters for a Type 3 truck matching the Ontario truck data for different spans was found to be a mean of 48 Kips and a standard deviation of 11 Kips. The truck has a legal weight of 50 Kips. Thus the upper fifth of the truck weight distribution can be described using a Type 3 truck with a normal distribution with a mean = 0.96 (= 48/50) × legal load limit, and a COV = 0.23 (= 11/48). This also suggests that about 8% of trucks are overloaded. It is observed that almost identical 0.95 and 25% statistical parameters were obtained when fitting Nowak's bending moment distributions for Ontario trucks by either the 3S2 AASHTO truck for the intermediate spans or the Type 3 AASHTO truck for the shorter spans.

The main effort in the calibration of load factors is the estimation of the maximum expected live load on a span during the evaluation interval, taken as a nominal 2-year interval. In the load factor calibration for Phase I, it was shown that the expected maximum live-load effect (fit to Nowak data [*14*]) in 2 years due to side-by-side random trucks is 3.3 times the load effect of a single legal 3S2 truck or 3.2 times the load effect of a legal Type 3 truck. It was also shown that the maximum moment and shears due to two side-by-side legally loaded SHV trucks satisfying Formula B would not exceed 3.0 times the load effect of a legal Type 3 AASHTO truck. This means that legal SHV trucks satisfying Formula B would produce a lower maximum live-load effect than the effect of the random commercial truck traffic modeled by Nowak and used in the LRFR calibration (*14, 16*). Thus the expected maximum live-load effect for both the Type 3 and Type 3S2 traffic is governed by "overweight" vehicles. Moments rather than actual weights are used for checking overloads as Nowak's statistical data are in the form of bending moments rather than truck weights.

In the LRFD and LRFR calibrations, it was shown that the maximum live-load effect is governed by overweight or illegal vehicles (about 8% of the vehicles for the Type 3S2 truck used for the LRFR calibration and the Formula B Type 3 truck used in the Phase I calibration). The same concept of considering overweight trucks should be true for the non-Formula B SHVs. Whether the proportions of SHV overweights are different than the numbers reported for LRFD and LRFR remains to be established from further WIM data to be collected and analyzed.

New WIM Data Collection Procedure

In Phase II, the research team collected new WIM data using existing sites and hardware to provide quantitative information on overweight statistics, the occurrence of side-by-side truck loadings, and the accuracy of axle weight data in terms of equipment type and calibration. In the LRFD calibration simultaneous occurrence assumptions for trucks were based on very limited statistical data (*14*). Data collection in Phase II of this project provided the statistical information to make an independent assessment of multiple-presence probabilities for use in calibration.

There are inherent difficulties in collecting reliable WIM data suitable for calibration studies. Accuracy of WIM axle weights is site-dependent, influenced by factors such as pavement roughness, roadway geometric features, traffic speeds, driver lane discipline, environmental factors, sensor technology, and equipment calibration. Presence of permit trucks in the traffic could also distort the data (and must be investigated for each site).

WIM equipment hardware currently in use in the various states is able to collect truck data using accurate time stamps (to the hundredth of a second), but, in the past, WIM data have not been reported to this resolution. The research team worked with Idaho DOT in experimenting with a different approach using "classifier road tube sensors" to record high-resolution time stamps of arrival times of vehicle axles. "Road tubes" refer to the hollow rubber tubes that are stretched across the roadway to act as sensors; these tubes generate an air impulse when an axle drives over them. This triggers a time-stamped sensor event to be recorded by the counter/classifier. According to the manufacturer's specifications, the systems can record time stamps up to a resolution of 1/100,000 of a second. Data were collected in all lanes using four road tube sensors with synchronized time stamps. Together with truck time-stamp data, weight data from the existing WIM equipment already in service were collected. By synchronizing the clocks of the WIM system and classifier, the accurate arrival time as well as axle weights and configuration of each truck were recorded.

A WIM site on I-84 in Idaho was first used to test the system and to iron out any operational issues. Data were then collected at this site for 6 days in fall 2004. Next, working with state DOTs, high truck-traffic sites in Michigan and Ohio were selected for higher resolution WIM data collection (see Table 10). Due to winter weather, further data collection was suspended until spring 2005 (classifier road tubes laid across the roadway are susceptible to damage from snowplows). Data were collected at the Michigan site in May 2005 (Figure 15). Data collection in Ohio was performed in August 2005.

Data from these three sites, including high-resolution time stamps, provide a representative sampling of U.S. truck traffic multiple-presence and overload probabilities. This project has provided independent real traffic data for establishing headway separations and side-by-side probabilities for trucks on multi-lane bridges. These data are important for establishing the maximum loading event during the evaluation period for calibration of load factors.

Side-by-Side Presence of Trucks

Maximum load is usually based on the occurrence of several heavy trucks simultaneously on the bridge, their headway probabilities, and the probabilities for the gross weights for the trucks. Nowak and Hong studied the maximum load effects for time periods from 1 day to 75 years on single-lane and two-lane bridges (*17*). For two-lane bridges, the maximum load effect was obtained with two trucks side-by-side with perfectly correlated weights. For the maximum 75-year moment, each side-by-side truck is represented by the 2-month truck.

Extreme loading on the structure is affected by the side-by-side probabilities and the sequence of trucks in each lane. The corresponding moment response can be calculated from the superposition of the response of each truck. Bridge evaluation codes have typically required the consideration of only a single truck in a given lane for spans up to 200 ft. Experimental determination of maximum loading on a bridge had been difficult due to the unavailability of high-quality traffic data, including accurate truck arrival times. Past studies have attempted to predict the maximum load on a bridge using procedures such as Monte Carlo simulations or numerical integration.

New WIM data, with refined time stamps, collected by the research team have provided independent data to examine past assumptions of multiple-presence probabilities. Side-by-side occurrences as a function of headway distance between two trucks were checked by using the truck arrival time stamps and the speed of individual trucks. The issue of what constitutes side-by-side presence needed to be resolved. Defining side-by-side presence as a function of headway separation (distance between the front axles of two trucks) of two trucks in adjacent lanes traveling in the same direction was the selected approach.

Headway separations of ±10 ft to ±60 ft may constitute side-by-side presence depending on the span and vehicle characteristics. A suitable cutoff needs to be established. A study was therefore performed to investigate the influence of headway

Table 10. New WIM data collection sites and dates.

State	Dates	Route	Sensor
Idaho	10/26/04 to 11/01/04	Interstate 84	Piezo
Michigan	5/8/05 to 5/13/05	US 23	Quartz
Ohio	August 20–22, 2005	Interstate 75	Bending Plate

Figure 15. Typical side-by-side presence of trucks.

distances on moments and shears on varying spans. As the focus of this research is short multi-axle trucks, two eight-axle 80-Kip SHVs (the same as the notional rating load [NRL]; see Chapter 4) were used for this study. Simple spans from 20 ft to 250 ft were included. Truck 1 was fixed at the maximum moment location in one lane, while Truck 2 location was varied in 5-ft increments in the adjacent lane to produce headway separations from 5 ft to 60 ft. Maximum moments and shears for various headway separations were calculated. A summary of the results normalized using Truck 1 moments is provided in Table 11.

It was observed that for spans under 100 ft, truck separation over 40 ft was less significant on span moments. For longer spans, vehicles with up to 60-ft headway separation should be considered as the second truck's load effects could be significant. For this project, a ±60 ft separation was chosen as the upper limit for determination of side-by-side presence probabilities. For longer spans and continuous spans, the headway separation in the same lane could also be important.

WIM data were collected in Idaho on I-84 using a WIM and classifier setup for high-resolution time stamps for a period of 6 days in October and November 2004. The site has two lanes in each direction, a nominal average daily traffic (ADT) of 18,000 in all four lanes, with 26% truck traffic. The site had free-flowing traffic with no unusual grade or ramps present and was not near a weigh station.

To calculate multiple-presence probabilities for side-by-side trucks, the following procedure was adopted:

1. For each of the 6 days, the total number of trucks, the trucks in the right lanes (Lane 0 or 1), and the trucks in the left lanes (Lane 2 or 3) were determined. (Note that for this four-lane highway, Lanes 0 and 2 are in one direction and Lanes 1 and 3 are in the opposite direction.) ADTT ranged from 1,169 to 3,119 for the various days.
2. The number of trucks in the left and right lanes in each direction for each day of measurement is given in Table 12. It was evident that about 90% of the trucks were in the right lane. Data collection durations varied from 11.1 h to 23.3 h, and the number of trucks measured during this period varied from 479 to 2,797.
3. For each truck crossing in the right lane, the likelihood of a second truck side-by-side in the left lane was examined using the truck arrival times and vehicle travel speeds. For the purposes of this analysis, headway separations from 5 ft to 60 ft were considered as side-by-side presence.
4. The number of side-by-side cases was determined for each 5-ft increment from 5 ft to 60 ft (see Table 13). The number of multiple-presence cases increased with increasing headway separations. The total side-by-side cases for all

Table 11. Normalized moments induced by side-by-side trucks.

Span (Ft)	Truck 1	Truck 2 @ Headway Separation Distance of (Ft)					
		10’	20’	30’	40’	50’	60’
20	1.0	0.63	0.21				
60	1.0	0.91	0.61	0.25	0.05		
100	1.0	0.97	0.85	0.66	0.40	0.15	0.03
140	1.0	0.99	0.93	0.83	0.69	0.51	0.30
200	1.0	0.99	0.97	0.92	0.85	0.76	0.65
250	1.0	0.99	0.98	0.95	0.90	0.85	0.78

Table 12. Ohio I-75 multiple-presence probabilities.

# of trucks			ADTT	data duration	Side-by-side occupation as function of definition (headway distance)																			
Date/Lanes	Lane	Lane			<5ft		<10ft		<15ft		<20ft		<25ft		<30ft		<35ft		<40ft		<50ft		<60ft	
	1	2		(hrs)	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%
8/20/2005 0:00-14:00 (Saturday) Lanes 1 & 2	1626	1364	5126	14.0	6	0.2	13	0.43	19	0.64	23	0.77	29	0.97	36	1.2	42	1.4	49	1.64	57	1.91	88	2.94
8/20/05 15:00-24:00 (Saturday) Lanes 1&2	707	588	3453	9.0	0	0	1	0.08	2	0.15	3	0.23	4	0.31	7	0.54	7	0.54	7	0.54	13	1	16	1.24
8/22/05 0:00-10:00 (Monday) Lanes 1&2	1646	1500	7550	10.0	7	0.22	10	0.32	17	0.54	24	0.76	29	0.92	32	1.02	39	1.24	50	1.59	62	1.97	86	2.73
8/22/05 10:00-24:00 (Monday) Lanes 1&2	2885	3270	10551	14.0	16	0.26	31	0.5	44	0.71	52	0.84	69	1.12	79	1.28	104	1.69	122	1.98	159	2.58	206	3.35

NOTES: 1. ADTT is calculated using the recorded vehicles.
2. Any two of these time periods may be combined to find an averaged ADTT and percentage of side-side cases.

Table 13. Total side-by-side events on Idaho I-84.

Headway Separation	Total Side-by-Side Events	Multiple-Presence Probabilities
< 5’	7	0.18
< 10’	20	0.37
< 15’	32	0.55
< 20’	40	0.55
< 25’	58	0.92
< 30’	70	0.92
< 35’	79	0.92
< 40’	95	1.11
< 50’	121	1.33
< 60’	138	1.37

days are given in the table below, which illustrates the likelihood of such events.

5. The multiple-presence probabilities for all trucks were calculated for each day for each increment of headway separation by dividing the number of side-by-side cases by the total number of trucks crossings in that particular period. The maximum values are given in Table 14.

The multiple-presence probabilities for this site are quite low (<1.37%) compared with past assumptions. LRFD used an assumed multiple-presence probability of 1/15 (= 6.7%). The site has moderate to heavy truck traffic typical of many Interstate highways. Truck overweight statistics for Idaho WIM data is given in Appendix B.

WIM data were collected in Ohio on I-75 using a WIM and classifier setup for high-resolution time stamps from August 20–22, 2005. The site has a very high ADTT >5,000 and three lanes in each direction, with two lanes instrumented. The site had free-flowing traffic with no unusual grade or ramps present and was not near a weigh station. The multiple-presence probabilities for all trucks were calculated for each day for each increment of headway separation by dividing the number of side-by-side cases by the total number of truck crossings in that particular period. The maximum multiple-presence probability for the right and center lanes was 3.35% for a headway separation of 60 ft (see Table 12). This also illustrates that multiple-presence probabilities are a function of the number of lanes of traffic. Trucks are more likely to travel in the center lane than in the left lane, leading to higher multiple-presence likelihood on three-lane highways.

The WIM and classifier setup were used to collect weight and time data on US-23 in Michigan from May 8–13, 2005. The site had two lanes in each direction with an ADTT >4,000 on weekdays. The maximum multiple-presence probability for all trucks was 3.47% for a headway separation of 60 ft (see Table 15). If the headway separation was limited to 30 ft, the maximum multiple presence is reduced to 2.12%.

Multiple presence should be viewed in conjunction with bridge span. As seen in Table 11, a larger definition of headway separation may produce a higher multiple presence, but may have a lower total moment. Headway separation of 60 ft gives a total moment of (1 + 0.65) on a 200-ft span and much lower values on shorter spans. For short spans, a headway separation greater than 30 ft may not be significant for moments; therefore, the 1/15 assumption used in LRFD calibration is very conservative even for high ADTT.

Table 14. Idaho I-84 multiple-presence probabilities.

Date/Lanes	# of trucks			Data Duration	Side-by-side occurrence as a function of headway distance																			
	Lane		ADTT		<5ft		<10ft		<15ft		<20ft		<25ft		<30ft		<35ft		<40ft		<50ft		<60ft	
	0 or 1	2 or 3		(hrs)	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%
10/26-27/04 Lanes 0&2	2208	222	2958	19.7	0	0	0	0	0	0	2	0.08	2	0.08	2	0.08	2	0.08	2	0.08	4	0.16	4	0.16
10/26-27/04 Lanes 1&3	2444	187	2764	22.8	0	0	1	0.04	2	0.08	3	0.11	4	0.15	4	0.15	4	0.15	4	0.15	4	0.15	6	0.23
10/27-28/04 Lanes 0&2	2409	213	2698	23.3	1	0.04	7	0.27	9	0.34	10	0.38	17	0.65	21	0.8	25	0.95	29	1.11	35	1.33	36	1.37
10/27-28/04 Lanes 1&3	2797	182	3119	22.9	2	0.07	3	0.1	4	0.13	6	0.2	10	0.34	11	0.37	11	0.37	16	0.54	19	0.64	22	0.74
10/28-29/04 Lanes 0&2	2127	248	2509	22.7	3	0.13	4	0.17	6	0.25	8	0.34	10	0.42	13	0.55	14	0.59	17	0.72	21	0.88	26	1.09
10/28-29/04 Lanes 1&3	2510	213	2875	22.7	0	0	2	0.07	6	0.22	6	0.22	7	0.26	7	0.26	8	0.29	10	0.37	19	0.7	25	0.92
10/31/04 Lanes 0&2	1096	96	1773	16.1	0	0	1	0.08	1	0.08	1	0.08	1	0.08	3	0.25	4	0.34	5	0.42	6	0.5	6	0.5
10/31/04 Lanes 1&3	1804	80	2792	16.2	0	0	0	0	1	0.05	1	0.05	2	0.11	2	0.11	2	0.11	2	0.11	2	0.11	2	0.11
11/1/04 Lanes 0&2	479	67	1169	11.2	1	0.18	2	0.37	3	0.55	3	0.55	5	0.92	5	0.92	5	0.92	5	0.92	5	0.92	5	0.92
11/1/04 Lanes 1&3	896	47	2037	11.1	0	0	0	0	0	0	0	0	0	0	2	0.21	4	0.42	5	0.53	6	0.64	6	0.64

NOTES: 1. No data are available for Oct.29 to Oct.31.
2. ADTT is calculated using the recorded vehicles.
3. Lanes 0,1 are right lanes; lanes 2,3 are left lanes.

Table 15. Michigan US-23 multiple-presence probabilities.

	# of trucks			data	Side-by-side occupation as function of definition (headway distance)																			
Date/Lanes	Lane 1	Lane 2	ADTT	duration (hrs)	<5ft		<10ft		<15ft		<20ft		<25ft		<30ft		<35ft		<40ft		<50ft		<60ft	
					# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%	# of cases	%
5/8/2005 (Sunday) Lanes 1 & 2	945	45	1431	16.6	0	0	0	0	0	0	0	0	0	0	1	0.1	2	0.2	5	0.51	7	0.71	7	0.71
5/9/05 Lanes 1&2	3980	338	4318	24.0	0	0	2	0.05	4	0.09	16	0.37	49	1.13	59	1.37	66	1.53	76	1.76	95	2.2	115	2.66
5/10/05 Lanes 1&2	2191	185	4636	12.3	1	0.04	2	0.08	3	0.13	4	0.17	21	0.88	25	1.05	25	1.05	33	1.39	38	1.6	45	1.89
5/11/05 Lanes 1&2	4527	395	4922	24.0	0	0	2	0.04	6	0.12	13	0.26	21	0.43	24	0.49	29	0.59	53	1.08	124	2.52	171	3.47
5/12/05 Lanes 1&2	2134	174	4616	12.0	0	0	0	0	0	0	1	0.04	11	0.48	15	0.65	20	0.87	23	1	27	1.17	29	1.26
5/13/05 Lanes 1&2	3520	354	5203	17.9	2	0.05	2	0.05	2	0.05	21	0.54	61	1.57	83	2.14	84	2.17	88	2.27	97	2.5	105	2.71

NOTES: 1. ADTT is calculated using the recorded vehicles.
2. Any two of these time periods may be combined to find an averaged ADTT and percentage of side-side cases.

CHAPTER 3

Interpretation, Appraisal, and Application

Development of Candidate Formula B Legal Loads

Based on the WIM data analysis, a suite of representative short wheelbase multi-axle trucks with three to eight axles was identified as candidate legal load models for further analysis (see Figures 16 and 17). The axle configurations extracted from the WIM data were compared with state legal loads currently is use as posting loads to see whether there are other reasonable Formula B multi-axle configurations (number of axles and spacings only) not seen in the WIM data. This was not found to be the case. Many trucks bear obvious similarities to North Carolina's legal loads (and Pennsylvania's TK527). There were posting loads with spread rear axle groups. All candidate load models have closely spaced rear axles, which can carry the same gross weight over a shorter total wheelbase than do trucks with spread axle groups. Short compact heavy trucks will impart a higher load effect, especially on the shorter spans seen to be the most vulnerable. Therefore, spread rear axle groups were not included in the candidate loads.

Once the number and arrangement of axles were decided upon, the axle loads were then manually maximized while staying within the federal weight laws and FBF limits. This required the repeated application of Formula B to the full truck and to consecutive axles in a group having two or more axles. The single axle federal weight limit of 20,000 lbs was also checked. The intent of this procedure was to maximize the load effects imposed on a bridge span by all likely Formula B trucks having similar axle configurations. The suite includes trucks with all fixed rear axles and carrying equal axle loads and trucks having fixed and liftable rear axles and variable axle loads.

The research team did not independently validate the accuracy of WIM data used in the analysis. A 10% to 15% margin of error on axle weights is not uncommon in WIM data. Accuracy of axle spacings is generally much better than for axle weights. The level of accuracy inherent in the WIM data is considered acceptable for the intended use of WIM data in this research. The use of WIM data in this project was mainly to extract information on unusual axle configurations (number and spacings of axles) seen in the traffic stream and not to calibrate axle loads. The axle loads were manually maximized in accordance with Formula B limits. The only limited use of axle weight data in the modeling was in ascertaining the probable locations of lift axles, which commonly have lower and variable axle loads compared with the fixed axles of the same axle group.

The axle configurations formed the basis for the development of a suite candidate legal load models to represent the newer Formula B truck configurations. The first task in this development procedure was to select the truck types and set their axle spacings. A commonly used axle spacing of 4 ft was chosen as a standard for all axles within a group. As seen in the WIM data, there were, however, large variations in the distance to the front axle, ranging from about 6 ft to 14 ft. Trucks with larger front axle distances and longer total wheelbases are allowed heavier loads on the front axle due to the increased Formula B gross weight limit. Further investigation was needed to understand the influence of front axle distance, and the corresponding adjustments to front axle load, on the induced moments. Simple- and continuous-span moments produced by a seven-axle truck with front axle spacing from 6 ft to 14 ft were computed and compared. Analyses show that the shorter front axles are slightly more critical for the shorter span lengths and the longer front axles are slightly more critical for the longer spans. However, the differences are usually not more than 5%.

Maximizing Axle Loads

The next task in the development of the candidate legal loads was to manually maximize axle loads for each truck in the suite of vehicles. This process was done simply by

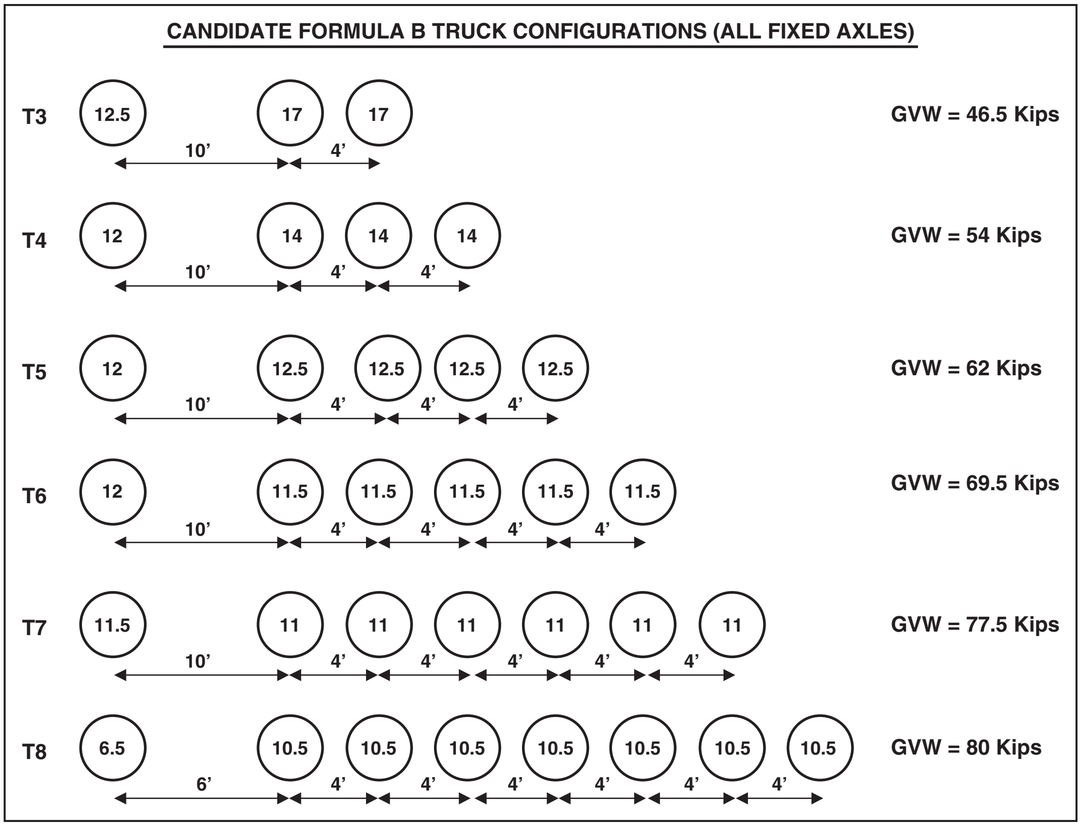

Figure 16. Candidate Formula B truck configurations with all fixed (equal) rear axles.

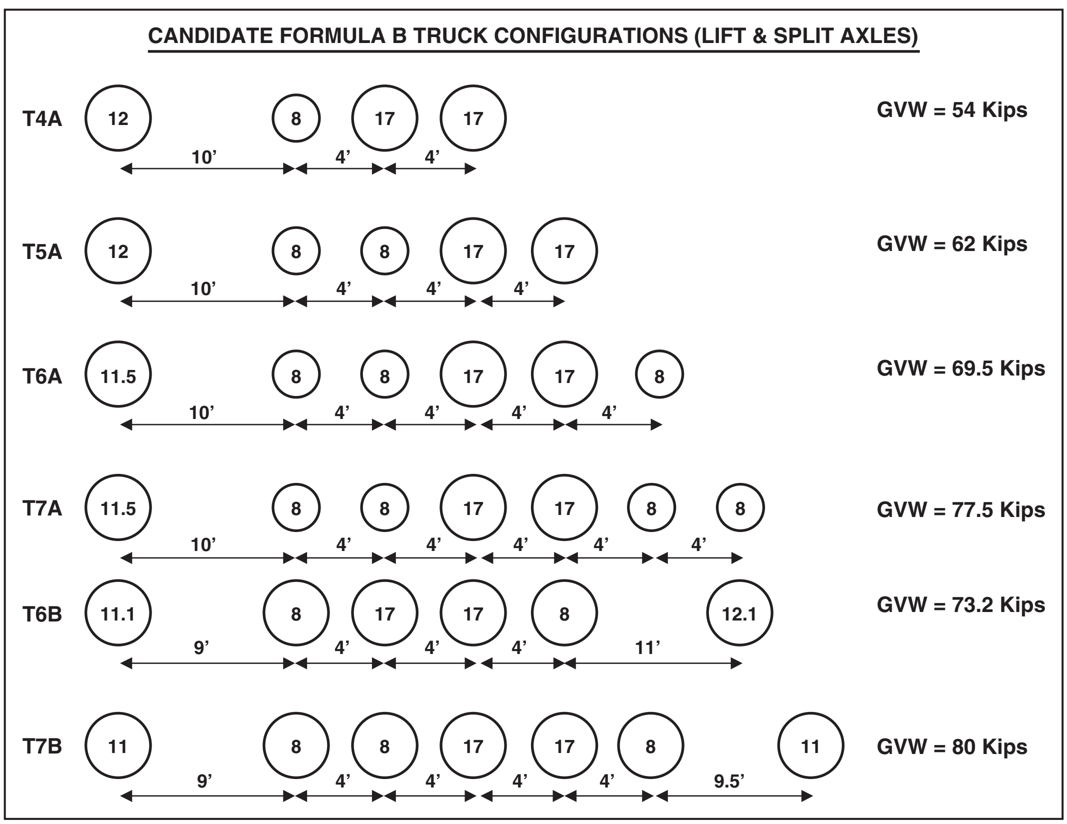

Figure 17. Candidate Formula B truck configurations with lift axles and split rear axle.

meeting Formula B limits for gross weight and for consecutive axles in an axle group (see Table 16). The other limits enforced were the federal gross weight limit of 80,000 lbs and the single axle weight limit of 20,000 lbs.

A suite of 12 candidate truck models with three to eight axles and having unusual truck configurations not represented by current AASHTO legal loads was developed. The loads will be used in the structural analysis of generic spans and will undergo further consideration as potential legal loads for posting. The eight-axle truck and one seven-axle truck are governed by the 80,000-lb gross weight limit as the FBF limit is higher. The total wheelbase for all trucks is less than 35 ft. The truck configurations are as shown in Figures 16 and 17. The first six truck configurations (T3 thru T8) have all fixed axles in the rear, spaced at 4 ft, and carry equal axle loads. This is a notional distribution of axle loads, as most trucks with four or more axles will usually have one or more rear lift axles, which will change the distribution of loads within the axle group. WIM data showed that many different lift axle combinations are in use on these multi-axle trucks and it is not possible to model all of them for bridge analysis. These six trucks with equal rear axles (see Figure 16) could serve as a baseline to compare the significance of introducing lift axles within an axle group and their influence on induced load effects.

The next four truck models, T4A thru T7A, represent four to seven axle trucks with rear lift axles that follow one commonly seen combination of lift and fixed axles. Clearly other lift and fixed axle combinations are possible and may need investigation if such positioning of lift axles within a group is seen to have a measurable influence on moments and shears. For the eight-axle truck (T8)—observed only in the Michigan data—all rear axles were assigned equal loads as the WIM data because Michigan did not show any discernable variation in rear axle loads. Additional WIM studies may provide information on similar trucks in Michigan or other states and substantiate the use of lift axles on eight-axle trucks and their preferred placement in the rear axle group. The last two truck models, T6B and T7B, represent six- and seven-axle trucks with a single split rear axle as seen in some states such as Idaho, Montana, and Washington. These trucks also have lift axles in the rear axle group. Truck T7B is governed by the 80,000-lb gross limit (not the FBF limit).

Table 16. FBF weight limit for consecutive axles.

No. of axles	Axle Spacing (ft)	FBF Limit (Kips)
2-Axle	4	34
3-Axle	4	42
4-Axle	4	50
5-Axle	4	58
6-Axle	4	66
7-Axle	4	74

Analysis Results for Generic Spans

Rating and posting loads aim to use only a limited number of truck models to envelop and represent the most severe loadings of vehicles. It may be possible to identify a few vehicles among the candidate load models that could serve as envelope vehicles for load effects induced by the suite of trucks. To develop these envelope vehicles and to verify that they will reliably exceed or envelop the force effects (moment and shear) induced by the suite of candidate Formula B load models and other Formula B state posting loads, a test suite of simple- and continuous-span bridges was assembled. In summary, the issues addressed in Phase I research include the following:

- Determine one or more governing rating vehicles that will reasonably envelop the load effects induced by the suite of 12 Formula B candidate load models over a range of spans and span types.
- Bridges that don't pass the check for the governing rating vehicle(s) will need further posting analysis to establish the weight limit(s) for posting. This may need other posting load models (other than the envelope rating vehicles) so that the weight restrictions are not too conservative for axle configurations that may not induce the same load effects per unit weight as the envelope rating vehicles. With the proliferation of multi-axle trucks, there is bound to be a greater need to consider variations in axle configurations in setting weight limits.
- A related issue is the types of spans and span lengths that are most at risk from these newer Formula B truck configurations. It is possible that not all bridges need to be routinely investigated for these unusual trucks. Some guidance on this issue also needs to be developed through these analytical studies.

A test suite of simple- and continuous-span bridges was assembled and used in the analysis of load effects. The span increments were 5 ft for spans under 100 ft and 10 ft for spans between 100 ft and 200 ft. The longer spans are less sensitive and less vulnerable to the effects of these short heavy trucks, and a 10-ft increment was considered satisfactory for the purposes of this study without compromising accuracy. The continuous spans were made up of two-span, three-span, and four-span continuous structures with span ratios selected to represent actual bridge configurations. For the two-span bridge, two equal spans were used. For the three-span bridge, each end span was set at 0.8 times the interior span. For the four-span bridge, the two equal end spans were 0.8 times the two equal interior spans. For the analysis of three- and four-span configurations, a more selective use of trucks in the suite of candidate loads was done, omitting trucks considered unlikely to govern based on the findings of the two-span analysis.

Bridges having transverse members were also included in the test suite assembled for this purpose. Floorbeam spacings from 10 ft to 30 ft (in 1-ft increments) were used in this study. The analytical studies were done to determine the stringer live-load reactions (stringers simply supported between floorbeams) on floorbeams and caps, which were compared with reactions from the AASHTO legal trucks. From the results it was also easy to identify the governing trucks for floorbeam and cap ratings. As live-load reaction is the key parameter that impacts load rating of transverse members, the results of this study will expose the potential impact of the candidate load models on transverse member ratings.

Detailed results of the analyses of generic spans for Formula B SHVs are contained in Appendix C. The series of tables and charts provided therein present the findings of the analytical studies. In the tables, the governing load effects are shaded for easy identification. Table 17 summarizes the results for simple and continuous spans. Results for transverse members are given in Table 18. In each table, the governing FBF truck moments and shears for all spans are compiled into a single column. Ratios obtained by dividing FBF trucks load effects by AASHTO trucks load effects provide a quick metric for the level of bridge overstress (see Table 19). Charts for simple-span moments and shears ratios are shown in Figures 18 and 19.

Some important findings from this analytical study are as follows:

- Three candidate FBF truck models—T7A, T7B, and T8 (with seven and eight axles)—are generally the governing (envelope) vehicles in most spans and impose the highest load effects (see Table 17). In a few instances, for very short spans under 20 ft, one of the other shorter trucks (T5A or T6A) could govern over these three trucks by a small margin.
- The eight-axle T8 truck, one of the heaviest trucks at 80 Kips, often governed shear and negative moments in continuous spans. Positive moment was governed by one of the seven-axle trucks (T7A or T7B).
- The spans most vulnerable to overstress (as measured by the overstress ratio or ratio of force effects) from the candidate FBF trucks were the shorter spans in the 10-ft to 75-ft span range (see Table 17). This observation applies to simple as well as to continuous spans.
- The highest ratio of force effects for spans from 10 ft to 75 ft varied from 1.00 to 1.49 (with one extreme value of 1.73 for negative moment in a 10-ft span). For spans over 100 ft, the ratio was usually under 1.3. The highest force effect ratios were found mostly in the 25-ft to 55-ft span range.
- Truck T7A also governed live-load reactions on transverse floorbeams (see Table 18). T7A live-load reactions were from 29% to 50% higher than the reactions from the governing AASHTO truck. One could expect a corresponding increase in floorbeam moments and shears.

The governing moments and shears for the candidate FBF trucks appear to envelop the force effects for state posting loads that satisfy all Formula B requirements. In other words, the three FBF trucks—T7A, T7B, and T8—taken together do seem to envelop all other candidate Formula B trucks developed in this project as well as the Formula B state rating and posting loads.

Acceptance Criteria for a Set of Legal Loads

The conclusion from this analysis is that if a jurisdiction adopts Formula B (with the 80-Kip limit) as its governing truck weight limit, then it will open itself to this new generation of trucks with load effects exceeding the existing AASHTO legal loads. The situation is especially critical for the short wheelbase trucks (SHVs), which is the focus of this study. This is because longer trucks are controlled by the 80-Kip limit whereas the AASHTO legal load for the short vehicle is the Type 3, which weights only 46.5 Kips—significantly below the 80 Kips that can be placed on a relatively short wheelbase vehicle. Analytical studies performed in this project have demonstrated the shear and moment effects of these new SHVs and show load effect increases up to 50% over the current AASHTO trucks.

In summary, the studies show the need to revise the present family of three AASHTO legal loads to better provide uniform safety for the new generation of Formula B truck configurations. The criteria for incorporating new legal loads are as follows:

1. The legal loads must cover all reasonable severe Formula B vehicles so that jurisdictions that adopt Formula B as a blanket legal load can be assured that their rating loads do cover all potential Formula B vehicles. It is intended that the proposed legal loads should not be a stop-gap measure covering some of the existing new SHV configurations, but must envelop the worst possible Formula B configurations that are either in operation now in the various states or considered likely to be seen in the future in other jurisdictions. For instance, the six-, seven-, and eight-axle Formula B configurations seen in certain states may not be currently operating in other states even though they are legal trucks. With constant pressure in the trucking industry to increase productivity and operating efficiency, it

Table 17. Summary of analysis results.

Single Span or Exterior Span (ft.)	Simple Spans				Two-Span Continuous						Three-Span Continuous						Four-Span Continuous					
	Governing FBF Truck for moment	Moment Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Shear	Shear Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Neg. Moment	Neg. Moment Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Positive Moment	Pos. Moment Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Shear	Shear Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Negative Moment	Neg. Moment Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Positive Moment	Pos. Moment Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Shear	Shear Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Negative Moment	Neg. Moment Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Positive Moment	Pos. Moment Ratio = FBF/AASHTO LEGAL	Governing FBF Truck for Shear	Shear Ratio = FBF/AASHTO LEGAL
10	T7A	1.03	T7B	1.05	T7A	1.32	T5A	1.00	T7A	1.10	T6A	1.73	T5A	1.03	T7A	1.13	T7A	1.34	T5A	1.05	T7A	1.13
15	T7A	1.14	T7B	1.17	T8	1.17	T6A	1.13	T7A	1.23	T8	1.38	T6A	1.13	T7A	1.24	T8	1.22	T6A	1.25	T7A	1.26
20	T7A	1.28	T7B	1.24	T8	1.24	T6A	1.23	T7A	1.34	T7A	1.22	T7A	1.27	T7B	1.27	T8	1.16	T7A	1.29	T7B	1.26
25	T7A	1.41	T7B	1.21	T7A	1.06	T7A	1.37	T7B	1.27	T7A	1.39	T7A	1.38	T7B	1.26	T7A	1.04	T7A	1.40	T7B	1.26
30	T7A	1.48	T7B	1.21	T7A	0.99	T7A	1.43	T7B	1.27	T7A	1.23	T7A	1.42	T7B	1.29	T7A	1.01	T7A	1.43	T7B	1.29
35	T7A	1.45	T8	1.24	T7A	0.97	T7A	1.42	T8	1.30	T7A	1.10	T7A	1.44	T8	1.35	T7A	1.02	T7A	1.45	T8	1.34
40	T7A	1.46	T8	1.30	T7A	0.97	T7A	1.43	T8	1.36	T8	1.10	T7A	1.46	T8	1.34	T8	1.07	T7A	1.47	T8	1.34
45	T7A	1.47	T8	1.33	T8	1.01	T7A	1.45	T8	1.35	T8	1.13	T7A	1.47	T8	1.30	T8	1.11	T7A	1.48	T8	1.30
50	T7A	1.48	T8	1.37	T8	1.05	T7A	1.47	T8	1.31	T8	1.17	T7A	1.48	T8	1.27	T8	1.15	T7A	1.48	T8	1.27
55	T7A	1.49	T8	1.27	T8	1.09	T7A	1.48	T8	1.28	T8	1.21	T7A	1.45	T8	1.25	T8	1.20	T7B	1.46	T8	1.25
60	T7A	1.45	T8	1.25	T8	1.13	T7A	1.46	T8	1.25	T8	1.27	T7B	1.42	T8	1.23	T8	1.25	T7B	1.42	T8	1.23
65	T7B	1.41	T8	1.24	T8	1.18	T7A	1.42	T8	1.23	T8	1.26	T7B	1.39	T8	1.21	T8	1.26	T7B	1.39	T8	1.20
70	T7B	1.38	T8	1.22	T8	1.23	T7A	1.39	T8	1.21	T8	1.22	T7B	1.37	T8	1.18	T8	1.22	T7B	1.37	T8	1.18
75	T7B	1.35	T8	1.21	T8	1.26	T7B	1.36	T8	1.19	T8	1.19	T7B	1.35	T8	1.17	T8	1.19	T7B	1.35	T8	1.16
80	T7B	1.33	T8	1.20	T8	1.24	T7B	1.34	T8	1.17	T8	1.16	T7B	1.33	T8	1.15	T8	1.16	T7B	1.33	T8	1.15
85	T7B	1.31	T8	1.17	T8	1.20	T7B	1.33	T8	1.15	T8	1.14	T7B	1.32	T8	1.14	T8	1.14	T7B	1.32	T8	1.13
90	T7B	1.30	T8	1.19	T8	1.18	T7B	1.31	T8	1.14	T8	1.13	T7B	1.30	T8	1.12	T8	1.12	T7B	1.31	T8	1.12
95	T7B	1.28	T8	1.15	T8	1.16	T7B	1.30	T8	1.13	T8	1.11	T7B	1.29	T8	1.12	T8	1.11	T7B	1.29	T8	1.11
100	T7B	1.26	T8	1.14	T8	1.14	T7B	1.29	T8	1.12	T8	1.10	T7B	1.27	T8	1.11	T8	1.10	T7B	1.27	T8	1.10
110	T7B	1.23	T8	1.12	T8	1.11	T7B	1.26	T8	1.10	T8	1.08	T7B	1.24	T8	1.09	T8	1.08	T7B	1.24	T8	1.09
120	T7B	1.20	T8	1.11	T8	1.09	T7B	1.23	T8	1.09	T8	1.07	T7B	1.22	T8	1.08	T8	1.07	T7B	1.21	T8	1.08
130	T7B	1.18	T8	1.10	T8	1.08	T7B	1.21	T8	1.08	T8	1.06	T7B	1.20	T8	1.07	T8	1.06	T7B	1.19	T8	1.07
140	T7B	1.17	T8	1.09	T8	1.07	T7B	1.19	T8	1.07	T8	1.05	T7B	1.18	T8	1.07	T8	1.05	T7B	1.17	T8	1.07
150	T7B	1.15	T8	1.08	T8	1.06	T7B	1.18	T8	1.06	T8	1.04	T7B	1.17	T8	1.06	T8	1.04	T7B	1.16	T8	1.06
160	T7B	1.14	T8	1.08	T8	1.05	T7B	1.16	T8	1.06	T8	1.04	T7B	1.15	T8	1.05	T8	1.02	T7B	1.15	T8	1.05
170	T7B	1.13	T8	1.07	T8	1.04	T7B	1.15	T8	1.05												
180	T7B	1.12	T8	1.07	T8	1.04	T7B	1.14	T8	1.05												
190	T7B	1.11	T8	1.06	T8	1.04	T7B	1.13	T8	1.04												
200	T7B	1.11	T8	1.06	T8	1.03	T7B	1.12	T8	1.04												

Table 18. Stringer live-load reactions on transverse members.

STRINGER SPAN (FT)	TYPE OF LOADING																			
	TYPE 3	TYPE 3S2	TYPE 3-3	Governing AASHTO Legal	HS-20	T3	T4	T5	T6	T7	T8	T4A	T5A	T6A	T7A	T6B	T7B	Governing FBF	Ratio = FBF/AASHTO LEGAL
10	13.6	12.4	11.2	*13.6*	16.0	13.6	15.4	15.0	15.0	14.3	13.7	16.0	16.8	17.6	17.6	16.8	17.6	*17.6*	**1.29**
11	13.9	12.7	11.5	*13.9*	16.0	14.5	15.9	15.9	16.2	15.5	14.8	16.5	17.5	18.6	18.6	17.5	18.6	*18.6*	**1.34**
12	14.2	13.1	11.7	*14.2*	16.0	15.2	16.3	16.7	17.3	16.5	15.8	16.8	18.2	19.5	19.5	18.2	19.5	*19.5*	**1.37**
13	14.4	13.7	11.9	*14.4*	16.0	15.8	16.7	17.3	18.1	17.8	17.4	17.2	18.7	20.2	20.5	18.7	20.2	*20.5*	**1.42**
14	14.6	14.2	12.0	*14.6*	16.0	16.4	17.0	17.9	18.9	18.9	18.8	17.4	19.1	20.9	21.4	19.5	20.9	*21.4*	**1.47**
15	14.8	14.6	12.2	*14.8*	17.3	16.8	17.7	18.7	19.6	19.8	20.0	18.1	19.5	21.4	22.2	20.3	21.4	*22.2*	**1.50**
16	15.3	15.0	12.3	*15.3*	18.5	17.2	18.3	19.5	20.1	20.6	21.0	18.6	19.9	21.9	22.9	20.9	21.9	*22.9*	**1.50**
17	15.8	15.4	12.7	*15.8*	19.5	17.6	18.8	20.2	20.6	21.4	21.9	19.1	20.2	22.3	23.5	21.5	22.5	*23.5*	**1.49**
18	16.4	15.6	13.3	*16.4*	20.4	17.9	19.2	20.8	21.1	22.0	22.8	19.6	20.4	22.7	24.0	22.0	23.2	*24.0*	**1.46**
19	16.8	15.9	13.7	*16.8*	21.3	18.2	19.6	21.3	21.8	22.9	23.7	19.9	21.0	23.3	24.8	22.5	24.0	*24.8*	**1.48**
20	17.2	16.1	14.2	*17.2*	22.0	18.4	20.0	21.8	22.5	23.7	24.5	20.3	21.5	23.9	25.5	23.2	24.8	*25.5*	**1.48**
21	17.6	16.3	14.5	*17.6*	22.7	18.7	20.3	22.2	23.0	24.4	25.2	20.6	22.0	24.4	26.1	23.9	25.5	*26.1*	**1.48**
22	18.0	16.5	14.9	*18.0*	23.3	18.9	20.6	22.6	23.6	25.0	25.9	20.9	22.4	24.9	26.7	24.5	26.2	*26.7*	**1.48**
23	18.3	16.7	15.2	*18.3*	23.8	19.1	20.9	23.0	24.1	25.6	26.5	21.2	22.7	25.3	27.2	25.0	26.8	*27.2*	**1.49**
24	18.5	16.9	15.5	*18.5*	24.3	19.2	21.2	23.3	24.5	26.2	27.1	21.4	23.1	25.7	27.7	25.5	27.3	*27.7*	**1.50**
25	18.8	17.0	15.7	*18.8*	24.8	19.4	21.4	23.6	25.0	26.7	27.6	21.6	23.4	26.1	28.1	25.9	27.9	*28.1*	**1.49**
26	19.0	17.5	16.2	*19.0*	25.2	19.5	21.6	23.9	25.3	27.2	28.1	21.8	23.7	26.4	28.5	26.3	28.3	*28.5*	**1.50**
27	19.3	18.2	16.8	*19.3*	25.6	19.7	21.8	24.2	25.7	27.6	28.5	22.0	24.0	26.7	28.9	26.7	28.8	*28.9*	**1.50**
28	19.5	18.8	17.5	*19.5*	26.0	19.8	22.0	24.4	26.0	28.0	28.9	22.2	24.2	27.0	29.3	27.1	29.2	*29.3*	**1.50**
29	19.7	19.4	18.0	*19.7*	26.3	19.9	22.2	24.7	26.3	28.4	29.3	22.4	24.4	27.3	29.6	27.4	29.5	*29.6*	**1.50**
30	19.9	20.1	18.8	*20.1*	26.7	20.0	22.3	24.9	26.6	28.7	29.7	22.5	24.7	27.5	29.9	27.7	29.9	29.9	**1.49**

Table 19. Overstress caused by Formula B SHVs.

Force Effect	Maximum Overstress Ratio = FBF / AASHTO Legal
Simple-Span Bending	1.49
Simple-Span Shear	1.37
Two-Span Cont. Positive Bending	1.48
Two-Span Cont. Negative Bending	1.26
Two-Span Cont. Shear	1.36
Three-Span Cont. Positive Bending	1.48
Three-Span Cont. Negative Bending	1.39
Three-Span Cont. Shear	1.35
Four-Span Cont. Positive Bending	1.48
Four-Span Cont. Negative Bending	1.34
Four-Span Cont. Shear	1.34

could be reasonably expected that there will be greater penetration of these multi-axle trucks into the other states in the years to come.

2. To the extent that is reasonable, the proposed AASHTO legal loads should envelop the extreme load effects that may be caused by all likely Formula B vehicles without excessive conservatism. The application of these legal loads should fall in all three rating philosophies including the allowable stress rating (ASR), load factor rating (LFR), and LRFR as adopted by AASHTO. The same legal loads must be suitable for inclusion in the AASHTO *MCE* (*1*) and the AASHTO LRFR Guide Manual (*2*) so that transition to the new LRFR procedures will not be confused by comparisons of ratings using different vehicle models.
3. The proposed AASHTO legal loads should satisfy Formula B limits for gross weights and axle weights and stay within the 80,000-lb gross weight limit. The procedure used in this project to develop the suite of Formula B trucks was to first extract the number and spacings of axles for these unusual truck configurations from the WIM data and state legal loads and then manually maximize the axle loads within limits prescribed by Formula B for gross and axle group weights.
4. The number of AASHTO legal loads should be limited so that weight or posting restrictions can be clearly identified. Any compromises, which lead to a bracketing of legal load configurations, should not lead to excessive conservatism for any particular vehicle type. For example, using a specific upper bound eight-axle truck to also represent six- and seven-axle configurations will be conservative. The ASR and LFR criteria are limited by requiring the identical safety margin for all situations. LRFR, however, is more flexible so that safety can be adjusted depending on site and expected maximum loading cases. Thus, the LRFR calibration can be used to reduce the number of AASHTO legal loads by bracketing loading categories and using same arbitrary percentage cut-off for comparisons.

Candidate Notional Rating Load Model

Load effects analyses for a test suite of simple- and continuous-span bridges showed that the critical vehicles for most load effects are the seven- and eight-axle trucks designated as T7A, T7B, and T8 (see Table 17). These vehicles essentially envelop the load effects of all reasonable

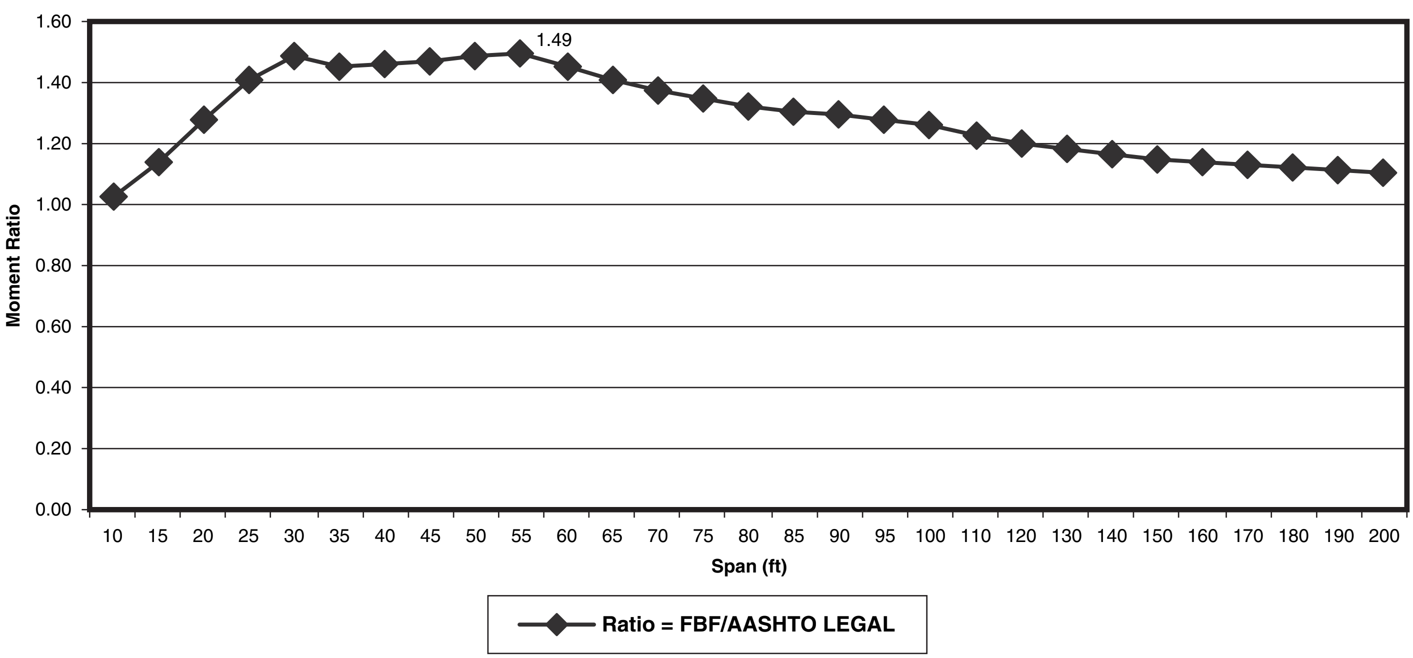

Figure 18. Simple-span moment ratios.

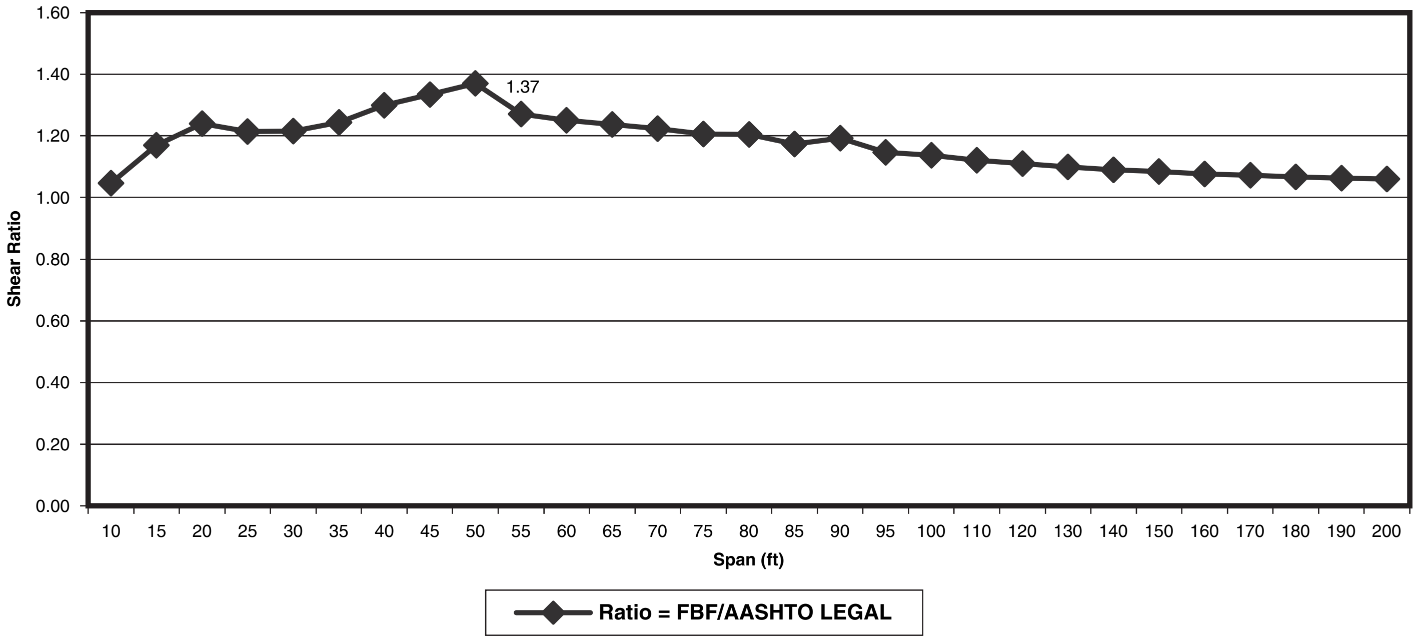

Figure 19. Simple-span shear ratios.

Formula B truck configurations on simple and continuous spans ranging from 10 ft to 200 ft in length. It could be possible through further studies to develop a single envelope legal vehicle or a "notional rating truck" to simplify the load rating analysis. This single rating truck will induce load effects at least equal to the governing load effects of T7A, T7B, and T8. The aim is to introduce a single rating truck (or a small number of additional load models if a single envelope load model is not feasible) into the family of AASHTO loads to be checked while at the same time ensuring that all reasonable Formula B SHV configurations are covered by the check. The notional truck will be defined only as a convenient device for load rating analyses and should not be construed as a standard for configuring actual trucks. Calling this envelope vehicle a "notional load" will make it clear to the trucking companies that the relaxed weight restrictions for this truck would not apply to actual legal trucks. Notional loads are already in use in U.S. bridge codes, and their meaning and intended use is familiar to most bridge engineers. If a bridge has a rating factor of 1.0 or higher for the notional rating load, the bridge can safely carry all legal loads satisfying Formula B.

The analytical studies have identified a single rating vehicle (80 Kips) that will envelop the load effects of all reasonable Formula B truck configurations on simple and continuous spans ranging from 10 ft to 200 ft in length (see Figure 20). This truck meets all Formula B requirements (inner and outer) and all federal weight laws. This candidate notional truck will be referred to herein as truck BFT (Bridge Formula Truck). Bridges that rate for the truck BFT are safe for all Formula B configurations represented by the 12 FBF truck models shown previously. A rating factor <1.0 indicates that further analysis is required to determine the need for posting. In some cases, posting may not be required as the load effects of the posting loads may be less than for the BFT.

When using truck BFT (see Figure 20), computation of load effects is to be done in accordance with the following guidelines:

1. Axles that do not contribute to the maximum load effect will be neglected, and
2. The drive axle spacing can be varied from 6 ft to 14 ft in order to maximize force effects.

The force effects induced by the candidate rating truck BFT and the suite of 12 representative Formula B trucks with three to eight axles (Formula B trucks are denoted as FBF trucks) are compared in Table 20.

A number of trials were performed prior to selecting truck BFT as the best envelope vehicle for the suite of FBF trucks. Moment and shear ratios (BFT/FBF) are also reported in the tables to facilitate easy comparison. A ratio greater than 1.0 indicates that the proposed rating truck BFT produces a higher force effect than the representative Formula B configurations. A desirable characteristic of the BFT truck selected is that the moment and shear ratios for the various span lengths and span configurations are consistently slightly above 1.0, except for a few very short continuous spans (less than 20 ft) where the ratios were slightly below 1.0. In summary, truck

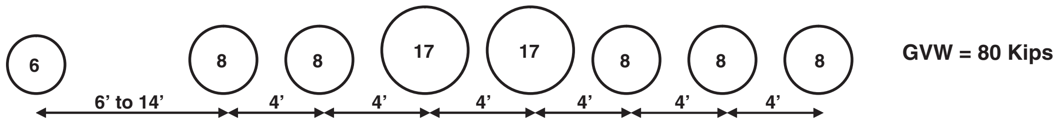

Figure 20. Bridge formula truck.

Table 20. Maximum and minimum ratios of force effects.

Force Effect	Ratio BFT/FBF: Min, Max
Maximum Moments – Simple Spans	1.00, 1.05
Maximum Shear – Simple Spans	0.99, 1.04
Maximum Positive Moments – Two-Span Cont	1.00, 1.05
Maximum Negative Moments – Two-Span Cont.	0.94, 1.04 Min @ span = 20 ft
Maximum Shear – Two-Span Cont.	1.00, 1.04
Maximum Shear – Three-Span Cont.	0.98, 1.02 Min @ span = 10 ft
Maximum Positive Moments – Three-Span Cont.	0.99, 1.04
Maximum Negative Moments – Three-Span Cont.	0.97, 1.03 Min @ span = 10 ft
Maximum Positive Moments – Four-Span Cont.	0.90, 1.04 Min @ span = 10 ft
Maximum Shear – Four-Span Cont.	0.95, 1.03 Min @ span = 10 ft
Maximum Negative Moments – Four-Span Cont.	0.99, 1.15 Max @ span = 10 ft

BFT appears to be a very good single envelope vehicle for the suite of FBF trucks.

The standard truck BFT configuration (eight-axle truck with 6-ft drive axle spacing) will generally govern the rating analyses of bridges. A few exceptions to this statement are evident and should be noted. In order to maximize the BFT positive moment in very short continuous spans, certain end axles had to be omitted during the analysis (see Appendix C). Typically, continuous-span bridges with span lengths of less than 25 ft required the omission of one or more end axles to maximize the positive moment. For the Formula B trucks (FBF trucks), the same force effect was governed by the five- or six-axle truck (T5A or T6A); therefore, it is to be expected that certain axles in the BFT load model that do not contribute to the maximum positive moments need to be neglected or they will contribute to bending in the opposite (negative) direction. Identifying the governing axle configuration may require a few trials; this is not considered particularly difficult as most continuous beam analyses are automated. This requirement should not affect many load ratings as the population of continuous bridges with spans under 25 ft is not likely to be significant. To guide the rating engineer, the manual commentary could explain that all simple spans and continuous spans with spans >25 ft would not be affected by the requirement to omit axles that do not contribute to the maximum load effect. Axles that fall outside the bridge are not affected by this requirement as they are automatically neglected in the analysis.

In a few cases, the drive axle spacing was also varied to increase the positive moments in short continuous spans (see Appendix C). Increasing the drive axle spacing from 6 ft to 14 ft resulted in a slight increase in positive moments for continuous-span bridges with spans less than 35 ft. Language in the manual commentary could guide the rating engineer as to where the variable drive axle spacing may be important and should be evaluated.

Comparison of Force Effects Induced by the Proposed Notional Rating Truck with HS20 and AASHTO Legal Loads

The test suite of simple- and continuous-span bridges (spans ranging from 10 ft to 200 ft) was used to compare the force effects induced by the proposed rating truck BFT and current AASHTO legal loads for posting to the forces produced by HS20 loading. The results are summarized in Table 21.

Some findings of these analyses are as follows:

1. The proposed rating truck BFT consistently produces higher force effects than the current AASHTO legal loads for the test suite of simple- and continuous-span bridges.
2. Simple-span BFT moments are about 10% to 20% higher than HS20 for spans governed by the HS20 truck loading. For longer spans governed by HS20 lane loading (over 170 ft), HS20 moments exceed BFT moments. BFT moments are significantly higher than AASHTO legal loads for most simple spans.
3. Simple-span shears for BFT and HS20 truck are within 8% for most spans.
4. HS20 negative moments are significantly higher than the BFT negative moments for most continuous-span configurations. The difference increases with increasing span. It should be noted that the HS20 negative moments are governed by the lane load model whereas the BFT negative moments are computed for a single truck. BFT negative

Table 21. Force effect ratios.

Force Effect	BFT/HS20 Range of Values	BFT/AASHTO Legal Range of Values
Maximum Moments – Simple Spans	0.70 to 1.22	1.03 to 1.56
Maximum Shear – Simple Spans	0.88 to 1.08	1.05 to 1.36
Maximum Negative Moments – Two-Span Cont	0.39 to 0.98	0.97 to 1.35
Maximum Positive Moments – Two-Span Cont.	0.67 to 1.20	1.00 to 1.54
Maximum Shear – Two-Span Cont.	0.72 to 1.08	1.04 to 1.40
Maximum Shear – Three-Span Cont.	0.79 to 1.07	1.05 to 1.35
Maximum Positive Moments – Three-Span Cont.	0.66 to 1.19	1.02 to 1.55
Maximum Negative Moments – Three-Span Cont.	0.47 to 1.04	1.01 to 1.28
Maximum Positive Moments – Four-Span Cont.	0.67 to 1.20	0.95 to 1.54
Maximum Shear – Four-Span Cont.	0.84 to 1.07	1.07 to 1.33
Maximum Negative Moments – Four-Span Cont.	0.48 to 0.99	1.00 to 1.54

moments, however, exceed the AASHTO legal load negative moments (also computed for a single truck).

5. BFT positive moments for most continuous spans are higher than the HS20 moments by up to 20% (truck governs). For the same force effect, BFT exceeds the AASHTO legal loads by over 50% in certain cases.
6. Continuous-span shears for BFT and HS20 generally do not vary by more than 8%, except when the lane load governs HS20 shear.

It should be noted that a rating factor (RF) <1.0 only indicates that further analysis is required to determine the need for posting. In some cases, posting may not be required as the load effects of the posting loads may be less than for the BFT.

Definition of Legal Loads for Posting

If a bridge fails to meet the required RF of 1.0 for the NRL, then trucks as severe as the rating vehicle should be prohibited. Setting weight limits for posting often requires the evaluator to determine safe load capacities for other common commercial legal truck types with axle configurations different from the notional truck in accordance with state weight limit regulations and posting practices. While a single envelope rating vehicle can provide considerable simplification of load rating computations and can establish posting eligibility, it may not be the ideal solution for all posting situations. A linear ratio of posting weights and ratings will not suffice as the moment effects per unit weight will be different for different axle configurations. This illustrates the need to uncouple rating loads and posting loads. Additional AASHTO legal loads for posting will be needed to give more accurate posting values.

A state will only post for vehicles that are allowed to operate in that state. There are many restrictions on multi-axle trucks from state to state, and this should be recognized. A single rating truck (legal or notional) may suffice to check bridges for all Formula B SHVs, but posting bridges that do not pass this check may need a posting analysis using a suite of posting loads. Even if RF <1.0 for the NRL, posting may not be required in certain cases. The evaluator will need to perform a separate posting analysis selecting posting loads applicable to that state from a suite of multi-axle legal loads provided. This is a flexibility that the states need to avoid. It may be too restrictive or introduce unnecessary load postings. This project will develop and recommend a suite of legal load models for posting for FBF trucks with three to eight axles. For axle configurations that induce similar moment effects per unit weight, the posting analysis may be simplified by checking only one representative truck from this class. This approach could limit the number of load cases that need to be evaluated in a posting analysis, and it will be considered in the development of the recommended legal loads for posting.

Another issue to be considered is that certain multi-axle configurations that cause the highest load effects appear to be common only in some states and they should not lead to reduced postings in all states. Setting weight limits for posting often requires the evaluator to determine safe load capacities for commercial truck types that operate within a given state in accordance with state posting practices. Two options were investigated for selecting the proposed legal loads for posting:

- **Option 1**: Includes the worst four-axle (T4A), worst five-axle (T5A), worst six-axle (T6A), and worst seven-axle (T7A) trucks as shown in Figure 21 (seven-axle is also representative of eight-axle trucks).
- **Option 2**: Includes the worst four-axle truck (T4A) and uses truck T5A as a single representative truck for Formula B truck configurations with five to eight axles (see Figure 22).

Under Option 1, for bridges that do not rate for truck BFT (RF <1.0), the rating engineer will perform a posting analysis to establish the need for posting and the posting load limit

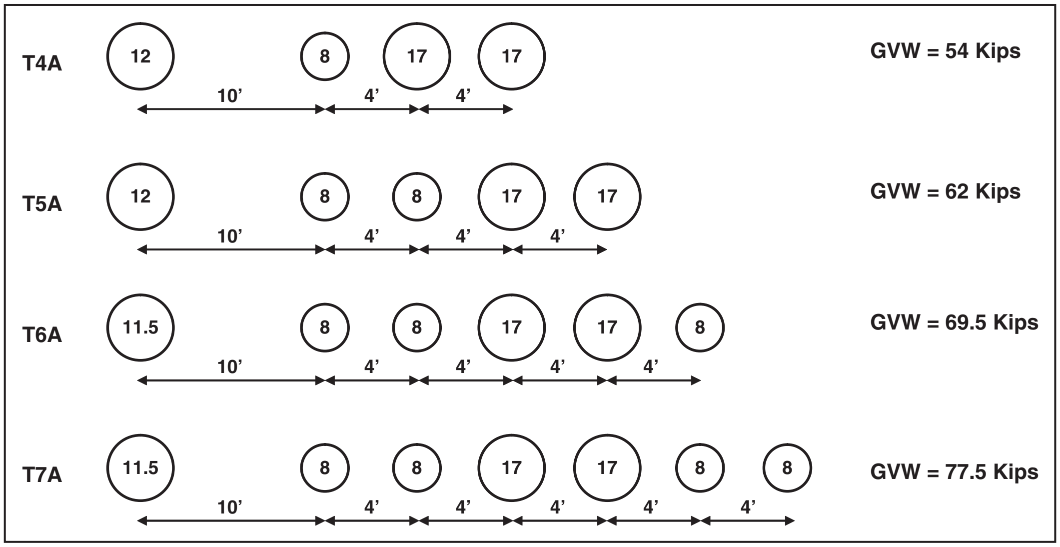

Figure 21. Candidate posting loads (Option 1).

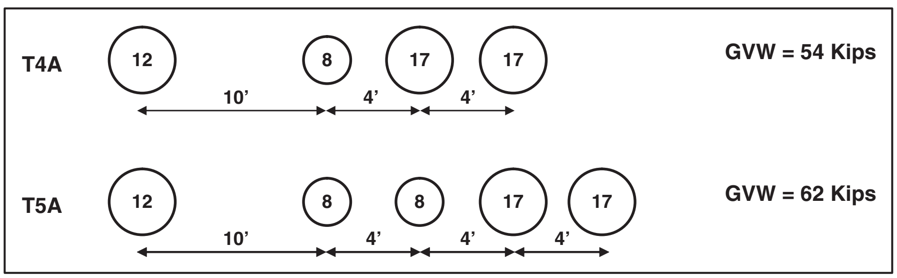

Figure 22. Candidate posting loads (Option 2).

using posting loads (selected from the suite of four trucks) representative of commercial trucks operating within the state. For instance, if a state does not have six- or seven-axle SHVs in the normal traffic stream, then only T4A and T5A will be used in the posting analysis. Posting signs can show a load limit for each truck type (four-axle, five-axle, etc.) or a single tonnage (governing) for all multi-axle single-unit trucks.

Further simplification of the posting analysis is possible if certain posting loads could be eliminated, thereby reducing the number of new posting loads. If it can be shown that a smaller subset of these four posting load models will consistently produce the governing posting load, then a procedure is available to eliminate certain load models from the posting analysis.

Analytical studies show that the posting load remains unchanged—regardless of truck weight and configuration—if a set of posting loads produces the same moment (or shear) per unit weight of truck (see Appendix C). In other words, the truck that produces the highest moment or shear per unit weight will govern the posting value (will result in the lowest weight limit).

The available live-load capacity for a bridge is a constant. The truck that produces the highest moment (or shear) per unit weight of truck will have the lowest weight limit for posting. This could be used to identify the critical truck for the posting analysis. This posting load characteristic is valid provided the span moments and shears result from truck loads and not axle loads as in the case of very short spans. For very short spans (spans <30 ft), the shorter trucks will always govern posting.

The moments induced per unit weight of each truck for the various span lengths are given in Table 22. Key findings from these analyses are as follows:

1. T4A consistently generates the highest moment per unit weight for all span lengths.
2. Of the other trucks with five to eight axles, T5A would be the most critical for posting although the differences in the moment per unit weight values for trucks T5A, T6A, T7A

Table 22. Moment per unit weight—simple spans.

Single Span (Ft)	T4A/Wt	T5A/Wt	T6A/Wt	T7A/Wt	T8/Wt	BFT/Wt
10	1.03	0.90	0.80	0.72	0.46	0.70
15	2.00	1.74	1.57	1.40	0.95	1.36
20	2.97	2.71	2.54	2.27	1.71	2.20
25	3.94	3.72	3.58	3.27	2.59	3.16
30	5.07	4.73	4.62	4.33	3.74	4.31
35	6.31	5.80	5.66	5.39	4.89	5.47
40	7.55	7.03	6.91	6.58	6.13	6.72
45	8.80	8.27	8.15	7.83	7.38	7.97
50	10.05	9.51	9.40	9.08	8.63	9.22
55	11.29	10.76	10.65	10.33	9.88	10.47
60	12.54	12.00	11.89	11.58	11.13	11.71
65	13.79	13.25	13.14	12.83	12.38	12.96
70	15.04	14.49	14.39	14.08	13.63	14.21
75	16.29	15.74	15.64	15.33	14.88	15.46
80	17.54	16.98	16.89	16.58	16.13	16.71
85	18.79	18.23	18.14	17.83	17.38	17.96
90	20.04	19.48	19.39	19.08	18.62	19.21
95	21.28	20.73	20.64	20.33	19.87	20.46
100	22.53	21.97	21.88	21.58	21.12	21.71
110	25.03	24.47	24.38	24.08	23.62	24.21
120	27.53	26.97	26.88	26.58	26.12	26.71
130	30.03	29.46	29.39	29.08	28.62	29.21
140	32.53	31.96	31.88	31.58	31.12	31.71
150	35.03	34.46	34.38	34.08	33.62	34.21
160	37.53	36.96	36.88	36.58	36.12	36.71
170	40.03	39.46	39.38	39.08	38.62	39.21
180	42.53	41.96	41.88	41.58	41.12	41.71
190	45.03	44.46	44.38	44.07	43.62	44.20
200	47.53	46.95	46.88	46.58	46.12	46.70

and BFT for spans greater than 40 ft are very small (under 5%). For spans under 40 ft, the differences are larger and are quite sensitive to span lengths.

If it is desirable to reduce the number of posting loads to simplify the posting analysis then it would be appropriate to select T4A and T5A as the candidate posting loads. This is designated as the second option for the selection of posting loads:

- **Option 2**: Includes the worst four-axle truck (T4A) and uses truck T5A as a single representative truck for Formula B truck configurations with five to eight axles (see Figure 22).

T4A is a very common SHV in most states (tri-axle dump truck) and would be a suitable posting load for use nationally. Many states already use such a vehicle as a state legal load (not all satisfy Formula B). As discussed previously, T4A would govern the posting, and some states such as Connecticut and Alabama use a truck symbol to post specifically for these trucks. In the posting analysis, T5A will serve as a single representative truck for Formula B configurations with five to eight axles. The posting weight limit determined for T5A will apply to all single-unit trucks with five or more axles. The posting sign could note this using text. A state may also choose the T4A posting load to apply to all single-unit trucks to further simplify the signing. Each simplification will introduce added conservatism in posting.

Note that the comparison of moments per unit weight assumes that the live-load factor is the same for all posting load models. Calibration may lead to different load factors for each truck model due to differences in volumes and moment ratios. More precise posting evaluation is possible in LRFR using targeted load factors for a suite of posting loads.

Another issue to be considered in the posting analysis is the likely "unbalancing" of the axle loads for a posted truck. The loads on a posted truck may not be placed in the same proportion as a fully loaded truck assumed in the analysis, which may affect the load effects induced per unit weight.

Analytical studies (discussed in Appendix C) provide additional data to support the selection of the posting load models. Using T5A as a single posting vehicle for all Formula B trucks having five through eight axles has advantages in its simplicity. Some disadvantages are as outlined below:

1. A bridge span may have an RF of greater than 1.0 for T5A, but may not rate (RF <1.0) for the worst six-, seven-, and eight-axle trucks. This will lead to a situation where the T5A is being used to determine a posting load for a bridge even though the bridge has adequate capacity for the T5A truck. The concern here is whether it will cause confusion in the minds of the rating engineers when implementing the new rating and posting loads and procedures. Theoretically, the simplification of using T5A as a single representative posting load for a series of trucks presents a valid approach if such practical difficulties are not considered a problem.
2. T5A as a single posting vehicle works quite well for spans over 40 ft governed by the full truck load. For very short spans where only a portion of the truck may be on the bridge, the posting values obtained using T5A may be too conservative (over 20% less) to be considered an acceptable simplification, especially when load restrictions are involved.
3. States that do not see all the multi-axle Formula B vehicle configurations represented by T5A, for posting purposes, may prefer to be more selective and post only for SHVs that are common in that state. Having more posting load models to choose from will allow the states to pick the appropriate load models to obtain more precise posting values. For instance, if a state finds that seven-axle trucks are in common use, but not the five- or six-axle trucks, then it would be more advantageous to post for the T7A than the T5A.
4. Having more posting loads would be beneficial to states that show truck symbols with associated weight limits on posting signs. Here the posting loads are targeted to specific vehicle configurations.

Panel review comments showed that there was no clear favorite for the posting load choices. This is understandable as the choice of posting loads is contingent on posting and signing practices and the use of truck symbols on posting signs. There is little uniformity here. The survey of states done for this project revealed that of the 48 states responding, 32 use truck symbols on posting signs. These states may favor more posting load choices to allow more selective use of truck symbols and weight limits. As Option 2 is a subset of Option 1, all four candidate posting loads were carried forward.

Application of the Recommended Legal Loads

The test suite of simple- and continuous-span bridges (10 ft to 200 ft) was used to compare the RFs (moment and shear) and posting loads for the proposed BFT rating truck and posting loads developed, the current AASHTO legal loads, and HS20 loading. To provide a uniform basis that will allow easy comparisons of ratings and postings, the member resistance for each span in the test suite was assumed such that the span will have a Inventory Rating Factor = 1.0 (Load Factor Rating) for the current family of three AASHTO legal loads. What this means is that under LFR ratings, these bridges will not have to be load posted for current AASHTO legal loads. The member resistances thus determined were then used to obtain new Inventory RFs and posting loads for the proposed BFT truck and the proposed posting vehicles (T4A, T5A, T6A, and T7A). HS20 ratings were also computed for each span. If a bridge rates less than 1.0 for the proposed legal loads, then it is a situation in which a bridge that is currently not posted will need to be posted in the future for the new generation of Formula B trucks. This process is important to understand the potential impact of the new legal loads on current bridge postings and also to ascertain the practical implications of reducing the number of new posting vehicles from four to two (i.e., Option 1 versus Option 2). Analytical studies were done on simple spans and continuous bridges with two to four spans (10 ft to 200 ft). Only the simple-span and two-span continuous bridges are discussed here. The findings are similar for the three- and four-span bridge configurations.

Live-load reactions were computed for transverse members for the proposed rating and posting vehicles. Transverse member ratings will also be governed by the seven- and eight-axle trucks (see Table 23). These trucks produce the highest live-load reactions on transverse members. The results of the analyses provide a detailed assessment of the performance of existing bridges under the new loadings and potential impacts on current ratings and postings:

- Truck BFT will have the lowest moment ratings, varying from 0.97 to 0.64 (see Table 24). This indicates that all spans should be subjected to a posting analysis for the new posting vehicles.
- The moment ratings for the seven- and eight-axle BFT trucks are lower than the HS20 ratings for most spans. This shows that HS20 is not a suitable screening load model for all Formula B trucks.
- Truck BFT will have the lowest shear ratings, varying from 0.96 to 0.74 (see Table 25). This indicates that all spans should be subjected to a posting analysis for the new posting vehicles.
- The shear ratings for the seven- and eight-axle BFT trucks are lower than the HS20 ratings for most spans. HS20 is not a suitable screening load model for all Formula B trucks.
- T4A will produce the lowest posting load of all Formula B vehicles (see Tables 26 and 27).

Table 23. Posting load—simple-span bending.

Single Span (ft.)	GOVERNING AASHTO LEGAL TRUCK	Posting Load in Tons							
		Governing AASHTO Legal Load RF	AASHTO Type 3	T4A	T5A	T6A	T7A	BFT	HS20
10	**Type 3**	**1.00**	25.0	26.3	30.2	33.9	37.78	39.0	24.48
15	**Type 3**	**1.00**	25.0	24.0	27.5	30.6	34.12	35.2	28.74
20	**Type 3**	**1.00**	25.0	23.2	25.4	27.2	30.28	31.3	30.98
25	**Type 3**	**1.00**	25.0	22.8	24.2	25.1	27.54	28.4	31.23
30	**Type 3**	**1.00**	25.0	22.3	23.9	24.4	26.10	26.2	28.82
35	**Type 3**	**1.00**	25.0	22.8	24.8	25.4	26.71	26.3	28.68
40	**Type 3**	**1.00**	25.0	23.1	24.9	25.3	26.56	26.0	27.98
45	**Type 3**	**1.00**	25.0	23.4	24.9	25.2	26.29	25.8	27.51
50	**Type 3**	**1.00**	25.0	23.6	24.9	25.2	26.10	25.7	27.17
55	**Type 3**	**1.00**	25.0	23.7	24.9	25.2	25.95	25.6	26.91
60	**Type 3-S2**	**1.00**	25.8	24.6	25.8	26.0	26.70	26.4	27.60
65	**Type 3-S2**	**1.00**	26.8	25.6	26.7	26.9	27.56	27.3	28.41
70	**Type 3-S2**	**1.00**	27.5	26.5	27.5	27.7	28.27	28.0	29.07
75	**Type 3-S2**	**1.00**	28.2	27.2	28.1	28.3	28.87	28.6	29.64
80	**Type 3-S2**	**1.00**	28.7	27.8	28.7	28.8	29.39	29.2	30.11
85	**Type 3-S2**	**1.00**	29.2	28.3	29.2	29.3	29.83	29.6	30.52
90	**Type 3-S2**	**1.00**	29.6	28.8	29.6	29.7	30.22	30.0	30.87
95	**Type 3-3**	**1.00**	30.0	29.2	30.0	30.1	30.56	30.4	31.19
100	**Type 3-3**	**1.00**	30.6	29.8	30.6	30.7	31.12	30.9	31.73
110	**Type 3-3**	**1.00**	31.6	30.8	31.5	31.6	32.04	31.9	32.60
120	**Type 3-3**	**1.00**	32.3	31.6	32.3	32.4	32.78	32.6	33.31
130	**Type 3-3**	**1.00**	33.0	32.3	33.0	33.0	33.40	33.3	33.89
140	**Type 3-3**	**1.00**	33.5	32.9	33.5	33.6	33.92	33.8	34.39
150	**Type 3-3**	**1.00**	34.0	33.4	34.0	34.1	34.36	34.2	34.07
160	**Type 3-3**	**1.00**	34.4	33.9	34.4	34.5	34.75	34.6	33.06
170	**Type 3-3**	**1.00**	34.8	34.2	34.7	34.8	35.08	35.0	32.08
180	**Type 3-3**	**1.00**	35.1	34.6	35.1	35.1	35.38	35.3	31.13
190	**Type 3-3**	**1.00**	35.3	34.9	35.3	35.4	35.64	35.5	30.22
200	**Type 3-3**	**1.00**	35.6	35.2	35.6	35.6	35.87	35.8	29.34

Table 24. Rating factor—simple-span bending.

Single Span (ft.)	GOVERNING AASHTO LEGAL MOMENT	GOVERNING AASHTO LEGAL TRUCK	Available Live Load Capacity = 2.17x LL Moment	Rating Factors							
				Governing AASHTO Legal Load RF	AASHTO Type 3	T4A	T5A	T6A	T7A	BFT	HS20
10	54.4	Type 3	118.0	1.00	1.00	0.97	0.97	0.97	0.97	0.97	0.68
15	95.8	Type 3	207.9	1.00	1.00	0.89	0.89	0.88	0.88	0.88	0.80
20	137.7	Type 3	298.8	1.00	1.00	0.86	0.82	0.78	0.78	0.78	0.86
25	179.9	Type 3	390.4	1.00	1.00	0.85	0.78	0.72	0.71	0.71	0.87
30	225.8	Type 3	490.0	1.00	1.00	0.83	0.77	0.70	0.67	0.65	0.80
35	287.7	Type 3	624.3	1.00	1.00	0.84	0.80	0.73	0.69	0.66	0.80
40	349.6	Type 3	758.6	1.00	1.00	0.86	0.80	0.73	0.69	0.65	0.78
45	411.7	Type 3	893.4	1.00	1.00	0.87	0.80	0.73	0.68	0.65	0.76
50	473.9	Type 3	1028.4	1.00	1.00	0.87	0.80	0.73	0.67	0.64	0.75
55	536.1	Type 3	1163.3	1.00	1.00	0.88	0.80	0.72	0.67	0.64	0.75
60	618.3	Type 3-S2	1341.7	1.00	1.03	0.91	0.83	0.75	0.69	0.66	0.77
65	707.1	Type 3-S2	1534.4	1.00	1.07	0.95	0.86	0.77	0.71	0.68	0.79
70	796.0	Type 3-S2	1727.3	1.00	1.10	0.98	0.89	0.80	0.73	0.70	0.81
75	885.1	Type 3-S2	1920.7	1.00	1.13	1.01	0.91	0.81	0.75	0.72	0.82
80	974.3	Type 3-S2	2114.2	1.00	1.15	1.03	0.93	0.83	0.76	0.73	0.84
85	1063.5	Type 3-S2	2307.8	1.00	1.17	1.05	0.94	0.84	0.77	0.74	0.85
90	1152.9	Type 3-S2	2501.8	1.00	1.19	1.07	0.95	0.86	0.78	0.75	0.86
95	1242.3	Type 3-3	2695.8	1.00	1.20	1.08	0.97	0.87	0.79	0.76	0.87
100	1343.0	Type 3-3	2914.3	1.00	1.22	1.10	0.99	0.88	0.80	0.77	0.88
110	1542.8	Type 3-3	3347.9	1.00	1.26	1.14	1.02	0.91	0.83	0.80	0.91
120	1742.5	Type 3-3	3781.2	1.00	1.29	1.17	1.04	0.93	0.85	0.82	0.93
130	1942.3	Type 3-3	4214.8	1.00	1.32	1.20	1.06	0.95	0.86	0.83	0.94
140	2142.2	Type 3-3	4648.6	1.00	1.34	1.22	1.08	0.97	0.88	0.84	0.96
150	2342.0	Type 3-3	5082.1	1.00	1.36	1.24	1.10	0.98	0.89	0.86	0.95
160	2541.9	Type 3-3	5515.9	1.00	1.38	1.25	1.11	0.99	0.90	0.87	0.92
170	2741.8	Type 3-3	5949.7	1.00	1.39	1.27	1.12	1.00	0.91	0.87	0.89
180	2941.7	Type 3-3	6383.5	1.00	1.40	1.28	1.13	1.01	0.91	0.88	0.86
190	3141.6	Type 3-3	6817.3	1.00	1.41	1.29	1.14	1.02	0.92	0.89	0.84
200	3341.5	Type 3-3	7251.1	1.00	1.42	1.30	1.15	1.03	0.93	0.89	0.82

Table 25. Rating factor—simple-span shear.

Single Span (ft.)	GOVERNING AASHTO LEGAL SHEAR	GOVERNING AASHTO LEGAL TRUCK	Available Live Load Capacity = 2.17x LL Shear	Rating Factors							
				Governing AASHTO Legal Load RF	AASHTO Type 3	T4A	T5A	T6A	T7A	BFT	HS20
10	**25.5**	**Type 3**	**55.34**	**1.00**	1.00	0.96	0.96	0.96	0.96	0.96	0.84
15	**28.3**	**Type 3**	**61.41**	**1.00**	1.00	0.89	0.85	0.85	0.85	0.85	0.88
20	**30.1**	**Type 3**	**65.32**	**1.00**	1.00	0.85	0.81	0.81	0.81	0.78	0.75
25	**34.1**	**Type 3**	**74.00**	**1.00**	1.00	0.87	0.83	0.83	0.83	0.80	0.76
30	**36.8**	**Type 3**	**79.86**	**1.00**	1.00	0.89	0.83	0.83	0.83	0.81	0.76
35	**38.7**	**Type 3**	**83.98**	**1.00**	1.00	0.89	0.82	0.81	0.81	0.80	0.75
40	**40.1**	**Type 3**	**87.02**	**1.00**	1.00	0.90	0.82	0.79	0.78	0.77	0.74
45	**41.4**	**Type 3-S2**	**89.84**	**1.00**	1.00	0.91	0.82	0.79	0.76	0.76	0.74
50	**42.1**	**Type 3-S2**	**91.36**	**1.00**	1.00	0.91	0.82	0.78	0.74	0.74	0.73
55	**47.0**	**Type 3-S2**	**101.99**	**1.00**	1.10	1.00	0.90	0.84	0.80	0.79	0.80
60	**49.1**	**Type 3-S2**	**106.55**	**1.00**	1.13	1.03	0.92	0.86	0.82	0.81	0.82
65	**50.8**	**Type 3-S2**	**110.24**	**1.00**	1.16	1.05	0.94	0.88	0.83	0.81	0.83
70	**52.3**	**Type 3-S2**	**113.49**	**1.00**	1.18	1.08	0.96	0.89	0.84	0.82	0.84
75	**54.0**	**Type 3-3**	**117.18**	**1.00**	1.21	1.10	0.98	0.91	0.85	0.83	0.86
80	**54.8**	**Type 3-3**	**118.92**	**1.00**	1.22	1.11	0.99	0.91	0.85	0.83	0.87
85	**57.0**	**Type 3-3**	**123.69**	**1.00**	1.26	1.15	1.02	0.94	0.87	0.86	0.89
90	**56.7**	**Type 3-3**	**123.04**	**1.00**	1.24	1.14	1.01	0.93	0.86	0.84	0.88
95	**59.5**	**Type 3-3**	**129.12**	**1.00**	1.30	1.19	1.05	0.97	0.89	0.88	0.92
100	**60.5**	**Type 3-3**	**131.29**	**1.00**	1.32	1.20	1.07	0.98	0.90	0.88	0.93
110	**62.3**	**Type 3-3**	**135.19**	**1.00**	1.34	1.23	1.09	1.00	0.92	0.90	0.95
120	**63.7**	**Type 3-3**	**138.23**	**1.00**	1.36	1.25	1.11	1.01	0.93	0.90	0.96
130	**65.0**	**Type 3-3**	**141.05**	**1.00**	1.39	1.27	1.12	1.02	0.94	0.91	0.98
140	**66.1**	**Type 3-3**	**143.44**	**1.00**	1.40	1.29	1.13	1.03	0.94	0.92	0.99
150	**67.0**	**Type 3-3**	**145.39**	**1.00**	1.41	1.30	1.15	1.04	0.95	0.93	1.00
160	**67.8**	**Type 3-3**	**147.13**	**1.00**	1.43	1.31	1.16	1.05	0.95	0.93	0.98
170	**68.5**	**Type 3-3**	**148.65**	**1.00**	1.44	1.32	1.16	1.05	0.96	0.93	0.95
180	**69.2**	**Type 3-3**	**150.16**	**1.00**	1.45	1.33	1.17	1.06	0.97	0.94	0.92
190	**69.7**	**Type 3-3**	**151.25**	**1.00**	1.46	1.34	1.18	1.06	0.97	0.94	0.88
200	**70.2**	**Type 3-3**	**152.33**	**1.00**	1.46	1.35	1.18	1.07	0.97	0.94	0.86

Table 26. Posting load—simple-span shear.

Single Span (ft.)	GOVERNING AASHTO LEGAL TRUCK	Posting Load in Tons							
		Governing AASHTO Legal Load RF	AASHTO Type 3	T4A	T5A	T6A	T7A	BFT	HS20
10	**Type 3**	**1.00**	25.0	25.8	29.6	33.2	37.0	38.2	30.20
15	**Type 3**	**1.00**	25.0	24.0	26.5	29.7	33.1	34.2	31.84
20	**Type 3**	**1.00**	25.0	23.0	25.0	28.0	31.3	31.0	27.09
25	**Type 3**	**1.00**	25.0	23.6	25.7	28.9	32.2	32.0	27.40
30	**Type 3**	**1.00**	25.0	23.9	25.6	28.8	32.1	32.5	27.37
35	**Type 3**	**1.00**	25.0	24.1	25.5	28.2	31.4	31.9	26.90
40	**Type 3**	**1.00**	25.0	24.3	25.4	27.6	30.2	31.0	26.59
45	**Type 3-S2**	**1.00**	25.1	24.5	25.5	27.4	29.5	30.3	26.47
50	**Type 3-S2**	**1.00**	25.0	24.4	25.3	26.9	28.8	29.5	26.22
55	**Type 3-S2**	**1.00**	27.5	26.9	27.8	29.3	31.1	31.8	28.63
60	**Type 3-S2**	**1.00**	28.3	27.7	28.6	30.0	31.7	32.2	29.36
65	**Type 3-S2**	**1.00**	28.9	28.5	29.2	30.5	32.1	32.6	29.93
70	**Type 3-S2**	**1.00**	29.5	29.1	29.7	31.0	32.4	32.8	30.42
75	**Type 3-3**	**1.00**	30.2	29.8	30.4	31.6	32.9	33.4	31.05
80	**Type 3-3**	**1.00**	30.4	30.0	30.6	31.7	32.9	33.4	31.22
85	**Type 3-3**	**1.00**	31.5	31.0	31.7	32.7	33.9	34.3	32.21
90	**Type 3-3**	**1.00**	31.1	30.7	31.3	32.3	33.3	33.7	31.84
95	**Type 3-3**	**1.00**	32.5	32.1	32.6	33.6	34.7	35.0	33.21
100	**Type 3-3**	**1.00**	32.9	32.5	33.0	34.0	34.9	35.3	33.56
110	**Type 3-3**	**1.00**	33.6	33.2	33.8	34.6	35.5	35.8	34.19
120	**Type 3-3**	**1.00**	34.1	33.8	34.3	35.0	35.9	36.1	34.69
130	**Type 3-3**	**1.00**	34.6	34.3	34.7	35.5	36.2	36.5	35.14
140	**Type 3-3**	**1.00**	35.0	34.8	35.1	35.8	36.6	36.8	35.57
150	**Type 3-3**	**1.00**	35.3	35.1	35.5	36.2	36.8	37.0	35.84
160	**Type 3-3**	**1.00**	35.7	35.4	35.8	36.4	37.0	37.3	35.32
170	**Type 3-3**	**1.00**	35.9	35.7	36.1	36.6	37.2	37.4	34.11
180	**Type 3-3**	**1.00**	36.2	36.0	36.3	36.8	37.4	37.6	32.95
190	**Type 3-3**	**1.00**	36.4	36.2	36.5	37.0	37.5	37.7	31.84
200	**Type 3-3**	**1.00**	36.6	36.4	36.6	37.1	37.6	37.8	30.82

Table 27. Live-load reactions on transverse floorbeams.

STRINGER SPAN (FT)	TYPE OF LOADING										Governing FBF	Ratio = FBF/AASHTO LEGAL	Ratio = Governing FBF/Truck BFT
	TYPE 3	TYPE 3S2	TYPE 3-3	Governing AASHTO Legal	HS-20	T4A	T5A	T6A	T7A	BFT			
10	13.6	12.4	11.2	13.6	16.0	16.0	16.8	17.6	17.6	17.6	17.6	1.29	1.00
11	13.9	12.7	11.5	13.9	16.0	16.5	17.5	18.6	18.6	18.6	18.6	1.34	1.00
12	14.2	13.1	11.7	14.2	16.0	16.8	18.2	19.5	19.5	19.5	19.5	1.37	1.00
13	14.4	13.7	11.9	14.4	16.0	17.2	18.7	20.2	20.5	20.2	20.5	1.42	1.01
14	14.6	14.2	12.0	14.6	16.0	17.4	19.1	20.9	21.4	20.9	21.4	1.47	1.02
15	14.8	14.6	12.2	14.8	17.3	18.1	19.5	21.4	22.2	21.4	22.2	1.50	1.04
16	15.3	15.0	12.3	15.3	18.5	18.6	19.9	21.9	22.9	21.9	22.9	1.50	1.05
17	15.8	15.4	12.7	15.8	19.5	19.1	20.2	22.3	23.5	22.3	23.5	1.49	1.05
18	16.4	15.6	13.3	16.4	20.4	19.6	20.4	22.7	24.0	23.0	24.0	1.46	1.04
19	16.8	15.9	13.7	16.8	21.3	19.9	21.0	23.3	24.8	23.7	24.8	1.48	1.05
20	17.2	16.1	14.2	17.2	22.0	20.3	21.5	23.9	25.5	24.3	25.5	1.48	1.05
21	17.6	16.3	14.5	17.6	22.7	20.6	22.0	24.4	26.1	24.8	26.1	1.48	1.05
22	18.0	16.5	14.9	18.0	23.3	20.9	22.4	24.9	26.7	25.3	26.7	1.48	1.06
23	18.3	16.7	15.2	18.3	23.8	21.2	22.7	25.3	27.2	26.0	27.2	1.49	1.05
24	18.5	16.9	15.5	18.5	24.3	21.4	23.1	25.7	27.7	26.6	27.7	1.50	1.04
25	18.8	17.0	15.7	18.8	24.8	21.6	23.4	26.1	28.1	27.1	28.1	1.49	1.04
26	19.0	17.5	16.2	19.0	25.2	21.8	23.7	26.4	28.5	27.6	28.5	1.50	1.03
27	19.3	18.2	16.8	19.3	25.6	22.0	24.0	26.7	28.9	28.1	28.9	1.50	1.03
28	19.5	18.8	17.5	19.5	26.0	22.2	24.2	27.0	29.3	28.5	29.3	1.50	1.03
29	19.7	19.4	18.0	19.7	26.3	22.4	24.4	27.3	29.6	28.9	29.6	1.50	1.02
30	19.9	20.1	18.8	20.1	26.7	22.5	24.7	27.5	29.9	29.3	29.9	1.49	1.02

Development of Candidate Non-Formula B Legal Loads

From the data set of non-Formula B trucks described in the Survey of States section in Chapter 2, certain trucks were identified as being the more severe in their class, based upon the excess load over the FBF limit (see Table 28 and Figure 23).

The suite of single-unit non-Formula B legal truck models with three or four axles includes configurations commonly seen in several state legal and posting loads (see Figure 23). Rating and posting loads aim to use only a limited number of truck models to envelop and represent the most severe loadings of vehicles. It may be possible to identify a few vehicles among the load models that could serve as envelope vehicles for load effects induced by the suite of trucks. To develop these envelope vehicles and to verify that they will reliably exceed or envelop the force effects (moment and shear) induced by the suite of non-Formula B state posting loads, a test suite of simple- and continuous-span bridges was assembled. These bridges include simple spans from 10 ft to 200 ft and two-span continuous bridges with equal span lengths from 10 ft to 200 ft. A suite of three-span and four-span continuous bridges having span lengths from 10 ft to 200 ft with span ratios chosen to reflect actual bridge configurations was also assembled and analyzed. Maximum moments and shears were calculated for the suite of simple- and continuous-span bridges. Moment and shear ratios were computed for the governing force effects from the non-Formula B trucks and the NRL representative of Formula B trucks (see Chapter 4 for a description of the NRL). Detailed

Table 28. More severe non-Formula B trucks.

DOT	Truck Designation	No. of Axles	Total Spacing	Truck Weight (Kips)	FBF Limit for Gross Wt (K)	Excess Over FBF Limit (K)
Delaware	DE 3	3	16.83	70.00	48.60	21.40
Florida	SU3	3	15.17	66.00	47.40	18.60
Connecticut	Construction Vehicle T4	4	18.20	76.50	54.10	22.40
Delaware	DE 4	4	17.00	73.00	52.90	20.10
Florida	SU4	4	18.34	70.00	53.70	16.30
Pennsylvania	ML80	4	18.00	75.48	54.00	21.48

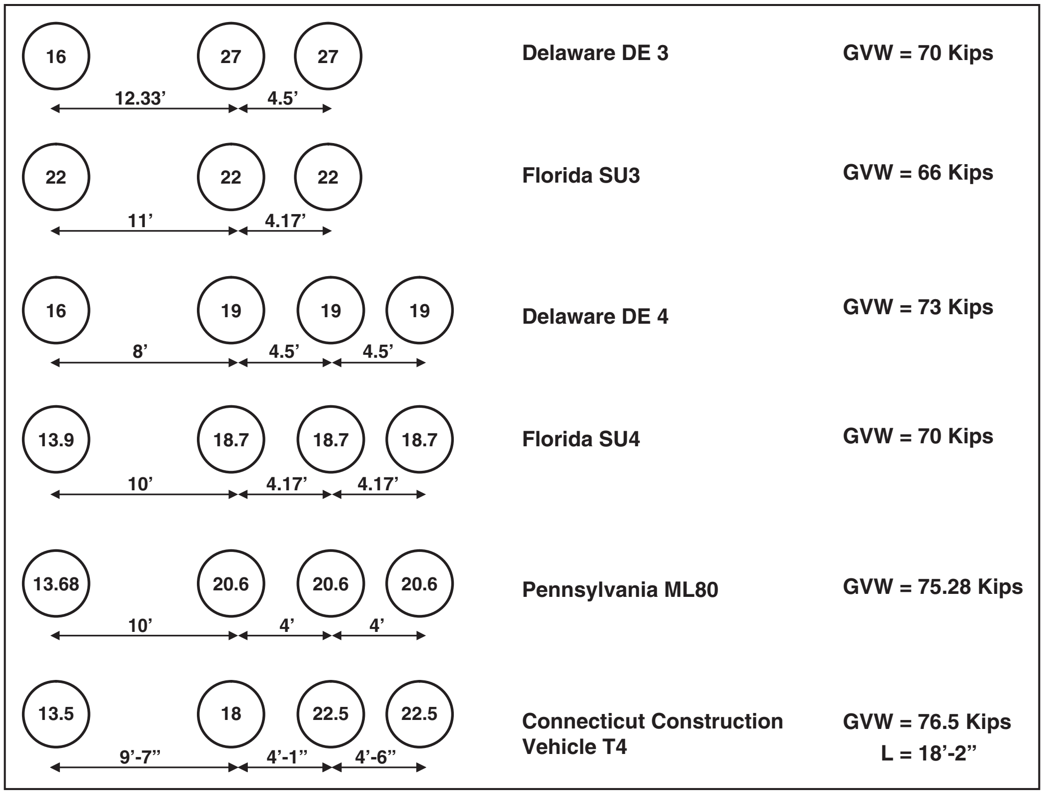

Figure 23. More severe non-Formula B trucks.

results of the analyses of generic spans for non-Formula B SHVs are contained in Appendix D. The governing load models (DE3 and T4) from the analysis of bridge spans are summarized in Table 29. These ratios serve as indicators of the level of overstress (or excess load effects) caused by the non-Formula B trucks when the posting is based solely on the NRL (see Table 30). Bridges having transverse members were also included in this study. Analysis results for floor-beam spacings from 10 ft to 30 ft in 1-ft increments are shown in Table 31.

Trucks Delaware DE3 and Connecticut T4 are the most severe of the family of three- and four-axle grandfather loads (see Figure 24). They can be used as representative of grandfather trucks, currently in use as state legal loads for rating and posting, for LRFR calibration and rating. The states can also use the calibrated load factor γ_L but apply a nominal loading based on their own non-Formula B truck. This will allow the states to post for their own grandfathered trucks by the LRFR process. Since there are many variations to federal weight law exclusions among the states, some flexibility in substituting state-specific grandfathered legal loads will be an important feature for national implementation. DE3 and T4 may be represented as two calibration trucks in the LRFR Manual that the states may use to benchmark their own vehicles.

Calibration of Live-Load Factors for SHV Trucks

Introduction

In load factor rating, all new legal trucks will adopt the same live-load factors as specified for the current AASHTO legal trucks. There will be no change in the live-load factor, safety factor, or any other aspect of the rating procedures specified in AASHTO's *MCE* (*1*). The sole change will be to add additional AASHTO legal loadings for the rating calculation. For LRFR evaluation, any new load models to be selected as described above may be used with their own district live-load factors, calibrated as part of the project activities. In LRFR it was found that for cases in which permit loads are being checked, a smaller live-load factor could be sufficient compared with live-load factors for routine high-traffic situations. It is expected that the heavy Formula B and non-Formula B SHVs that are a small percentage of the total traffic stream will fall in a category leading to reduced live-load factors.

The research approach herein will be to maintain consistency with the calibration carried out for the AASHTO LRFR specifications. This calibration is described in *NCHRP Report 454* (*16*). LRFR calibration focused on the 3S2 AASHTO legal load model (tractor-semi trailer) since it represents the major part of the truck traffic. The calibration involves taking the particular

Table 29. Governing load models for non-Formula B trucks.

Exterior Span (ft.)	Simple Spans				Two Span Continuous (Equal Spans)					
	Moment 3 Axle	Shear 3 Axle	Moment 4 Axle	Shear 4 Axle	Pos. Moment 3 Axle	Neg. Moment 3 Axle	Shear 3 Axle	Pos. Moment 4 Axle	Neg. Moment 4 Axle	Shear 4 Axle
10	DE3	DE3	Conn T4	Conn T4	DE3	SU3	DE3	HS20	Conn T4	Conn T4
15	DE3	DE3	Conn T4	Conn T4	DE3	DE3	DE3	Conn T4	Conn T4	Conn T4
20	DE3	DE3	Conn T4	Conn T4	DE3	DE3	DE3	Conn T4	Conn T4	Conn T4
25	DE3	DE3	Conn T4	Conn T4	DE3	HS20	DE3	Conn T4	Conn T4	Conn T4
30	DE3	DE3	Conn T4	Conn T4	DE3	HS20	DE3	Conn T4	HS20	Conn T4
35	DE3	DE3	Conn T4	Conn T4	DE3	HS20	DE3	Conn T4	HS20	Conn T4
40	DE3	DE3	Conn T4	Conn T4	DE3	HS20	DE3	Conn T4	HS20	Conn T4
45	NRL	DE3	Conn T4	Conn T4	DE3	HS20	DE3	Conn T4	HS20	Conn T4
50	NRL	DE3	Conn T4	Conn T4	NRL	HS20	DE3	Conn T4	HS20	Conn T4
55	NRL	DE3	Conn T4	Conn T4	NRL	HS20	DE3	Conn T4	HS20	Conn T4
60	NRL	DE3	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
65	NRL	DE3	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
70	NRL	DE3	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
75	NRL	NRL	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
80	NRL	NRL	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
85	NRL	NRL	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
90	NRL	NRL	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
95	NRL	NRL	Conn T4	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
100	NRL	NRL	NRL	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
110	NRL	NRL	NRL	Conn T4	NRL	HS20	NRL	Conn T4	HS20	Conn T4
120	NRL	NRL	NRL	Conn T4	NRL	HS20	NRL	NRL	HS20	NRL
130	NRL	NRL	NRL	Conn T4	NRL	HS20	HS20	NRL	HS20	NRL
140	NRL	NRL	NRL	Conn T4	NRL	HS20	HS20	NRL	HS20	NRL
150	NRL	NRL	NRL	Conn T4	NRL	HS20	HS20	NRL	HS20	NRL
160	NRL	NRL	NRL	Conn T4	NRL	HS20	HS20	NRL	HS20	NRL
170	NRL	NRL	NRL	Conn T4	NRL	HS20	HS20	NRL	HS20	NRL
180	HS20	HS20	HS20	HS20	NRL	HS20	HS20	NRL	HS20	NRL
190	HS20	HS20	HS20	HS20	HS20	HS20	HS20	NRL	HS20	NRL
200	HS20	HS20	HS20	HS20	HS20	HS20	HS20	NRL	HS20	NRL

Exterior Span (ft.)	Three Span Continuous (Ext. Span=0.8xInt Span)						Four Span Continuous (Ext. Span=0.8xInt Span)					
	Pos. Moment 3 Axle	Neg. Moment 3 Axle	Shear 3 Axle	Pos. Moment 4 Axle	Neg. Moment 4 Axle	Shear 4 Axle	Pos. Moment 3 Axle	Neg. Moment 3 Axle	Shear 3 Axle	Pos. Moment 4 Axle	Neg. Moment 4 Axle	Shear 4 Axle
10	HS20	SU3	DE3	HS20	HS20	Conn. T4	HS20	HS20	DE3	HS20	HS20	Conn. T4
15	DE3	HS20	DE3	Conn. T4	HS20	Conn. T4	DE3	HS20	DE3	Conn T4	HS20	Conn. T4
20	DE3	HS20	DE3	Conn. T4	HS20	Conn. T4	DE3	HS20	DE3	Conn T4	HS20	Conn. T4
25	DE3	HS20	DE3	Conn. T4	Conn. T4	Conn. T4	DE3	HS20	DE3	Conn T4	Conn. T4	Conn. T4
30	DE3	HS20	DE3	Conn. T4	Conn. T4	Conn. T4	DE3	HS20	DE3	Conn T4	Conn. T4	Conn. T4
35	DE3	HS20	DE3	Conn. T4	Conn. T4	Conn. T4	DE3	HS20	DE3	Conn T4	Conn. T4	Conn. T4
40	DE3	HS20	DE3	Conn. T4	Conn. T4	Conn. T4	DE3	HS20	DE3	Conn T4	HS20	Conn. T4
45	NRL	HS20	DE3	Conn. T4	Conn. T4	Conn. T4	NRL	HS20	DE3	Conn T4	HS20	Conn. T4
50	NRL	HS20	DE3	Conn. T4	HS20	Conn. T4	NRL	HS20	DE3	Conn T4	HS20	Conn. T4
55	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
60	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
65	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
70	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
75	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
80	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
85	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
90	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
95	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	Conn T4	HS20	Conn. T4
100	NRL	HS20	NRL	Conn. T4	HS20	Conn. T4	NRL	HS20	NRL	NRL	HS20	Conn. T4
110	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20
120	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20
130	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20
140	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20
150	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20	NRL	HS20	HS20
160	NRL	HS20	HS20	NRL	HS20	HS20	HS20	HS20	HS20	HS20	HS20	HS20
170												
180												
190												
200												

Table 30. Maximum overstress ratios.

Force Effect	*Maximum Overstress Ratio = DE3 / NRL or HS20*	*Maximum Overstress Ratio = T4 / NRL or HS20*
Simple-Span Bending	1.45	1.27
Simple-Span Shear	1.47	1.29
Two-Span Cont. Positive Bending	1.50	1.28
Two-Span Cont. Negative Bending	1.11	1.25
Two-Span Cont. Shear	1.40	1.24
Three-Span Cont. Positive Bending	1.47	1.35
Three-Span Cont. Negative Bending	1.11	1.13
Three-Span Cont. Shear	1.42	1.33
Four-Span Cont. Positive Bending	1.46	1.33
Four-Span Cont. Negative Bending	1.05	1.04
Four-Span Cont. Shear	1.40	1.30

Table 31. Live-load reactions on transverse floorbeams.

STRINGER SPAN (FT)	TYPE OF LOADING									
	TYPE 3	TYPE 3S2	TYPE 3-3	Governing AASHTO Legal	HS-20	DE3	SU3	T4	SU4	Governing Grandfather Truck -- T4
10	13.6	12.4	11.2	*13.6*	16.0	20.9	17.4	22.8	20.3	22.8
11	13.9	12.7	11.5	*13.9*	16.0	21.5	17.8	23.6	21.0	23.6
12	14.2	13.1	11.7	*14.2*	16.0	21.9	19.1	23.2	21.6	23.2
13	14.4	13.7	11.9	*14.4*	16.0	22.7	20.2	24.8	22.1	24.8
14	14.6	14.2	12.0	*14.6*	16.0	23.6	21.1	25.4	22.5	25.4
15	14.8	14.6	12.2	*14.8*	17.3	24.4	21.9	26.3	23.2	26.3
16	15.3	15.0	12.3	*15.3*	18.5	25.0	22.6	27.0	24.0	27.0
17	15.8	15.4	12.7	*15.8*	19.5	25.6	23.2	27.7	24.6	27.7
18	16.4	15.6	13.3	*16.4*	20.4	26.2	23.7	28.3	25.2	28.3
19	16.8	15.9	13.7	*16.8*	21.3	26.6	24.2	28.8	25.7	28.8
20	17.2	16.1	14.2	*17.2*	22.0	27.0	24.7	29.3	26.2	29.3
21	17.6	16.3	14.5	*17.6*	22.7	27.4	25.1	29.7	26.6	29.7
22	18.0	16.5	14.9	*18.0*	23.3	27.8	25.4	30.1	27.0	30.1
23	18.3	16.7	15.2	*18.3*	23.8	28.1	25.7	30.4	27.3	30.4
24	18.5	16.9	15.5	*18.5*	24.3	28.4	26.1	30.8	27.7	30.8
25	18.8	17.0	15.7	*18.8*	24.8	28.6	26.3	31.1	27.9	31.1
26	19.0	17.5	16.2	*19.0*	25.2	28.9	26.6	31.3	28.2	31.3
27	19.3	18.2	16.8	*19.3*	25.6	29.1	26.8	31.6	28.5	31.6
28	19.5	18.8	17.5	*19.5*	26.0	29.3	27.0	31.8	28.7	31.8
29	19.7	19.4	18.0	*19.7*	26.3	29.5	27.3	32.1	28.9	32.1
30	19.9	20.1	18.8	*20.1*	26.7	29.7	27.4	32.3	29.1	32.3

AASHTO legal load model and determining a corresponding live-load factor. This factor is established at the code-writing stage to satisfy the target safety index for the LRFR.

The goals of uniform reliability in the rating process were maintained in this project by directly and independently calibrating the ratings for a series of bridges, which are influenced by the heavy shorter trucks (SHVs). Distinct live-load factors for different site conditions and traffic are already part of the LRFR procedures; thus, there should be no confusion for rating engineers to consider different live-load factors for the SHV-based legal load models. This is not the case for ASR and LFR ratings, which have fixed criteria and load factors in all cases.

The ASHTO LRFR Manual for rating maintains the same philosophy as the AASHTO LRFD Bridge Design Specifications now adopted by most states for routine practice in design of new bridge structures. The LRFR Manual uses much of the same statistics as the AASHTO LRFD Design Specifications, but also accounts for some of the site-specific properties of the bridge being rated including truck traffic volume and current bridge inventory properties. Unlike the *MCE* (*1*), there is not a distinction in the LRFR Manual based on inventory and operating ratings. Rather, a single rating is determined that achieves the target safety index for the bridge being rated. The target safety index is similar to the average reliability found for different spans, which just satisfies the operating criteria.

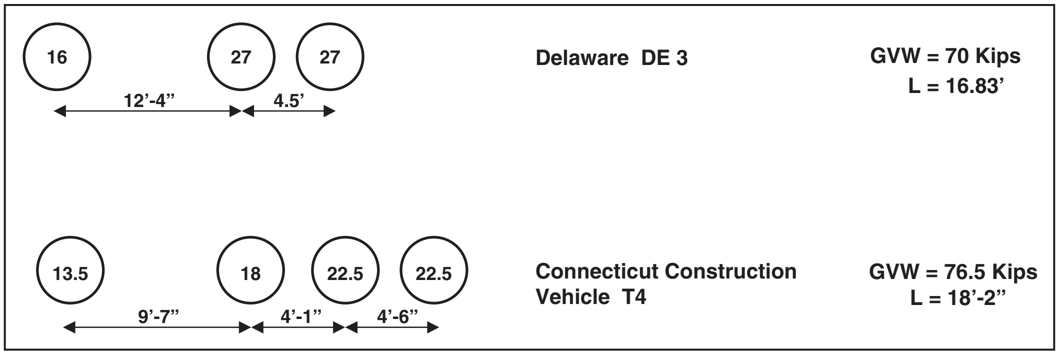

Figure 24. Governing non-Formula B trucks.

To make it easier for bridge engineers to use the new reliability concepts in design or evaluation, the probabilistic background of the codes is made transparent to users of the code. Engineers work directly with factored load effects and factored strength calculations in what appears as a deterministic check of safety.

In the present study, the focus is on calibration for SHVs satisfying Formula B and for those exceeding Formula B limits. It will not be necessary to use the same load factor as applied to the 3S2 legal load model in LRFR, but rather a new calibration was performed for the SHVs. The load factor will be fixed for any new legal load covering the SHV range in order to meet the target reliability level defined in LRFR for evaluation.

Calibration Approach

Safety Criteria

Code calibration is the process for choosing live- and dead-load factors and resistance factors for tabulation in a specification that checks structural components. In reliability-based formats such as the AASHTO LRFD or LRFR, the criteria for selecting factors is to achieve a uniform target reliability. In the AASHTO LRFD development, the checking format was calibrated to produce uniform reliability comparable with the average reliability inherent in a group of "good" designs. In NCHRP Project 12-46, the AASHTO LRFR Manual was calibrated to achieve rating reliabilities consistent with existing AASHTO operating safety criteria.

The reliability level in a design depends on the statistical database describing live- and dead-load effects and the strength of components. For the calibration of the LRFD design format, a very severe truck loading regime was used. It consisted of some 10,000 heavy trucks weighed at a static station in Ontario during the 1970s. The corresponding traffic volume was taken as ADTT of 5,000 corresponding to a very severe truck volume. The extreme load effects determined by simulation occurred when there were multiple presences on a bridge span of more than one heavy truck, especially where numerous events occurred with trucks side by side while crossing the span.

Using this severe loading environment, it was determined that uniform reliability for different bridge spans and geometries would be achieved using the HL-93 load model. The target reliability index was taken as 3.5 after reviewing reliability or safety indexes computed for the array of "good" bridge designs mentioned above. The target safety index of 3.5 is not intended to reflect any actual risk, nor was it an input to the calibration process; rather, the 3.5 target index was a direct consequence of the statistical parameters used to model dead, live, and resistance effects in this array of bridge designs.

It should be noted that the HL-93 model also uniformly envelops the AASHTO legal loads (a ratio close to 1.77). In the LRFR calibration, the nominal rating checks could use the HL-93 for a design load rating and also the AASHTO legal loads for legal load rating and posting requirements. For the severe traffic case of 5,000 ADTT, a live-load factor of 1.8 was calibrated to correspond to operating levels. The corresponding target safety indexes were in the range of 2.3 to 2.5. Again, it should be emphasized that the so-called "target safety indexes" reflect the database used as well as the array of "good" designs and is not based on any target actuarial values.

Maximum Expected Live Load, L_{max}

The development of the live-load factors in the LRFR for routine traffic and for checking permits and SHVs used the Ontario truck weight database as a reference. This led to the live-load factor γ_L of 1.8 for the severe (5,000 ADTT) traffic sites. It is unnecessary to repeat the safety index calculations for other traffic volume or truck weight regimes, such as the SHVs; rather, uniform reliability for the checking format can be maintained as follows:

1. For any given truck weight statistics and truck traffic volume, compute the maximum expected live load. This is denoted as L_{max}.

2. Compare the value of L_{max} with a reference value of L_{max} based on the extreme traffic regime just cited, namely the Ontario weight data and the 5,000 ADTT. This reference value of L_{max} is denoted as $L_{max,ref}$. The corresponding live-load factor for the reference case ($\gamma_{L,ref}$) is 1.8. Details of the derivation can be found in the calibration report for this project, and *NCHRP Report 454* (*16*) details the calibration of the factors in the AASHTO LRFR Manual.
3. The corresponding live-load factor γ_L for any other given traffic situation is then

$$\gamma_L = \left[\gamma_{L,ref}\right]\frac{L_{max}}{L_{max,ref}}. \tag{1}$$

4. The required live-load factor to satisfy the target reliability index is proportional to L_{max}, the expected maximum live-load effect for that traffic situation. The reason for this simple ratio is that the calculation of the safety index depends on the ratio of the mean value of resistance divided by the mean value of load. Keeping this ratio fixed keeps the safety index constant. Raising the live-load factor raises the mean resistance needed to achieve a rating factor of 1.0. If the live-load factor is made proportional to the expected live load, then the ratio of resistance and load is constant, so the safety index is kept constant. More details of this observation are provided in the NCHRP Project 12-63 calibration report, Part A (see Appendix G).

Truck Weight Data

The next step in the calibration process is to determine the value of L_{max} for the reference case and for the SHV traffic situation for which a live-load factor must be calibrated. The truck weight statistics for the reference case are the Ontario data used in the LRFD calibration. These data represented the best database available at the time the LRFD was being formulated. (Recent advances in WIM and other data-gathering studies should improve the database; however, it is not possible to merely substitute a "better" database to calibrate γ_L. In that situation, the entire AASHTO code calibration study must be redone, including the derivation of a target safety index based on an array of "good" designs.)

The Ontario data can be summarized as follows: the top 20% of trucks can be assumed to follow a normal distribution for load effects (moment and shears). The contribution to L_{max} from the remainder of the population can be ignored. By examining both short and longer spans, it was observed that the top 20% of the Ontario data can be modeled by the same parameters—namely, a mean equal to 0.95 times the legal load effect and a COV (standard deviation divided by the mean) of 25%. The fitting of these two parameters is reported in *NCHRP Report 454* (*16*) and in Part B of the NCHRP Project 12-63 calibration report (see Appendix G). In the absence of other site-specific data, these two parameters—the 0.95 ratio of mean and legal denoted as the bias—and the COV of 25% should be used. Comparison of the bias and COV for other sites recorded as part of this project are discussed in Part C of the calibration report.

Multiple-Presence Modeling

Besides the description of the truck weight data, the other important characteristic of the truck traffic is the multiple presence—that is, what is the likelihood of two heavy trucks moving side by side across a span and thereby magnifying the live-load effect? It was found in simulations by Nowak (*14*) that side-by-side loading events controlled the maximum live-load effect. Since available multiple-presence data for high-traffic volumes is scarce, Nowak assumed that 1 in 15 heavy-truck crossings is accompanied by a heavy truck alongside it. In fact, if all trucks are included, this means that a heavy truck crossing is accompanied by a second truck alongside, either heavy or not, in 1 of 3 crossings. The only available multiple-presence data were that of Moses and Ghosn (*15*), but included volumes up to about 2,000 ADTT. For the latter case, about a 1% multiple presence was applicable. Since multiple-presence data were not available for a 5,000-ADTT site, Nowak's assumption for the AASHTO LRFD derivation was also used for the AASHTO LRFR calibration. Field WIM data collected in Phase II of this project validated multiple-presence probabilities of around 1% to 2%, even for very high ADTT. Nevertheless, since it affects Nowak's calibration and the selection of a target safety index, a change in multiple-presence value for the high-volume case is not warranted in the present study.

Thus, the present LRFR calibration of live-load factors uses multiple-presence percentages p_{sxs}, for heavy trucks of

- 1/15 for 5,000 ADTT,
- 1% for 1,000 ADTT, and
- 0.001 for 100 ADTT.

Live-Load Modeling

The next step in the calibration is to calculate L_{max}. Four traffic cases are considered in NCHRP Project 12-63 in order to determine the most severe loading case:

1. Single-lane loads,
2. Multiple presence of routine trucks,
3. An SHV alongside an SHV, and
4. An SHV alongside a routine truck.

The calibration steps in each case are as follows:

1. Find N, the number of repetitions of the loading during the exposure period (e.g., evaluation interval).
2. Compute the normal distribution fractile, t, from the normal distribution probability table corresponding to a cumulative probability of $(1-1/N)$.
3. Express the mean loading and the standard deviation for the load case being considered.
4. The maximum expected load L_{max} is

$$L_{max} = \text{Mean} + t\ (\text{standard deviation}). \tag{2}$$

5. Normalize Equation 2 in terms of the load bias, COV, and nominal legal load L_{legal} as follows:

$$\frac{L_{max}}{L_{legal}} = \text{Bias}\left[1 + t(\text{COV})\right] \tag{2'}$$

where

L_{max} = the expected maximum load during the exposure period;
t = the variate based on the corresponding number of load events, N;
L_{legal} = the corresponding maximum legal truck load for the jurisdiction; and
COV = the coefficient of variation of the truck weights, typically 25%.

6. Use Equation 1 to give the corresponding live-load factor γ_L applied to the AASHTO legal load model. Next, adjust γ_L using Equation 3 below if the nominal load check uses the SHV load model or some other loading model such as the non-FBF model.

The statistics for routine trucks are described by the Ontario data mentioned above. When checking for routine trucks, the nominal loads in the AASHTO LRFR are the family of three AASHTO legal trucks—namely, the Type 3, Type 3S2, and Type 3-3. When checking the SHV or other legal loads in excess of the AASHTO legal loads (e.g., the non-Formula B SHV situation considered in Phase II of this project), the nominal load becomes the corresponding legal load. In that case, the live-load factor γ_{SHV} used to factor the SHV load becomes

$$\gamma_L = \gamma_{SHV} = \left[\gamma_{L,ref}\right]\frac{\bar{L}}{\alpha \bar{L}_{ref}} \tag{3}$$

where α is the ratio of SHV load effect compared with the AASHTO legal load used as the reference load for rating. Because of this ratio, α, which is usually greater than 1.0, it is possible for the live-load factors for the SHV checking to fall below the live-load factors for routine rating. That is, the increase in the expected maximum load for the SHV loading case does not increase as much as the nominal load effects of the SHV model. Since the nominal load for SHV checking is the SHV envelope model, the live-load factor may in some cases be relaxed relative to the live-load factor for the routine checks given in the LRFR Manual. The same observation was made for checking the non-Formula B load models.

Selection of Codified Factors

All four load cases described above were checked in the NCHRP Project 12-63 calibration study to calculate respective γ_L for different truck volume; ADTT; SHV volume, N(SHV); and also a different ratio, α. The governing load case between one- and two-lane cases also depends on the ratio of girder distribution factors (g_m/g_1) for one- and two-lane cases, respectively. Since the tabulation of live-load factors in the LRFR must be easy to apply, a number of trials was made to simplify a table of acceptable recommended live-load factors.

Thus, γ_L s for the ADTT values of 5,000, 1,000, and 100 that are tabulated in the LRFD were considered in the NCHRP Project 12-63 study with different numbers of SHV volume, N(SHV), as low as 20 and as high as 2,000 per day. The range of load ratios α—a parameter that does not directly appear in the LRFR Manual—was studied from a value of 1.0 up to a maximum ratio of 2.0. The range of girder distribution factor (DF) considered was based on recent AASHTO analyses methods and is described and compared in *NCHRP Report 454* (*16*). DF ratios of 1.5 and 1.7 are discussed in Part C of the calibration report (see Appendix G). All this information was reviewed by the research team, and, based on these results, recommendations for tabulated γ_L to cover the SHV checks were made to the NCHRP Project 12-63 Panel.

As additional WIM data become available, more precise γ_L can be determined with the formulations described above. In particular, the NCHRP Project 12-63 WIM studies in Idaho, Ohio, and Michigan observed bias values for the top 20% of trucks from 1.03 to 1.21 compared with the 0.95 from the Ontario data. This mean truck load increase, however, was balanced by COV values in the range of 6% to 20% compared with the 25% for Ontario data. Overall, as shown in comparisons in the calibration Report, Part C, L_{max} based on this new WIM data averaged closely to the value predicted from the Ontario data. However, the multiple-presence value, p_{sxs}, from the new WIM data was significantly below the value used by Nowak (*14*) in the AASHTO LRFR and will be further studied in the future.

Simulation Study

A Monte Carlo simulation was performed to validate the approach used to project the existing WIM data and to estimate the expected maximum load effect for two side-by-side SHVs. This study is presented in Appendix E.

Non-Formula B Trucks

Phase I of the project provided calibration of live-load factors appropriate for jurisdictions that satisfy the Formula B trucks. In Phase II the calibration was extended to the jurisdictions that exceed the Formula B limits for SHV trucks. Studies have identified state legal trucks DE3 (Delaware) and T4 (Connecticut) as the most severe of the family of three- and four-axle grandfather loads. The overstress ratios ranged from 1.05 to 1.50 for DE3 and from 1.04 to 1.35 for T4. This clearly demonstrates the significant overstress that will result from non-Formula B trucks in spans load rated using either HS20 or the NRL load model specified for Formula B vehicles (see Chapter 4).

These trucks define the "upper bound non-Formula B trucks" used in the calibration of load factors for rating and posting. It is likely that in any given jurisdiction, the agency will use its respective maximum non-formula B truck as the nominal loading. The load factors calibrated for the "worst" cases in this project can be used with these less severe state loads. DE3 and T4 may be represented as two calibration trucks in the LRFR Manual that the states may use to benchmark their own vehicles. Since there are many variations to federal weight law exclusions among the states, some flexibility in substituting state-specific grandfathered legal loads will be an important feature for national implementation. The Delaware Truck DE3 has been renamed as EX-3. The Connecticut construction vehicle T4 has been renamed as EX-4. The "EX" prefix was chosen to signify that these vehicles are "exclusion" trucks (see Chapter 4).

Calibration Report

A report on the calibration of the LRFR live-load factors for the SHV trucks is included in Appendix G. The calibration report discusses the derivation of the LRFR load factors for the proposed rating and posting loads. The report also includes a discussion of the impact of the recommended loads and load factors on rating and posting practices in AASHTO's *MCE* (*1*) and LRFR Manual (*2*).

The calibration report is composed of three parts. Part A includes background material on reliability-based calibration of evaluation load models to assist readers not familiar with the basics of code calibrations. Part B of the report covers the calibration of live-load factors for Formula B SHV trucks. Part C covers the calibration of non-Formula B trucks, which operate in jurisdictions that are exempt from the FBF requirements. The methodology is the reliability-based calibration used for the AASHTO LRFD and LRFR specifications. The database for the calibration is the same as in the LRFR Manual except that the live-load effect is modified to reflect the presence of the SHV trucks. Comparisons are given of the maximum expected live-load effect of side-by-side SHV and random trucks. The largest ratio of load effects for the worst Formula B SHV model to the AASHTO legal model was about 1.50. For high volumes of SHVs, the governing load effect is controlled by side-by-side SHVs crossing a bridge span. For low volumes of SHVs, the maximum loading is similar to a special permit crossing with the maximum load effect due to an SHV alongside a random truck. A table of live-load factors is provided in the calibration report for sites with different ADTT and volumes of SHV.

Available traffic data at this time may not support the estimation of SHV traffic at a site. This situation is addressed in the calibration manual through the use of conservative estimates of SHV traffic as a percentage of site ADTT. For sites with unknown volume of SHVs, the load factors given in Table 32 are compared with the current LRFR load factors for AASHTO legal trucks (Type 3, Type 3S2, and Type 3-3).

Table 32. LRFR live-load factors for Formula B SHVs.

Traffic Volume (One direction)	*Load Factor for AASHTO Legal Loads*	*Recommended Load Factors for Formula B SHV*
ADTT > 5,000	1.80	1.60
ADTT = 1,000	1.65	1.40
ADTT < 100	1.40	1.15

CHAPTER 4

Conclusions and Suggested Research

Conclusions

SHVs such as dump trucks, construction vehicles, and other hauling vehicles with short wheelbases are a mainstay in many segments of the economy. Newer truck configurations with short-wheelbase multiple axles have allowed these trucks to carry the maximum load of up to 80,000 lbs and still meet the Formula B requirements. As they comply with all federal weight laws, these trucks are allowed unrestricted operation. Although the federal weight limits generally apply both on and off the Interstate system, only seven states apply the federal limits statewide without modification or "grandfather right" adjustment. Many states currently exempt hauling trucks from the FBF under "grandfather rights," mostly on non-Interstate routes. Over the years, special exemptions to the federal weight limits have been enacted for individual states, sometimes applying only to the transportation of specific commodities that are important to the state economy.

The objective of this research was to investigate the recent developments in specialized truck configurations and state legal loads and to prepare draft recommended revisions to AASHTO's *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating* (*LRFR*) *of Highway Bridges* (*2*). The revisions cover recommended load models and load factors for single-unit trucks meeting Formula B (Phase I) and those not meeting Formula B (Phase II). Recommended revisions to the AASHTO Manuals from Phases I and II and illustrative examples—the primary products of this research—are included in Appendix E. All appendixes for this report are available on the NCHRP Project 12-63 website (www.trp.org/crp/nchrp/nchrp.asp). At the 2005 AASHTO Bridge Meeting, the Subcommittee on Bridge Structures adopted the recommended revisions to the AASHTO Manuals developed under NCHRP Project 12-63 Phase I. At this meeting, AASHTO also adopted the LRFR Manual to replace the 1994 *MCE* (*1*) and to adopt it as *The Manual for Bridge Evaluation*. The new manual for bridge evaluation will include the new legal load models for Formula B SHVs adopted at the 2005 AASHTO Bridge Meeting.

Proposed Revisions to the AASHTO Evaluation Manuals

A summary of the proposed revisions to the *AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating* (*LRFR*) *of Highway Bridges* (*2*) contained in Appendix F is as follows:

1. Vehicles considered to be representative of the newer Formula B configurations were investigated through the analysis of recent WIM data and survey data of state legal loads obtained from the states. Based on this study, a NRL has been recommended as a single-load model for load rating bridges for all likely Formula B truck configurations (see Figure 25). These SHV trucks cause force effects that exceed the stresses induced by HS20 in bridges by up to 22% and by the Type 3, 3S2, or 3-3 posting vehicles by over 50% in certain cases. The shorter bridge spans are most sensitive to the newer SHV axle configurations. The NRL represents a single-load model that will envelop the load effects on simple- and continuous-span bridges of the worst possible Formula B single-unit truck configurations with multiple axles up to 80 Kips. It is called "notional" because it is not intended to represent any particular truck. In the NRL loading, axles that do not contribute to the maximum load effect under consideration shall be neglected. Bridges that rate for the NRL loading will have adequate load capacity for all legal Formula B truck configurations up to 80 Kips.
2. For bridges that do not rate for the NRL loading, a posting analysis should be performed to resolve posting requirements for single-unit multi-axle trucks. While a single envelope NRL can provide considerable simplification of load rating computations, additional legal loads

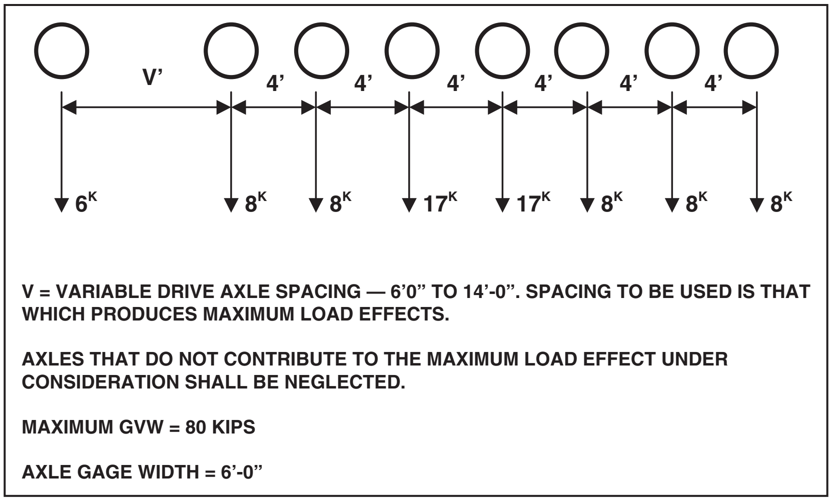

Figure 25. NRL for single-unit SHVs that meet Formula B requirements.

for posting are needed to give more accurate posting values. Certain multi-axle Formula B configurations that cause the highest load effects appear to be common only in some states, and they should not lead to reduced postings in all states. Further, some states may have specific rules that prohibit certain Formula B configurations. Bridges that do not rate for the NRL loading representative of Formula B trucks should be investigated to determine posting needs using a suite of new single-unit (SU) posting loads SU4, SU5, SU6, SU7 specified (see Figure 26). These SU trucks were developed to model the extreme loading effects of SU SHVs with four or more axles. This series of loads affords the evaluator the flexibility of selecting only posting loads that model commercial Formula B trucks in a particular state or jurisdiction.

3. Generalized live-load factors for the Strength I limit state are given in Table 33 for the NRL and posting loads for SHVs satisfying Formula B. The live-load factors were determined by reducing the target beta level from the design level of 3.5 to the corresponding operating level of 2.5, according to *NCHRP Report 454* (*16*), which describes the calibration of LRFR live-load factors. The live-load factors provided in Table 33 account for the multiple presence of two heavy trucks side by side on a multi-lane bridge as well as the probability that trucks may be loaded in such a manner that they exceed the corresponding legal limits. Since there are typically fewer SHVs than routine commercial trucks in the traffic stream, the live-load factors in Table 33 are appreciably smaller than the corresponding factors for routine commercial traffic represented by the three AASHTO legal loads. A more refined table of γ_L values based on both ADTT and the volume of SHVs is given in the NCHRP Project 12-63 calibration report included in Appendix G.
4. The vehicles referred to as "exclusion vehicles" are SU short-wheelbase trucks weighing up to 80 Kips that do not meet the weight guidelines of FBF B. Trucks EX-3 and EX-4 (see Figure 27) represent typical upper-bound SU exclusion vehicles currently in use as state legal loads in states that exempt SHVs from the Bridge Formula under the grandfather rights. SU trucks EX-3 and EX-4 have been specified as two calibration trucks for deriving the LRFR load factors for exclusion vehicles. Trucks EX-3 and EX-4 may be used as representative exclusion vehicles for load-rating bridges. The states can also use the calibrated load factors, but apply a nominal loading based on their own exclusion vehicles. Since there are many variations to federal weight law exclusions among the states, some flexibility in substituting state-specific grandfathered legal loads is an important feature for national implementation of LRFR procedures for exclusion vehicles.
5. Generalized live-load factors for the Strength I limit state as given in Table 34 have been calibrated for these exclusion vehicles. The live-load factors in Table 34 were determined by reducing the target beta level from the design level of 3.5 to the corresponding operating level of 2.5, according to *NCHRP Report 454* (*16*), which describes the calibration of LRFR live-load factors. The live-load factors provided in Table 34 account for the multiple presence of two heavy trucks side by side on a multi-lane bridge as well as the probability that trucks may be loaded in such a manner that they exceed the corresponding legal limits. Since there are typically fewer exclusion vehicles than routine commercial trucks in the traffic stream, the live-load factors in Table 34 are appreciably smaller than the corresponding factors for routine commercial traffic. A more refined table of γ_L values based on both ADTT and the volume of SHVs is

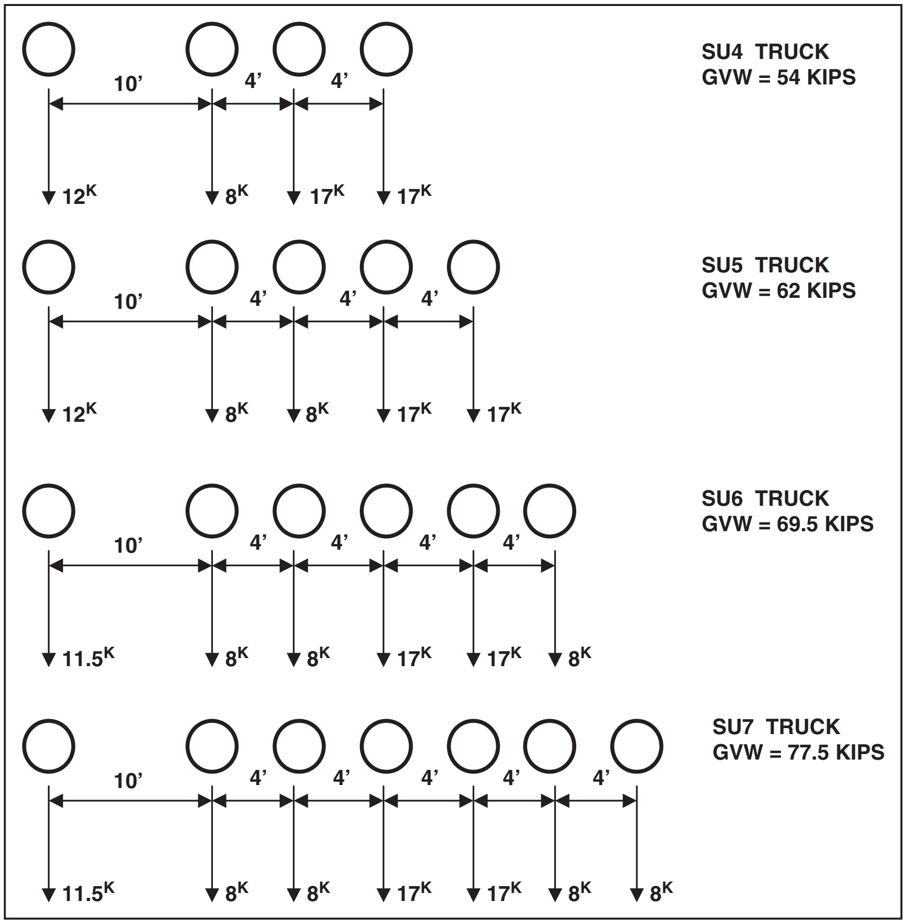

Figure 26. Bridge posting loads for single-unit SHVs that meet Formula B requirements.

given in the NCHRP Project 12-63 calibration report in Appendix G.

6. When the maximum legal exclusion load under state law exceeds the safe load capacity of a bridge, restrictive load posting may be required. The live load to be used for posting considerations could be a state's own exclusion vehicles or one of the exclusion vehicles provided herein. The live-load factors given in Table 34 can be used with less severe grandfathered state loads or with grandfathered state loads that only moderately exceed the EX-3 and EX-4 load effects.

Table 33. Live-load factors, γ_L for Formula B SHVs.

Traffic Volume (one direction)	*Load Factor for NRL, SU4, SU5, SU6, and SU7*
Unknown	1.60
ADTT $\geq$ 5,000	1.60
ADTT = 1,000	1.40
ADTT $\leq$ 100	1.15

Suggested Research

Research on this topic suggested for the future is as follows:

1. **SHV Load Model.** Additional WIM data are needed to resolve assumptions on the SHV truck weight distribution: can the model used for routine commercial truck traffic (i.e., 0.95 bias and 25% COV for top 20% trucks) be used also for SHVs? It is likely that more than the top 20% of SHVs may be important to load distribution and that the overload amounts may be greater due to many SHVs carrying very dense products and operating close to the weight limit. Also, the issue of axle load distribution in SHVs needs further investigation as it could have a significant effect (overstressing) on short-span bridges.
2. **SHV Multiple-Presence Model.** The same probabilities of multiple presence as routine traffic, based on ADTT values, was used in the calibration. Further research is needed

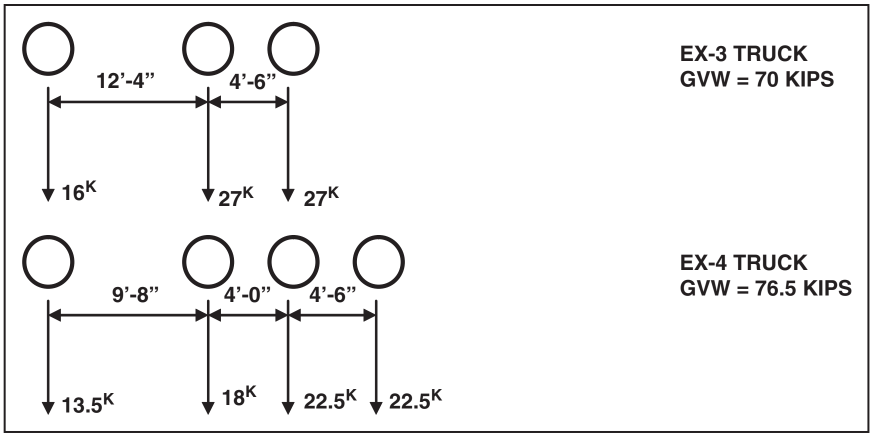

Figure 27. Calibration trucks for exclusion vehicles (non-Formula B SHVs).

Table 34. Live-load factors, γ_L for exclusion vehicles.

Traffic Volume (one direction)	*Load Factor for EX-3, EX-4, State Exclusion Vehicles*
Unknown	1.60
ADTT ≥ 5,000	1.60
ADTT = 1,000	1.40
ADTT ≤ 100	1.30

to investigate the likelihood of an SHV alongside an SHV (which controls load effect, in many cases) as a function of overall ADTT and the SHV volume. Also, the likelihood of a heavy SHV alongside a heavy routine truck must also be studied.

3. **Target Reliability Index.** The target reliability index for SHVs was taken to be in the range of operating levels, which is the same as for routine commercial truck traffic. Is this appropriate in all cases? Safety and operational needs may necessitate deviations from this set target for the class of SHV trucks. Additional research on this topic is suggested.

References

1. AASHTO. *Manual for Condition Evaluation of Bridges (MCE)*. Washington, DC (1994).

2. AASHTO. *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges*. Washington, DC (2003).

3. AASHTO. *Guide for Maximum Dimensions and Weights of Motor Vehicles and for the Operation of Non-Divisible Load Oversize and Overweight Vehicles.* Washington, DC (1987).

4. FHWA. *Truck Characteristics Analysis.* Washington, DC (1999).

5. Fancher Jr., P.S., and T.D. Gillespie. *NCHRP Synthesis of Highway Practice 241*: *Truck Operating Characteristics.* Transportation Research Board, National Research Council, Washington, DC (1997).

6. Fu, G., et al. *NCHRP Report 495: Effect of Truck Weight on Bridge Network Costs*. Transportation Research Board of the National Academies, Washington, DC (2003).

7. Nix, F., and M. Boucher. *Economics and Liftable Axles on Heavy Trucks.* Ontario Ministry of Transportation, Toronto (1990).

8. *TRB Special Report 267: Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles*. Transportation Research Board, National Research Council, Washington, DC (2002).

9. *TRB Special Report 225: Truck Weight Limits: Issues and Options.* Transportation Research Board, National Research Council, Washington, DC (1990).

10. *TRB Special Report 227: New Trucks for Greater Productivity and Less Road Wear.* Transportation Research Board, National Research Council, Washington, DC (1990).

11. USDOT. *Comprehensive Truck Size and Weight Study, Volumes I, II and III.* Washington, DC (2000).

12. Washington State Transportation Center. *An Evaluation of the Lift Axle Regulation (WAC 468.38.280) in Washington.* University of Washington, Seattle (1994).

13. Imbsen, R.A. *NCHRP Synthesis of Highway Practice 108: Bridge Weight-Limit Posting Practice.* Transportation Research Board, National Research Council, Washington, DC (1984).

14. Nowak, A.S. *NCHRP Report 368: Calibration of LRFD Bridge Design Code.* Transportation Research Board, National Research Council, Washington, DC (1999).

15. Moses, F., and M. Ghosn. *A Comprehensive Study of Bridge Loads and Reliability: Final Report.* Case Western University, Ohio DOT, and FHWA (1985).

16. Moses, F. *NCHRP Report 454: Calibration of Load Factors for LRFR Bridge Evaluation.* Transportation Research Board, National Research Council, Washington, DC (2001).

17. Nowak, A.S., and Y.K. Hong. "Bridge Live Load Models," *Journal of Structural Engineering,* vol. 117, no. 9, Sept, 1991; pp. 2757–2767.

Bibliography

AASHTO (1987). *Guide for Maximum Dimensions and Weights of Motor Vehicles and for the Operation of Non-Divisible Load Oversize and Overweight Vehicles.* Washington, D.C.

AASHTO (2004). *LRFD Bridge Design Specifications, 3rd Edition*. Washington, D.C.

Bailey, S.F., and R. Bez (1995). "Site-Specific Traffic Load Models for Bridge Evaluation," *Proceedings, IABSE Symposium on Extending the Lifespan of Structures,* IABSE Report, v 73/2, pp. 835–840.

Baker, M., et al. (2003). *NCHRP Report 485: Bridge Software—Validation Guidelines and Examples.* Transportation Research Board, National Research Council, Washington, DC.

Bakht, B., and L.G. Jaeger (1990). "Bridge Evaluation for Multipresence of Vehicles," *Journal of Structural Engineering*, v. 116, n. 3, Mar 1990, pp. 603–618.

Bartlett, F.M., P.G. Buckland, and D.J.L. Kennedy (1992). "Canadian Highway Evaluation: Derivation of Clause 12 of CAN/CSA S6-88," *Canadian Journal of Civil Engineering,* 19(6).

Bez, R., R. Cantieni, and J. Jacquemoud (1987). "Modeling of Highway Traffic Loads in Switzerland." *IABSE Proceedings,* P-117/87, pp. 153–168.

Billings, J.R., F.P. Nix, M. Boucher, and B. Raney (1990). *On the Use of Liftable Axles by Heavy Trucks,* Ontario Ministry of Transportation, December 1990.

Buckland, P. (1991). "North American and British Loan-Span Bridge Loads," *ASCE Journal of Structural Engineering*, October 1991.

Canadian Standards Association (1990). *CAN/CSA-S6-88-1990, Existing Bridge Evaluation Supplement to Design of Highway Bridges.*

Center for Transportation Analysis, Oak Ridge National Laboratory (1998). *Analysis of Vehicle Classification and Truck Weight Data of the New England States, Final Report*.

Center for Transportation Research, University of Texas at Austin (1997). *Traffic-Load Forecasting Using Weigh-in-Motion Data.*

Center for Transportation Research, University of Texas at Austin (2000). *Alternatives to Weight Tolerance Permits.*

Center for Transportation Research, University of Texas at Austin (2001). *Effect of Truck Size and Weights on Highway Infrastructure and Operations: A Synthesis Report*, March 2001.

Cohen, H., G. Fu, and F. Moses (1997). "Truck Load Spectra Influenced by Truck Weight Limits," *Proceedings of the 8th ASCE Specialty Conference on Probabilistic Mechanics and Structural and Geotechnical Reliability.*

Fancher, P.S., Jr., and T.D. Gillespie (1997). *NCHRP Synthesis of Highway Practice 241: Truck Operating Characteristics*, Transportation Research Board, National Research Council, Washington, DC.

FHWA (1985). *FHWA/OH-85/005 (1985): Comprehensive Study of Bridge Loads and Reliability.*

FHWA (1985). *FHWA/RD-85/012: Loading Spectrum Experienced by Bridge Structures in the United States.*

Florida DOT (1995). *Bridge Load Rating, Permitting and Posting Manual, Volume 3.*

Fu, G., and O. Hag-Elsafi (1994). "Overweight Trucks and Safety of Bridges," *Proceedings of the 1994 Structures Congress,* ASCE, New York; pp. 284–289.

Fu, G., and O. Hag-Elsafi (1996). "Bridge Live Load Model Including Overloads," *Proceedings of the 7th ASCE Specialty Conference on Probabilistic Mechanics and Structural and Geotechnical Reliability;* pp. 34–37.

Fu, G., and F. Moses (1991). "Overload Permit Checking Based on Structural Reliability," *Transportation Research Record 1290*, Transportation Research Board, National Research Council, Washington, DC; v. 1, pp. 279–289.

Ghosn, M. (1992). "Bridge Overloading Criteria." *Proceedings of the 3rd ASCE Specialty Conference on Probabilistic Mechanics and Structural and Geotechnical Reliability;* pp. 575–578.

Ghosn, M. (2000). "Development of Truck Weight Regulations Using Bridge Reliability Model," *ASCE Journal of Bridge Engineering,* November 2000.

Ghosn, M., and D.M. Frangopol (1996). "Site Specific Live Load Models for Bridge Evaluation" *Proceedings of the 7th ASCE Specialty Conference on Probabilistic Mechanics and Structural and Geotechnical Reliability.*

Ghosn, M., and F. Moses (1986). "Reliability Calibration of Bridge Design Code," *Journal of Structural Engineering*, v 112, n 4, Apr 1986, pp 745–763.

Ghosn, M., and F. Moses (1987). "Calibration of a Bridge Rating Formula for Overload Permits," *Bridges and Transmission Line Structures.*

Ghosn, M., F. Moses, and F. Gabriel (1990). "Truck Data for Bridge Load Modeling," *Second Workshop on Bridge Engineering Research in Progress*, Reno, NV.

Heywood, R.J. (1992). "Multiple Presence Model for Bridges," *Proceedings of the 3rd ASCE Specialty Conference on Probabilistic Mechanics and Structural and Geotechnical Reliability;* pp. 579–582.

Heywood, R.J., and A.S. Nowak (1989). "Bridge Live Load Models," *Proceedings of the ICOSSAR 5th International Conference on Structure Safety and Reliability;* pp. 2147–2154.

Imbsen and Associates, Inc. (1990). "NCHRP Project 12-28(11) Final Report: Development of Site-Specific Load Models for Bridge Rating," NCHRP, TRB.

Jacobsohn, A.P. (1997). "Truck Weights: A Long and Winding Road," *Waste Age,* v 28, n 6, June 1997; pp. 58–68.

James, R.W., R.A. Zimmerman, and J.H. Loper (1988). *Effects of Repeated Heavy Loads on Highway Bridges.* Texas Transportation Institute Research Report 462-1F, July 1988.

Kulicki, J.M. (1994). "Development of Bridge Live Load Models," *Proceedings of the 1994 Structures Congress,* ASCE, New York.

Kulicki, J.M., and D.R. Mertz (1991). "New Live Load Model for Bridge Design," *Proceedings of the 8th Annual International Bridge Conference,* Pittsburgh, PA.

Laman, J.A., and A.S. Nowak (1995). "Site-Specific and Component Specific Bridge Load Models," *Proceedings of the 6th IFIP WG7.5 Working Conference on Reliability and Optimization of Structural Systems;* pp. 167–176.

Lichtenstein, A.G., and C.M. Minervino (1990). "Revisions to the AASHTO Manual for Maintenance Inspection of Bridges." *Development in Short and Medium Span Bridge Engineering 1990.* Papers presented at the Third International Conference on Short and Medium Span Bridges, Toronto 1990.

Lichtenstein Consulting Engineers, Inc. (2001). *NCHRP Web Document 28: Manual for Condition Evaluation and Load Rating of Highway Bridges Using Load and Resistance Factor Philosophy.* Transportation Research Board, National Research Council, Washington, DC.

Lichtenstein Consulting Engineers, Inc. (2003). "NCHRP Project 12-63 Interim Report," NCHRP, Transportation Research Board, October 2003.

Lui, W.D., C.A. Cornell, and R.A Imbsen (1988). "Analysis of Bridge Truck Loads" *Probabilistic Methods in Civil Engineering.*

Mertz, D.R., and J.M. Kulicki (1995). "Impact of Load and Resistance Factor Design Specifications on Short- to Medium-Span Steel Bridges," *Proceedings of the Fourth International Bridge Engineering Conference*, San Francisco.

Minervino, C.M., B. Sivakumar, F. Moses, D. Mertz, and W. Edberg (2004). "New AASHTO Guide Manual for Load and Resistance Factor Rating of Highway Bridges," *ASCE Journal of Bridge Engineering*, January 2004.

Moses, F. (1982). "Load Spectra for Bridge Evaluation," *Proceedings of the IABSE Symposium on Maintenance, Repair, and Rehabilitation of Bridges,* Washington, DC; pp. 63–73.

Moses, F., and G.K. Fu (1990). "Load Factors for Evaluating Permit Vehicles," *Development in Short and Medium Span Bridge Engineering 1990.* Papers presented at the Third International Conference on Short and Medium Span Bridges, Toronto 1990.

Moses, F., and M. Ghosn (1986). "A Reliability Calibration of a Bridge Design Code," *ASCE Journal of Structural Engineering*, v. 112, n. 4, April 1986.

Moses, F., M. Ghosn, and R.E Snyder (1984). "Application of Load Spectra to Bridge Rating," *Transportation Research Record 950,* Transportation Research Board, National Research Council, Washington, DC; v 1, pp. 45–53.

Moses, F., and D. Verma (1987). *NCHRP Report 301: Load Capacity Evaluation of Existing Bridges,* Transportation Research Board, National Research Council, Washington, DC.

Nassif, H.H., and A.S. Nowak (1995). "Dynamic Load Spectra for Girder Bridges," *Transportation Research Record 1476,* Transportation Research Board, National Research Council, Washington, DC; pp. 69–83.

Nix, F.P., and M. Boucher (1990). *Economics of Liftable Axles on Heavy Trucks,* Ontario Ministry of Transportation Report CV-90-04, November 1990.

Nowak, A.S. (1993). "Live Load Model for Highway Bridges," *Structural Safety*, v 13, n 1–2, December 1993, pp. 53–66.

Nowak, A.S. (1995). "Calibration of the LRFD Bridge Code," *Journal of Structural Engineering,* v 121, n 8, August 1995, pp. 1245–1251.

Nowak, A.S., J. Eom, and A. Sanli (2000). "Control of Live Loads on Bridges," *Transportation Research Record 1696,* Transportation Research Board, National Research Council, Washington, DC; pp. 136–143.

Nowak, A.S., and H.N. Grouni (1982). "Safety Criteria in Calibration of the OHBD Code." *Proceedings of the International Conference on Short and Medium Span Bridges,* Toronto.

Nowak, A.S., and J.M. Kulicki (1992). "Live Load Models for Bridge Evaluation." *Proceedings of the 3rd International Workshop on Bridge Rehabilitation,* Technical University Darmstadt and the University of Michigan.

Nowak, A.S., and N.C. Lind (1979). "Practical Code Calibration Procedures," *Canadian Journal of Civil Engineering,* v. 6, pp. 112–119.

Nowak, A.S., and H. Nassif (1992). "Live Load Models Based on WIM Data," *Proceedings of the 3rd ASCE Specialty Conference on Probabilistic Mechanics and Structural and Geotechnical Reliability;* pp. 587–590.

Nowak, A.S., H. Nassif, and L. Defrain (1991). "Truck Loads on Michigan Highways," University of Michigan Technical Report.

Sivakumar, B. (2000). "Serviceability Criteria for Load Rating Bridges using the LRFD Philosophy," *Proceeding of the 7th Annual International Bridge Conference,* Pittsburgh, PA.

Sivakumar, B., and W. Edberg (2000). "Trial Rating of Bridges Using Load and Resistance Factor Procedure," *Proceedings of the 2000 ASCE Structures Congress*, Philadelphia.

Sivakumar, B., and C.M. Minervino (1999). "Load Rating and Permit Review Using Load and Resistance Factor Philosophy." *TRB Circular 498: Presentations from the 8th International Bridge Management Conference,* Transportation Research Board, National Research Council, Washington, DC; pp. K-6/1–8.

Task Force on Vehicle Weights and Dimensions Policy (1999). *Heavy Truck Weight Limits and Dimensions Limits for Interprovincial Operations in Canada*, May 1999.

Zokaie, T., T.A. Osterkamp, and R.A. Imbsen (1991). *NCHRP Research Results Digest 187: Distribution of Wheel Loads on Highway Bridges,* Transportation Research Board, National Research Council, Washington, DC.

APPENDIXES

All appendixes for this report are available online at www.trb.org/news/blurb_detail.asp?id=7566. The appendixes are as follows:

- Appendix A: Survey Questionnaires and Responses,
- Appendix B: WIM Data Analyses,
- Appendix C: Analyses of Generic Spans for Formula B Trucks,
- Appendix D: Analyses of Generic Spans for Non-Formula B Trucks,
- Appendix E: Estimating Maximum Loading by Simulation,
- Appendix F: Recommended Revisions to AASHTO Manuals,
- Appendix G: NCHRP Project 12-63 Calibration Report,

Appendix A contains the questionnaires used in the surveys and tabulated responses for Phases I and II. Appendix B includes spreadsheets documenting the results of WIM data from 18 states obtained and analyzed in this project, including state-by-state results of WIM data analyses. Results of the analyses of generic simple and continuous spans for load effects induced by candidate Formula B and non-Formula B SHVs are included in Appendixes C and D, respectively. A Monte Carlo simulation performed to estimate the expected maximum load effect for two side-by-side SHVs and to validate the statistical projection approach used in this project is described in Appendix E. Appendix F contains the draft recommended revisions to the AASHTO MCE and LRFR manuals to allow the inclusion of the new legal load models developed in this project. Appendix G is the calibration report for this project documenting the live-load calibrations for Formula B and Non-Formula B trucks.

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