ADVANCING BRIDGE LOAD RATING: STATE OF PRACTICE AND FRAMEWORKS

Office of Infrastructure
Office of Bridges and Structures

U.S. Department of Transportation
Federal Highway Administration

FHWA-HIF-22-059

December 2022

FOREWORD

State departments of transportation (DOTs) perform or cause to be performed a load rating for each highway bridge that carries a public road to ensure bridge safety within the State's borders. State DOTs also rely on bridge load rating information in making operational and management decisions such as bridge load posting or restrictions, overweight permitting, rehabilitation, or replacement. To meet the requirement for bridge load rating and posting set forth in the National Bridge Inspection Standards (23 CFR 650 Subpart C), State DOTs have been managing the safe operation of more than 600,000 bridges across the nation. As such, State DOTs have amassed a significant amount of safe load carrying capacity data and analytical modeling for these bridges.

The goals of this research were to identify the state of practice and develop a framework that offers a preview of what bridge load rating may consist of in the future. The framework provides a scalable and conceptual process in bridge load rating, posting, and overweight permitting and promotes efficiency and consistency that ultimately will improve safety and mobility through implementation of advanced technologies.

With additional development and partnerships between government, industry, and academia, I am excited about the possibilities and look forward to benefiting from the opportunities.

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Technical Report Documentation Page

1. Report No. FHWA-HIF-22-059	**2. Government Accession No.**	**3. Recipient’s Catalog No.**	
4. Title and Subtitle Advancing Bridge Load Rating: State of Practice and Frameworks		**5. Report Date** December 2022	
		6. Performing Organization Code	
7. Author(s) Brent Phares, Zhengyu Liu, and Katelyn Freeseman		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No. (TRAIS)**	
		11. Contract or Grant No. 693JJ319D000020 TO693JJ320F000170	
12. Sponsoring Organization Name and Address Federal Highway Administration Office of Infrastructure 1200 New Jersey Avenue, SE Washington, DC 20590		**13. Type of Report and Period Covered** Final Report. 5/1/2020 to 7/31/2022	
		14. Sponsoring Agency Code FHWA-HIF/HIBS-10	
15. Supplementary Notes FHWA Task Order COR (Task Order Manager): Lubin Gao, PhD, PE FHWA Contracting Officer Representative (COR): Donna Harris Technical Advisory Panel: Matt Farrar (Idaho Transportation Department), Henry Sung (Arizona DOT, retired), Murugesu Vinayagamoorthy (California DOT), Jennifer Hart (Indiana DOT), Dominique Shannon (Kansas DOT), Gichuru Muchane (North Carolina DOT), Jon Rooper (Oregon DOT), and Richard Runyen (Pennsylvania DOT)			
16. Abstract The U.S. has more than 600,000 bridges, making the distributed load rating and posting processes across the nation a significant effort that does and can benefit from improvements in efficiency. Bridge load rating, posting, and overweight permitting processes evolve due to the regulatory requirements regarding the frequency of inspections and relevant changes to bridges that necessitate re-rating them. These factors include changes to the dead load, strength of members, and any maintenance or rehabilitation work. As such, States are interested in modifying their procedures to implement technology and improved means and methods to reduce the time associated with load rating. Being able to load rate bridges efficiently and accurately is a necessity, particularly in the use case of permit load routing. Based on the extensive findings during the information collection processes for this project, frameworks for future bridge load rating, posting, and overweight permitting were developed to improve productivity, efficiency, and consistency by closing process gaps and through the application of newer technologies. The newer technologies include digital twin concepts; integrating various (new) data; creating, updating, and reusing models; integrating sensing data (bridge, traffic, weigh-in-motion); and better analysis methods. This work may help develop the state of practice.			
17. Key Words bridge load posting—bridge load rating—frameworks—load rating practices—overweight permitting—permit load routing		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 125	**22. Price** NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units.

Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
24/7	24 hours a day, 7 days a week
2D	two-dimensional
3D	three-dimensional
AASHTO	American Association of State Highway and Transportation Officials
AAT	automated ambient traffic
ADOT	Arizona Department of Transportation
ADTT	average daily truck traffic
ASD	allowable stress design
ASR	allowable stress rating
BECAS	Bridge Engineering Condition Assessment System
BIM	building information modeling
BOPR	Bridge Overweight Permit Review
BWIM	bridge weigh-in-motion
Caltrans	California Department of Transportation
CBM	condition-based maintenance
CDOT	Colorado Department of Transportation
CFR	Code of Federal Regulations
COOPR	Colorado Oversize Overweight Permitting and Routing
CPS	cyber-physical system
DDOT	Washington District of Columbia Department of Transportation
DOT	department of transportation
DSRC	dedicated short range communication
EV	emergency vehicle
FAST	Fixing America’s Surface Transportation (Act)
FE	finite element
FEM	finite element model
FHWA	Federal Highway Administration
GIS	geographic information system
GPS	global positioning system
GVW	gross vehicle weight
IDOT	Illinois Department of Transportation
IEEE	Institute of Electrical and Electronics Engineers
INDOT	Indiana Department of Transportation
IoT	internet of things
IP	internet protocol
ITS	intelligent transportation systems
KDOT	Kansas Department of Transportation
KYTC	Kentucky Transportation Cabinet
LaDOTD	Louisiana Department of Transportation and Development
LARS	Load Analysis and Rating System
LF	load factor (method)
LFD	load factor design

Abbreviation	**Meaning**
LFR	load factor rating
LRFD	load and resistance factor design
LRFR	load and resistance factor rating
LTAP	Local Technical Assistance Program
MBE	Manual for Bridge Evaluation
MDOT	Michigan Department of Transportation
MDOT SHA	Maryland Department of Transportation State Highway Administration
MnDOT	Minnesota Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices (for Streets and Highways)
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards
NCHRP	National Cooperative Highway Research Program
NDOR	Nebraska Department of Roads (now Department of Transportation)
NDOT	Nevada Department of Transportation
OBE	on-board equipment
ODOT	Ohio Department of Transportation
ODOT	Oregon Department of Transportation
OS/OL	oversize/overlength
OS/OW	oversize/overweight
OW	overweight
OW/OD	overweight/over-dimensional
PDF	portable document format
PennDOT	Pennsylvania Department of Transportation
QA	quality assurance
QC	quality control
RF	rating factor
RFID	radio-frequency identification
RSD	roadside safety device
RSE	roadside equipment
SaaS	software as a service
SHM	structural health monitoring
SHV	specialized hauling vehicle
SU	single unit
U.S.C.	U.S. Code (and § stands for Section after U.S.C.)
UDOT	Utah Department of Transportation
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VDOT	Virginia Department of Transportation
VWIM	virtual weigh-in-motion
WIM	weigh-in-motion
WisDOT	Wisconsin Department of Transportation
WSN	wireless sensor network
WVDOT	West Virginia Department of Transportation
WYDOT	Wyoming Department of Transportation

EXECUTIVE SUMMARY

The importance of the load rating of bridges has been apparent since the establishment of the National Bridge Inventory (NBI) and the extension of the National Bridge Inspection Standards (NBIS) to all bridges in 1979. Since then, many updates to the process have been implemented. Ratings play a role in prioritizing and distributing bridge funds, helping to determine the allocation of resources for the United States transportation infrastructure.

Further, load rating is critical to ensuring bridge safety by assessing each bridge’s ability to safely support traffic and other loads. The roles of inspecting and load rating fall largely upon individual States and local agencies, resulting in a large number of individuals independently assessing infrastructure.

Bridge load rating, posting, and overweight permitting processes are constantly evolving due to changes to the dead load, strength of members, and any maintenance or rehabilitation work. The United States has more than 600,000 bridges, making the process of load rating and posting a significant effort. Load rating bridges efficiently and accurately is a necessity, particularly in the use case of permit load routing.

The work summarized in this report addresses the needs via the review of state of practice and the development of frameworks for next-generation bridge load rating, posting, and permitting. The specific objectives were as follows:

- Synthesize the state of practice regarding the load rating, posting, and overweight permitting programs for bridges from State departments of transportation (DOTs)
- Develop a framework for consistent future load rating efforts

CHAPTER 1. INTRODUCTION

1.1 Background

The importance of the load rating of bridges has always been apparent and gained additional attention since the establishment of the National Bridge Inventory (NBI) and the extension of the National Bridge Inspection Standards (NBIS) to all bridges in 1979. Since then, many updates to the process for load rating of bridges have been implemented, including adaptation to changing truck configurations, increase in permit loads, and State laws allowing for heavier legal loads.

Ratings play a role in prioritizing and distributing bridge funds, thus helping to determine the allocation of resources for the United States transportation infrastructure. Load rating also is critical to ensuring bridge safety by assessing each bridge's ability to safely support traffic and other loads. The roles of inspecting and load rating fall largely upon individual States and local agencies, resulting in a large number of individuals independently assessing infrastructure.

Recently, efforts have continued to ensure uniformity in load rating processes, and particularly by the Federal Highway Administration (FHWA). Between 2014 and 2019, the FHWA has held six regional peer exchanges on the topic of bridge load rating. These peer exchanges provided beneficial opportunities for States to share knowledge, expertise, and practices.

1.2 Problem Statement

Bridge load rating, posting, and overweight permitting processes evolve with respect to the dead load, strength of members, and any maintenance or rehabilitation work. The United States has more than 600,000 bridges, making the process of load rating and posting a significant effort.

States indicated through the above mentioned peer exchanges that they are very interested in modifying their procedures to implement technology and improved means and methods to reduce the time associated with load rating.

Being able to load rate bridges efficiently and accurately is a necessity, particularly in the use case of permit load routing. In many instances, the permit office within different agencies evaluates non-standard loadings that potentially traverse complex structures to avoid negative impacts to commerce. The considerations that are made by States in the load-rating process may include the following:

- Implementation of the American Association of State Highway and Transportation Officials' (AASHTO's) load rating standards and methodology although the AASHTO standards are not incorporated by reference into regulations and are not legally binding
- Adaptation to changes in Federal and State truck size and weight regulations
- Management of bridge rating digital assets (i.e., load rating data and models)
- Maintenance (and updates) of bridge load rating data and bridge analysis models

- Load limit signing and communication of safe load limits (or bridge capacity) with truckers and the public (vehicle to bridge connectivity)
- Use of weigh-in-motion (WIM) devices in load rating and posting enforcement
- Load posting implementation and verification
- Overweight load permitting that ensures bridges are rated prior to issuing permits
- Synchronization and integration of digital bridge assets (load ratings and analysis models) in overweight permitting
- Collaboration between load rating units and the overweight permitting office
- Quality management (i.e., quality control and quality assurance measures)
- Automation and system integration for efficiency, consistency, collaboration, and interoperability (e.g., automated rating system, automated permitting system, integrated infrastructure asset management system)
- Digital asset maintenance, stewardship, and governance (e.g., bridge load rating data, structural analysis models [and geospatial data, building information modeling (BIM), etc.], data exchange, automated model update, cloud computing and service, software as a service [SaaS])
- Application of digital twin concepts in bridge load rating, and bridge reliability and safety performance management
- Connectivity and communication technology (e.g., internet of things [IoT], vehicle to bridge [V2X], dedicated short range communication [DSRC], radio-frequency identification [RFID], connected bridges)
- WIM, sensors, and sensing technologies (e.g., intelligent [digital, smart, connected] bridges)
- Intelligent transportation systems (ITS) and technology (e.g., ITS architecture and services, roadside equipment [RSE], on-board equipment [OBE], electronic digital signing, load and clearance posting, bridge closure or restriction)

1.3 Objectives and Benefits

This report addresses the future bridge rating needs via the review of the state of practice and the development of frameworks for next-generation bridge load rating, posting, and permitting. The specific objectives were as follows:

- Synthesize state of practice regarding load rating, posting, and overweight permitting programs for bridges from State DOTs
- Develop a framework for future bridge load rating efforts

Due to the vast bridge inventory in the United States, establishing an efficient framework for the load rating, posting, and overweight permitting of bridges may be of great benefit to State agencies by providing consistency and by helping to optimize technological advancement capabilities. Advancements should improve the efficiency of decision-making while taking advantage of better load rating tools. This also could improve management of rehabilitation and replacement budgets.

1.4 Report Organization

The following is an overview of the structure of this report:

Chapter 1 contains introductory information.

Chapter 2 is the review and findings from a desk scan and literature research related to States' processes and procedures for bridge load rating, posting, and overweight load permitting.

Chapter 3 covers the results of a State DOT survey and findings from a comprehensive review of select State DOT programs, along with the analysis of NBI data.

Chapter 4 synthesizes the state of practice and develops a framework for next-generation bridge load rating, posting, and permitting.

Chapter 5 is a summary of findings and final conclusions.

CHAPTER 2. DESK SCAN AND LITERATURE SEARCH

A desk scan and literature search were conducted to collect information about the state of practice and emerging technologies for bridge load rating, posting, and overweight permitting. The information collection included published documentation such as relevant State practice manuals, technical reports, and research papers.

2.1 State Department of Transportation Practice

Relevant, publicly available State DOT manuals and guidance regarding bridge load rating, posting, and overweight load permitting were reviewed.

2.1.1 State-Published Practices and Procedures

A search for State-specific information was conducted for all States and included Washington DC and Puerto Rico (pursuant to 23 USC § 101(a)(26)). The documents reviewed for each included bridge design manuals, bridge inspection manuals, and bridge load rating manuals electronically published by the respective DOTs, as well as a few memoranda. The research team found that the load rating-related information for each was primarily documented in one of the three types of manuals. Table 1 includes the title of the document that contained the load rating information for each, along with the year for the document.

Table 1. State manuals reviewed

No.	State	Year and Title
1	Alabama	2017 *Bridge Inspection Manual*
2	Alaska	2017 *Alaska Bridges and Structures Manual*
3	Arizona	*ADOT Bridge Load Rating Guidelines* (Retrieved 2020)
4	Arkansas	2019 *Local Government Procedures for Compliance with the National Bridge Inspection Standards*
5	California	Not available online
6	Colorado	*Bridge Design Manual* (Retrieved 2020)
7	Connecticut	2018 *Bridge Rating Manual*
8	Delaware	2019 *Bridge Design Manual*
9	Florida	2020 *Bridge Load Rating Manual*
10	Georgia	Not available online
11	Hawaii	Not available online
12	Idaho	2014 *Idaho Bridge Inspection Coding Guide*
13	Illinois	2018 *Bureau of Local Roads and Streets Manual*
14	Indiana	2017 *INDOT Bridge Inspection Manual*
15	Iowa	2015 *Bridge Rating Manual*
16	Kansas	2013 *Bridge Design Manual*
17	Kentucky	2020 *Kentucky Bridge Inspection Procedure Manual*
18	Louisiana	2009 *The Policies and Guidelines for Bridge Rating and Evaluation*

No.	State	Year and Title
19	Maine	2015 *Load Rating Guide*
20	Maryland	2019 *Guidelines and Procedures Memorandums: Structure Inspection Section*
21	Massachusetts	*LRFD Bridge Manual: Part I – Design Guidelines* (Retrieved 2020)
22	Michigan	2009 *Bridge Analysis Guide*
23	Minnesota	2018 *MnDOT Bridge Load Rating and Evaluation Manual*
24	Mississippi	*Bridge Safety Inspection Policy and Procedures* (Retrieved 2020)
25	Missouri	1994 *Load Rating Steel and Concrete Girder Bridges in Missouri* (Barker et al.)
26	Montana	2018 *Bridge Inspection and Rating Manual*
27	Nebraska	2010 *Bridge Inspection Program Manual*
28	Nevada	2008 *NDOT Structures Manual: Chapter 28 – Nevada Bridge Inspection Program*
29	New Hampshire	2017 *Bridge Inspection Manual*
30	New Jersey	2010 *Load Analysis and Rating System (LARS) Specification Analysis Manual* (Bentley Systems, Inc.)
31	New Mexico	2018 *Bridge Procedures and Design Guide*
32	New York	2016 *Bridge Inspection Manual*
33	North Carolina	Not available online
34	North Dakota	2019 *NDDOT Load Rating Manual*
35	Ohio	2008 *Bridge Design Manual*
36	Oklahoma	Not available online
37	Oregon	2018 *ODOT Load and Resistance Factor Rating (LRFR) Manual*
38	Pennsylvania	2010 *Bride Safety Inspection Manual*
39	Rhode Island	2019 *Bridge Load Rating Guidelines*
40	South Carolina	2019 *SCDOT Load Rating Guidance*
41	South Dakota	2020 *Bridge Design Manual*
42	Tennessee	Not available online
43	Texas	2020 *Bridge Inspection Manual*
44	Utah	2017 *Bridge Management Manual*
45	Vermont	2010 *VTrans Structures Design Manual*
46	Virginia	2007 *Structure and Bridge Division Instructional and Informational Memoranda*
47	Washington	2017 *Bridge Design Manual*
48	West Virginia	2016 *Bridge Design Manual*
49	Wisconsin	*Bridge Manual* (Retrieved 2020)
50	Wyoming	Not available online
51	Puerto Rico	Not available online
52	Washington DC	2017 *Design and Engineering Manual*

Publicly available load rating-related information was found for 43 States and Washington, DC. No published information or guidelines related to load rating could be found for the other seven States or Puerto Rico (although that does not imply that published information does not exist). Among those for which information could be found, about half had a standalone bridge load rating manual, while most of the others had the relevant information as a chapter in either their bridge design manual or inspection manual.

A review of the State practices and procedures indicated that almost all state that the load rating procedures must follow the AASHTO MBE. The actual versions of the MBE referenced varied. Note that the 3rd Edition MBE (2018), including Interim Revisions through 2020, is incorporated by reference in 23 CFR 650.317(a)(1)–(a)(3).

Most of the DOTs publish their manuals to include State-specific details in addition to the information listed in the AASHTO MBE. The information documented in the following sections of this report focuses on the practices that are included in one or more State manuals but are not included in the AASHTO MBE.

2.1.2 Load Rating Analysis

The AASHTO MBE states that bridge load rating provides a basis for determining the safe load carrying capacity of a bridge. A review of the State manuals indicated that States also recognize that understanding the load carrying capacity of each bridge is critical for (1) determining whether a structure may need posting or other remedial action, (2) allocating available resources for rehabilitation or replacement, (3) assisting the overload permit review process, and (4) providing safety to the traveling public.

Load ratings are typically determined by analytical methods based on information taken from bridge plans, supplemented by information gathered from field inspections, testing, or both. Computer software is commonly used to calculate the load rating factor, with various structural analysis software packages available to provide opportunities for rating engineers to quickly complete the calculation(s).

Usually, each individual computer software package is effective for one or more particular structure types, with no one package capable of load rating all bridge types. A common practice is to use one or more software packages for each type of structure.

Routine load ratings consist of computations made from design plans, as-built drawings, field measurements, or inspection reports, or some combination of these, and are based on common analytical methods, such as the girder-line distribution factor analysis method.

A load rating engineer reviews the original design plans as the first source of information for specific material properties. If the material strengths are not explicitly stated on the design plans, construction and material specifications applicable at the time of bridge construction are commonly reviewed.

The AASHTO MBE also provides data on older bridge types and materials that allow for the evaluation of existing bridges when the original design specifications are not available.

More refined load ratings consist of routine computations adjusted for actual material properties as determined from field sampling and tests of the materials. These load ratings may also use refined methods of analysis such as two-dimensional (2D) grillage models or three-dimensional

(3D) finite element models (FEMs). Refined methods of analysis are commonly justified where needed to avoid load posting or to ease restrictions on the flow of permitted overweight trucks. Some of the newer, more complex structures were designed using sophisticated analysis methods, and therefore a sophisticated level of analysis may also be needed to properly rate these structures.

The load rating of a bridge could also be accomplished by conducting a load test, since the actual performance may be more favorable than conventional theory predicts. The safe load capacity for a structure can be determined from nondestructive field load tests, which may be desirable to establish a higher safe load carrying capacity than that calculated by a more conservative traditional analysis.

2.1.3 Truck Type

A review of the State load rating requirements indicates that most States generally use the AASHTO MBE truck types. All structures are to have an inventory and an operating rating value in terms of HS20-44 or HL-93 loading. A structure's capacity will be assessed by those legal trucks as defined by the AASHTO MBE at the operating or legal load evaluation level.

Some States have additional trucks used during the legal load level evaluation based on the local traffic needs as governed by State regulations and laws. Examples include the following:

- S220, S335, S437, T330, T435, and T540 (Delaware)
- LA Type 3, LA Type 3-S2, LA Type 6, and LA Type 8 (Louisiana)
- Maine Legal Load Configurations 1 through 5 and 7 and 8 (Maine)
- H-15, Type 3, Type 4, HS-20, and 3S2 (Maryland)
- Ohio Legal Loads 2F1, 3F1, 4F1, and 5C1 (Ohio)
- SC-SHV1A (65k), SC-SHV1B (70k), SC-SHV3A (85k), SC-SHV3B (90k), SC School Bus, and SC-SU2 (40k) (South Carolina)
- Fixing America's Surface Transportation (FAST) Act emergency vehicles (EVs) (as codified under 23 U.S.C. § 127(r)): EV2 and EV3 (all States)

With respect to the issuance of permit trucks, Mlynarski et al. (2011) indicated that a wide range of truck loads are being used to rate bridges for "typical" permit vehicles throughout the United States. Furthermore, the AASHTO MBE does not list the truck types for evaluating permit loads.

Mlynarski et al. (2011) narrowed down the large number of trucks in four regions across the country, resulting in a total of eight trucks that are somewhat representative of the standard permit trucks in each region: WA-02 and OR-06 for the northwest region, NM-04 and TX-04 for the southwest region, IL-01 and DE-07 for the northeast region, and FL-04 and NC-21 for the southeast region. The trucks identified by Mlynarksi et al. represent an "average truck" and a "heavy truck" for each region.

Examples of trucks listed in various State manuals include the following:

- California permit vehicles P13, P11, P9, P7, and P5 (California and Nevada)
- AC2, AC3, AC4, and AC5 (Delaware)
- 90 kip six-axle vehicle (Kentucky)
- 136 kip (A) seven-axle truck with triple-axle configuration (Kentucky)
- 136 kip (B) seven-axle truck with quad-axle configuration (Kentucky)
- 156 kip eight-axle truck with a quad-axle (Kentucky)
- UT-P6, UT-P7, UTP8, UT-P9a, and UT-P9b (Utah)
- OL1 and OL2 (Washington)

2.1.4 Management of Load Rating Data

Each year, States submit bridge design level inventory and operating load ratings to the FHWA along with whether specific bridges are posted as part of their NBI annual submittal. After load rating work is completed, a common practice at the State level is to have the rating engineer submit the necessary documents to the State DOT. These documents are used to update the NBI record and are stored for future use in the DOT database. These documents usually include the following:

- Date of recent inspection
- Load rating summary sheet
- Load rating report
- Electronic model of the rated structure

The summary sheet is used for quick access to the bridge's basic information and load rating results, and some States post these sheets on the DOT website. A summary sheet typically includes the following information:

- Bridge ID
- Name of engineer(s) responsible for the rating and the individual responsible for review
- Rating date
- Software and version used
- Superstructure type
- Year built
- Bridge length
- Number of spans
- Span length
- Wearing surface type and thickness
- Facility carried
- Average daily truck traffic (ADTT)
- Rating factor and tons for load rating vehicle
- Major assumptions used in the analysis

The load rating report is signed, sealed, and dated by a State-licensed professional engineer. The load rating report generally includes the following items:

- Title sheet
- Geometric and material summary of the bridge
- Changes in live load or truck configurations that increase truck force effects on bridge elements
- Load rating method or program(s) used
- Assumptions
- Analysis levels
- Limit states
- List of references used in the load rating analysis
- Load rating computations
- Controlling member and location
- Sketches of section losses incorporated into the load rating analysis
- Rating factors and load capacity for each applicable legal and routine permit vehicle
- Safe posting load, as necessary, for each applicable legal and routine permit vehicle
- Discussion, sketches, and photos of deterioration
- Summary of bridge rating
- Bridge rating details
- Supplementary photos, documents, and relevant information

The electronic model of the rated structure usually refers to the models created utilizing structural analysis software. If a bridge structure is rated using a spreadsheet or the rating analysis is supplemented by spreadsheets or hand calculations, a copy of the spreadsheets and the digitized hand calculations are to be stored.

Some State DOTs also store (1) the plan sheets used to perform the analysis; (2) inputs, intermediate calculations, and summarized outputs; (3) the results from a comprehensive check after initial load rating; and (4) the inspection report showing the inspection date and the condition that generated the need for re-rating.

Most States require documented load rating results to be submitted as a standalone report or as part of an inspection. Some State DOTs have built online database systems to facilitate storing, accessing, and updating the data with the data stored in the cloud or on a central server.

2.1.5 Update of Load Rating Data

The AASHTO MBE (incorporated by reference at 23 CFR 650.317(a)(1)) provides three load rating methods in Section 6: the load and resistance factor rating (LRFR) method in Section 6A and the allowable stress rating (ASR) and load factor rating (LFR) methods in Section 6B. The review of State DOT manuals found that LRFR has been used for the load rating of bridges in many States. However, in many cases LFR is used. In States that predominantly use LRFR, an alternative method such as ASR or LFR is permissible but subject to State DOT approval (like the practice of the Rhode Island DOT). Note that States use ASR primarily for timber and masonry structures.

Farrar et al. (2014) conducted a desk scan on State DOT superload permit processes and practices to identify best practices from 18 surveyed States. The results from Farrar et al. indicated that 44 percent predominantly or exclusively use LFR, while 28 percent also used other methods, such as LRFR and ASR.

For existing structures, a prior load rating has already been stored on file. These load ratings reflect the condition of the bridge at the time of load rating. Structures need to be re-rated when it is determined that a change has occurred in the condition of the structure or when the load ratings on file are not consistent with current structural condition. Reviewing and, if necessary, updating load ratings is also needed when there is an increase to the legal weight limit of trucks using the structure (23 CFR 650.313(k)). In general, a revised load rating may be necessary if any of the following conditions have occurred:

- Deterioration of structural components
- Changes in configuration (due to widening of the bridge, bridges made continuous, etc.)
- Changes in dead loads (due to overlay application, barrier changes, utility attachments, etc.)
- Changes in live loads (due to upgraded roadway classification, overweight vehicles, etc.)
- Changes in rating or posting policy
- A change in the primary member condition rating
- Cracking in primary members
- Losses at critical connections
- Changes in traffic volume, lane striping
- Specification changes
- Issuance of overweight permits
- Soil and substructure settlement and slope stability changes
- Bridge rehabilitation that affects structural components, structural or non-structural weight
- A change in State or Federal laws regulating truck weights
- Structural damage resulting from a bridge hit, ice damage, flood damage, fire damage, or another cause
- Rotated or displaced beams
- Steel section loss
- Broken welds or missing bolts
- Exposed reinforcing or prestressing steel in the critical locations
- Splitting, cracking, or rot of timber members

Note that the above list is not all inclusive and an item may overlap with others.

Updating of the load rating may be performed on the stored digital assets including electronic files, computer models, etc. The detailed procedures for updating load ratings are not documented in State design or load-rating manuals, but most organizations have a standard operating procedure.

2.1.6 Posting Procedures and Communication

It is the bridge owner's responsibility to keep a bridge posted (23 CFR 650.313(l)). After the load rating is completed, the posting limits are documented in the load rating report. Bridge owners must install signs in accordance with the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) (FHWA 2009) showing the maximum safe load-carrying capacity of posted bridges (23 CFR 650.313(c) and 655.603(a)). Typically, a bridge management individual from the State DOT will confirm that the proper signs have been installed within a certain number of days of the distribution of the load posting documents (Hearn 2014).

The NBIS requires posting of load limits if the maximum legal load or unrestricted routine permit vehicle produces stresses in excess of the operating stress level permitted under the operating rating (23 CFR 650.313(l)). The actual criteria for posting a bridge are quite different from State to State. These criteria primarily change with posting vehicle types, bridge types, etc.

The MUTCD has a note within the section for load posting signs that states advanced warning signs should also be placed at locations or road intersections where prohibited vehicles can either detour or turn around (FHWA 2009). Bridge owners should also consider this in load posting by determining where to install advanced warning signs, especially in urban areas.

Common practice for posting a bridge is to erect bridge weight limit signs at each end of the bridge and install advance signs to alert truck drivers to a posted bridge ahead. Posting signs restrict vehicles from using the bridge if the vehicle exceeds the posted weight limit.

Signs R12-1 to R12-5 are the primary load posting signs used by State DOTs. Sign R12-4 can be used to combine the information contained on signs R12-1 and R12-2. Sign R12-5 is the most common bridge load posting sign.

In Nebraska, for the R12-5 sign, the top line showing the tonnage for single unit (SU) vehicles displays the lowest of the following vehicles: Nebraska Type 3, SU4, SU5, SU6, or SU7. In addition, some States have their own signs. For example, South Carolina uses R12-6-48 as a primary sign. For bridges with additional axle weight restrictions to account for any potential shear failures that could occur from an individual axle loading, sign R12-7-60 is placed below sign R12-6-48 to show three-axle configurations and their associated weight limits. The Kentucky Transportation Cabinet (KYTC) maintains an online list of posted bridges that is available to the public with the following information: bridge ID, county, route, mile point, crossing, and posting tonnages.

2.1.7 Overload Permit Procedures

When the load of a truck is greater than the legal load, an overload permit may be used to allow the truck to use the bridge under certain, limited conditions. Farrar et al. (2014) conducted a desk scan on the State DOT superload permit processes and practices to identify best practices in the superload permitting processes. The desk scan was conducted on 18 selected States. The results indicated that 78 percent of the surveyed States were in the process of adopting new changes in their permit processing, especially toward automated permitting and paperless processing.

Schaefer and Todd (2018) conducted a research study on State oversize-permitting and overweight-permitting practices, including automated vehicle routing and escort driver certification and identified the areas of best practices. The researchers found that, by 2018, 30 States were using automated permit systems.

For the current project, the research team reviewed State manuals to identify the way overload permitting procedures are recorded. Examples included the following:

- In Colorado, structures on the State highway system are given an Overload Color Code rating, which defines their capacity for loads heavier than the maximum legal loads in terms of the Colorado Modified Tandem Vehicle or the Colorado Permit Vehicle. The Overload Color Code ratings are used to determine the maximum group axle weights of the permit vehicles that will be allowed to travel on Colorado bridges and the routes these vehicles can follow.

- The Delaware DOT's (DelDOT's) Bridge Management Section reviews permit applications for superloads, which the agency defines as a gross vehicle weight (GVW) exceeding 120,000 lbs or any individual axle weight exceeding 25,000 lbs. A Policy Directive allows for Oversize/Overweight Blanket Permits (Annual Crane Permit). These permits allow unrestricted movement of cranes that exceed the legal load limits.

- The Iowa DOT conducts overweight/over-dimensional (OW/OD) checks for superload permits. The Division of Motor Carriers' OW/OD Branch screens the permit for roadway restrictions and then sends the permit to the load rating engineer to check the bridges on the route for weight capacity and vertical and horizontal clearance. Possible restrictions for superloads are as follows:

    - The vehicle cannot stop or park on the bridge
    - The vehicle must travel at a reduced speed (which reduces the dynamic impact)
    - No other vehicles can be on the bridge when the load crosses it (exclusivity)
    - The vehicle's axles are extended to spread the load transversely (crabbing)
    - The vehicle must exit off, then back onto, a road to avoid a bridge (avoidance)

- The Louisiana Department of Transportation and Development (LaDOTD) uses single trip permits and annual permits to control the access of over-load trucks. Single trip permits are used for one-way or round-trip movement of overweight vehicles. These permits are valid only for the specific date, time, vehicle, and route designated in the permit. Annual permits are issued for the movement of overweight vehicles over a specified route or within a restricted area. Annual permits are usually valid for unlimited trips over a period not to exceed one year. The permit vehicle may mix in the traffic stream and move at normal speeds without any restrictions. Annual permit analysis is performed using distribution factors for two or more lanes of loading. A similar method is also used by the Wisconsin DOT (WisDOT).

- In Nevada, very heavy and large transporter vehicles are allowed to travel over the State's highways by an over-dimensional permit. Nevada allows double-wide vehicles operating with these permits to carry double the load allowed for an 8 ft wide vehicle. Nevada uses the same single-trip permit methodology as California and Arizona. Bridges are load rated for California DOT (Caltrans) P5, P7, P9, P11, and P13 permit vehicles as permit loads, and a database of these ratings is maintained by the Nevada DOT's (NDOT's) Structures Division. A transporter truck is classified by its axle weights and axle spacing in terms of loading intensity and number of axles. The highest loading intensity allowed is called Purple Loading. Bridges on a proposed route are checked for adequacy based on the load rating for a P truck with the same number of axles as the transporter. Additional load is allowed for vehicles with extra width and more than two wheel-lines per axle. A single-wide transporter at Purple Loading produces stresses in a bridge up to those produced by a P truck with the same number of axles. Similarly, a double-wide transporter with Purple Loading is equivalent to up to two P trucks side by side, each with the same number of axles as the transporter. Bridges listed as having a P13 permit truck design are expected to carry a double-wide transporter equivalent to two P13 trucks side by side.

- In New Hampshire, the specific axle weight criteria used to identify vehicles for a bridge review are identified. Bridge reviews conducted as part of an overweight (OW) permit application are handled using the Bridge Overweight Permit Review (BOPR) software created in-house. Using BOPR and a bridge map, a list of bridges to be crossed on an applicant's proposed route of travel is assembled. The BOPR software identifies bridges in the list for which the applied load effects of the permit vehicle exceed the safe live load capacity of the structure. The software accomplishes this task by computing the load effects produced by the permit vehicle on each span length and comparing this information to a database of Bridge Capacity Summary sheets kept on file for all bridges in the inventory. Final determination for approving or denying permits and stipulating controlled crossing conditions for specific bridges is made by the engineer processing the bridge review.

2.1.8 Quality Management

Quality management is one key to ensuring the accuracy of load rating results. The AASHTO MBE provides a general description for quality control (QC) and quality assurance (QA) as related to bridge load rating and evaluation. A similar statement of quality management is usually included in State bridge load rating procedures as well. A review of the details of these management procedures indicates that most States created their rules based on the AASHTO MBE. If detailed responsibilities could be found from individual State bridge load rating procedures, they are summarized in this section.

Usually, the bridge load rating is accomplished through the cooperation of multiple engineers with different responsibilities. These personnel include a load rater and a checker for QC and a checker for QA. Some DOTs assign a bridge management engineer or chief load rating engineer to oversee the QA activities, assist with the QC process, and be responsible for load posting bridges. Any load rating that results in a recommended bridge load restriction posting might be reviewed and approved by the bridge management engineer; however, not all States have this position.

The load rater is the individual meeting the qualifications outlined in the individual State's requirements who is assigned to perform the load rating of a specific bridge. The rater usually ensures that the most up-to-date rating summary sheet, computer program manuals, and any other materials to perform bridge ratings are used.

The checker is the person responsible for verifying that the rating is accurate, the rating process follows established procedures, and the rating package is complete. If the checker finds any inaccuracies or omissions, the checker returns the rating package to the rater for corrections. Usually, one of the load rating engineers, including the rater and checker, is a State-licensed professional engineer and will stamp the load rating results. Typically, two checkers are assigned for a load rating project: one for QC and one for QA.

The person responsible for QC is an independent reviewer of the load rating package. A process of applying systematic procedures to ensure accuracy and consistency during bridge load rating analyses and their documentation is desired. QC is applied to all stages of the bridge load rating analysis. The person performing the load rating is not the QC reviewer. Typical QC procedures include the use of checklists to ensure uniformity and completeness, the review of reports and computations by a person other than the originating individual, and periodic field review of the inspection teams and their work. Examples of the work performed by the QC checker, as defined by some States, include the following:

- Perform detailed checking of design calculation procedures
- Use provided templates and report formats to maintain consistency
- List all assumptions considered for the load rating
- Include the results of each live load and applicable limit state
- Check computer program input procedures
- Check completeness and accuracy
- Provide additional calculations as necessary to support computer program input
- Document the load rating report in a file separate from the load rating report
- Verify the appropriate equations and calculations for load rating
- Verify that the summary of the load capacity information accurately reflects the analysis
- Verify the accuracy and suitability of the computer program
- Assist the load rater in documenting and resolving any discrepancies found by the load rating checker

The objective of QA is the continual improvement of the total delivery process to enhance quality and productivity. The person responsible for QA is an independent reviewer of the QC process and the load rater, which ensures that the load rating package is consistent with the State requirements. QA procedures consist of reviewing a sample of load rating reports annually to verify the quality level of the load rating program and the adequacy of the QC procedures to meet or exceed the standards established by the agency or the consultant performing the load ratings.

2.2 Review of Peer Exchange Meeting Content

From August 2014 through August 2019, the FHWA Office of Bridges and Structures and Resource Center facilitated six peer exchanges attended by State DOT and FHWA Division office representatives. Table 2 shows the State attendees for each regional meeting.

Table 2. Regional State load rating peer exchanges

Exchange	Participating States
Northeast	CT, MA, ME, NH, NJ, NY, PA, RI, and VT
Southeast	AL, FL, GA, KY, LA, MS, NC, SC, and TN
Mid-Atlantic	AR, DC, DE, KS, MD, PR, VA, and WV
Midwest	IA, IL, IN, MI, MN, MO, OH, and WI
Southwest	AZ, CA, HI, MN, NV, OR, and TX
Northwest	CO, ID, MT, ND, NE, SD, UT, WA, and WY

The presentations from the regional bridge load rating peer exchanges were reviewed by the research team. The following is a list of major topics discussed at the peer exchanges and expanded upon in the subsequent sections:

- Accommodating deterioration in load rating
- Rating of gusset plates
- Re-rating triggers and follow-up
- Rating of concrete box culverts
- QA/QC procedures for load rating
- Responsibilities for load rating and posting of locally owned bridges
- Rating of FAST Act emergency vehicles
- Load posting procedures and signage

2.2.1 Accommodating Deterioration

The accommodation of deterioration in the load rating process was discussed by the representatives from two State DOTs. One re-rates a bridge when defects occur or extend at the critical location in a shear or moment zone. These defects include: (1) bottom flange and web section losses on a steel girder; (2) spalling or delamination along the bottom, tension steel, and stirrups with corrosion, often near construction joints on reinforced concrete beams; (3) prestressing strands corroded or broken in prestressed concrete beam; and (4) decayed timber, corroded steel, and increased unbraced length or scour for piles.

The other State DOT mainly used commercial software to calculate the rating factor for most bridge structures. A few tips were introduced to account for deterioration in the calculation of the load factor. For example, for a steel beam bridge, the section loss of the tension/compression flange and web could be accounted for by inputting the loss of thickness in the software. A study from van de Lindt and Ahlborn (2005) describes the relationship between web loss and residual capacity for W-beams.

In general, for reinforced concrete beams and slabs, the loss of capacity due to spalling of the reinforced section could be accounted for by reducing the area of reinforcement based on the section, and the concrete deterioration in the compression zone could be modeled by reducing the compressive strength of concrete. The reduced compressive strength could be obtained by conducting material testing on the field-obtained samples or using condition reduction factors from the AASHTO MBE.

For prestressed concrete beams, the effect of exposed strands could be considered by simply removing the visible and adjacent strands. Top flange concrete deterioration could be modeled by reducing the compressive strength of concrete using commercial software.

For trusses, the loss in the tension or compression member section could be modeled by inputting reduced capacity in the commercial software. Gusset plate deterioration could be modeled by calculating the capacity reduction and then inputting the reduced capacity in the software.

A common practice was to use design codes or the AASHTO MBE and analytical methods for natural deterioration. However, how to appropriately accommodate deterioration in the load rating process lacked codified guidance in statutes or regulations. Additional research is needed in this area to evaluate the effect of different types of deterioration on the load rating.

2.2.2 Rating of Gusset Plates

One State DOT had 25 truss bridges in its system, all of which were rated for HS20-44 loading for the floor system. Some of the bridges were rated for truss members, and none had been rated for gusset plates at the time of the peer exchange. It was pointed out that there was no guidance for load rating gusset plates when the State DOT started the work. The State DOT had developed procedures and gusset plate check spreadsheets. The agency assumed a section loss of 5 percent for upper members and gusset plates and 15 percent for lower members and joints.

After the Minneapolis I-35W bridge collapse on August 1, 2007, the FHWA issued Technical Advisory 5140.29, Load-Carrying Capacity Considerations of Gusset Plates in Non-Load-Path-Redundant Steel Truss Bridges (FHWA 2008). The FHWA also updated bridge inspection and training courses to address proper inspection and load rating for gusset and other connection plates.

2.2.3 Re-Rating Triggers and Follow-Up

One State DOT performed routine load rating for each bridge every 10 years and a condition-based re-rating when the NBI condition rating was lower than 4. Another reason to trigger a re-rating was to include new legal loads in the load rating. The routine load rating used the LRFR method, included additional legal, emergency, permit, and bus vehicles, and incorporated recent research results.

Condition-based re-ratings usually involved modification of beam section properties to account for deterioration. The re-rating process was also triggered when bridge rehabilitation or modifications occurred and when there was a change of construction loading, including cranes, stockpiling, or paint containment systems. Re-rating for bridge rehabilitation or modification started with the existing load rating data, file, or model and accounted for bridge geometry, load distribution, and material property changes.

2.2.4 Rating of Concrete Box Culverts

Two State DOTs load rated concrete box culverts following the AASHTO LRFD and AASHTO MBE. Culverts in one State were rated utilizing either the LFR or the LRFR method. It was pointed out that a few challenges exist during the load rating process for concrete culverts, including a lack of plans, specifications, or shop drawings and a lack of culvert load rating guidance in Section 6B of the AASHTO MBE.

Another State DOT was currently using a commercial software package to load rate box culverts. Before that, a spreadsheet was used. The commercial software is capable of performing load ratings utilizing both the LFR and LRFR methods.

2.2.5 Quality Assurance and Quality Control Procedures

One State DOT delivered a presentation on QC/QA procedures for structures during the Northwest peer exchange to discuss the agency’s common approach to performing QA and QC checks, including QC check color codes, etc. The State DOT’s procedures define expectations, processes, procedures, and requirements for performing QC and QA of structural work.

It was indicated that the procedures are a tool and cannot replace the sound judgment and experience of competent professionals. The structures QC and QA procedures are implemented on all deliverables and according to the stages, activities, and guidelines for the State. Structures QC and QA procedures consisted of five independent roles: design, QC check, QA audit, reviews, and acceptance.

2.2.6 Responsibilities for Load Rating and Posting of Locally Owned Bridges

In one State, all local agencies inspected and load rated its own structures. The rating software provided by the State DOT included a commercial software package, corrugated metal pipe analysis spreadsheets, gusset plate analysis spreadsheets, and other packages. Local agencies could contact the State DOT through the Local Technical Assistance Program (LTAP) for additional technical support via phone or email and for training via webinars and workshops. The State DOT monitored local agency load rating and posting through its bridge management system. Local agencies were responsible for installing load posting signs and updating the information in the State's bridge management system.

Another State DOT performed monthly data checks for load posting issues and notified agencies of potential deficiencies. Other State agencies manage the inspection and load rating of local agency bridges. One State DOT would then issue a load posting recommendation to local agencies if deemed necessary. The responsibility then went to the bridge owner to post the bridge with the State DOT following up to verify that the owner had posted the bridge within 30 days.

2.2.7 Rating of FAST Act Emergency Vehicles

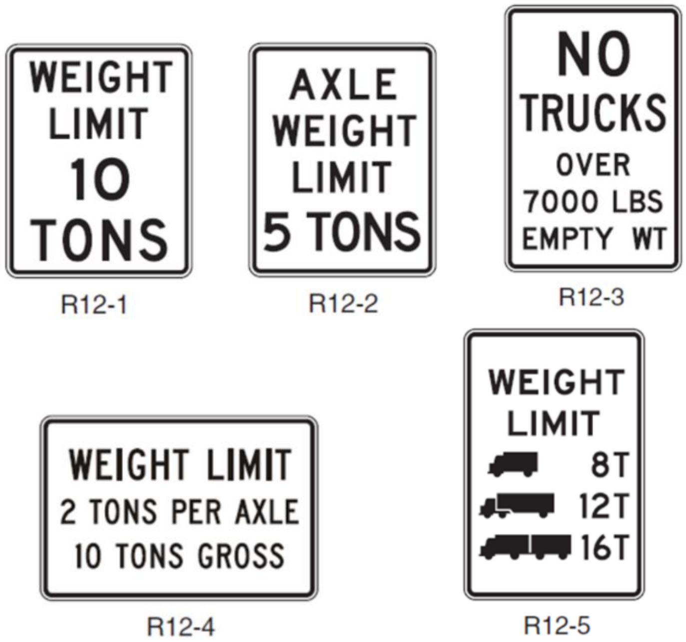
One DOT had been working on including FAST Act EVs (which were subsequently codified under 23 U.S.C. § 127(r)) in its load rating process. It was found that these vehicles were heavier, larger, or both than HS20-44 loading, and the agency's software had not yet been updated to account for the difference. More work needed to be done to align the software with the load rating and posting guidance and to include the new EVs in the software.

Another DOT was in the sixth year of its 10-year re-rating improvement plan. During the first five years, all State-owned bridges that could be rated with a particular commercial software package and 51 percent of local bridges were re-rated. To include all loadings listed in the AASHTO MBE and the FAST Act's EV2 and EV3 (as codified under 23 U.S.C. § 127(r)), the DOT had to open nearly every bridge report from the first five years to generate one complete rating report.

2.2.8 Load Posting Procedures and Signage

One DOT presented its load posting procedures at the Southwest peer exchange. After load rating, the State bridge engineer notifies the district office what to post and how to sign the bridge accordingly. The most commonly used sign in the State was either R12-1 or R12-4. There were no specific changes to the signage based on bridge type. That DOT requests images of signage from districts as verification of completion and stores these in a file for oversight review. A few issues with these procedures were reported, including: (1) follow up by and with districts on posting is difficult due to, perhaps, no tracking and verification system or unwillingness to post by local officials, (2) follow up by and with counties is even more difficult, even with a plan of corrective action, and (3) district staff have non-redundant information, skills, or both.

At the Northwest peer exchange, the attendees discussed their individual State load posting procedures and signage. Six of the nine States had a formal written policy on bridge closures, and the timeframe to post once notification has been received for State and local bridges was between 10 and 90 days. All nine States kept records of posting notifications and images of postings were included in a bridge file, while posting signs vary widely (see Figure 1).



MUTCD (FHWA 2009)

Figure 1. Posting signs

2.2.9 Automated Permitting System

Over-legal loads may have significant effects on the infrastructure system compared to regular legal vehicles. Automated bridge permitting systems have been used by States for many years because they offer a method for States to provide efficient service for truck drivers. The National Cooperative Highway Research Program (NCHRP) U.S. Domestic Scan Project 20-68A (Farrar et al. 2014) indicated that, although successful pioneering practices have been conducted to improve the efficacy and uniformity of superload permitting processes, significant differences among States still exist.

During the peer exchanges, engineers from at least four States reported that an automated permitting system existed in their States. The most commonly used system allowed for a completely automated and full analysis (including clearances, bridge analysis, and restrictions) in minutes. This commercial software system was capable of releasing a single permit application (subject to permit application completion and a compliance check), issuing a possible third-party verification (for insurance, taxation, and safety), and performing a complete analysis that included clearances, bridge analysis, and restrictions. One State DOT recommended good communication with bordering States to help eliminate cross-routing issues.

One state was customizing the commercial software, and it could be used for routing and all oversize/overlength (OS/OL) vehicle permitting and enforcement. The system was being tested in parallel with the existing, non-automated permitting process. A few challenges were presented: (1) the permit passing rate was low, (2) the algorithms lacked an engineering judgment factor, (3) it seemed very challenging to keep the structural condition up to date for the system to use, and (4) concerns existed regarding general system performance.

One State's permitting office utilized an automated permit routing system to assist in movement through the State. The system enabled a large variety of functionality to all users, including bid route functionality built into the system to provide assistance in preliminary routing for planning purposes. For oversize/overweight (OS/OW) annual permit holders, an annual permit routing utility was in place to help users navigate throughout the State, taking into consideration weight-restricted structures and construction-related limitations as they self-routed. A list of restrictions was also located on the State DOT's main website, along with a portable document format (PDF) version of the Pilot Escort map.

The Colorado Oversize Overweight Permitting and Routing (COOPR) system has the on-system structures listed in its database. As these structures are rated, the automated system has the ability to automatically route around these critical structures to help prevent any additional degradation to them. Only the color-rated structures were immediately routed around at this juncture. There were a large number of critical structures that were not color rated because they had been upgraded from a rating perspective through the years.

2.3 Literature Search on Related Advanced Technology

Load rating information is usually used to (1) prioritize structures for repair or replacement, (2) restrict the weight of vehicles that are allowed on a particular bridge, and (3) determine routes for permit vehicles (Chajes et al. 2000). Although most load ratings are being accomplished utilizing the previously discussed analytical methods, for almost all load ratings, the results can be improved by conducting load tests or performing long-term monitoring.

Structural health monitoring (SHM) technology today is smaller, more flexible and accurate, easier to use, less expensive, and more reliable than it was 20 years ago, and, hence some advanced technology has been incorporated into the bridge load rating process. This section presents currently used and emerging technologies for load rating, posting, and overweight permitting. The primary focus of this information collection was published literature in the form of journal papers, reports, and DOT circulars.

2.3.1 Bridge Load Testing

In the AASHTO MBE, the two main types of load tests for bridge condition and capacity rating are diagnostic tests and proof tests. Yost et al. (2005) summarized a procedure that is commonly used to conduct a load test: (1) instrumentation plan development, (2) sensor installation and data acquisition configuration, and (3) performance of the load test.

Before the load test is conducted, an engineer should have thorough knowledge of load rating so that critical members and member locations can be identified for instrumentation. The commonly captured structural response includes strain and displacement while under live load(s). In some cases, tilt and vibration or acceleration data are also measured. The strain is typically measured from an electrical resistance device such as a foil strain gage. Axle weights are typically provided by the driver, who obtains them from a local scale. The wheelbase and axle spacings of the test truck are measured on site. Finally, the data acquisition system is started, transducers are zeroed out, and the test truck proceeds across the bridge (commonly) at a crawl speed.

Two passes of each load case are conducted to ensure that the structural response is reproducible. To match the test data with the physical location of the truck, the datum approach is utilized (details can be found in Yost et al. 2005). To reduce the on-site labor associated with checking the truck position or datum, devices have been developed to automatically perform this task.

2.3.1.1 Proof Load Test

In a proof load test, a bridge is loaded incrementally up to a target live load (Cai and Shahawy 2003). In many cases, an accurate analytical rating is not possible due to the uncertainty of field factors including diaphragm action, parapet stiffening, contribution of secondary members, concrete hardening, unintended composite action, unintended bearing restraints, corrosion of steel members, loss of sections due to cracking, material deterioration, etc. In these instances, a proof load test may be used to establish the maximum safe load capacity of a bridge, where the bridge behavior is within the linear-elastic range. The proof load rating is a proven lower-bound method.

2.3.1.2 Diagnostic Load Test

Diagnostic load tests are performed to determine certain response characteristics of a bridge and to validate or improve analytical procedures. The diagnostic load rating has been proven to be similar to linear extrapolation, making it somewhat of an upper bound approach in nature. Chajes et al. (2000) summarized the situations when diagnostic tests are preferred as follows:

- Information from inspection and analysis shows that the bridge cannot risk taking the target live load of a proof load test
- The loading capacity of test vehicles cannot deliver the target live load of a proof load test
- Traffic conditions prevent placing testing vehicles in all possible combinations for a proof load test to produce the maximum live load effects
- Based on previous experience with similar bridges and observed behavior, further loading is not necessary, and a test is terminated before the target live load

A diagnostic load test is typically followed by an analytical simulation. Often, these analytical simulations are performed utilizing finite element (FE) methods. The field test data are used to calibrate the FE models. To facilitate calibration, forced compatibility between field sensor locations and FE model nodal point topology is recommended. Additional stiffening features such as parapets, diaphragms, bracing, and curb lines can also be included as needed.

To reduce the computation time, Yost et al. (2005) suggested that the deck slab be modeled using shell elements and the supporting beams and diaphragms be modeled using frame elements. Elastic restraint at the supports is modeled using spring elements with calibrated stiffness as appropriate. The live load response of the model is calculated by applying the distributed moving load to the deck elements. The accuracy of the model is determined by comparing calculated and measured strain histories. The parameters of the FE model, including the Young's modulus, support conditions, etc., can be adjusted to calibrate the model response to the field-measured response until an acceptable agreement is achieved. Finally, critical dead and live load effects are applied to the FE model, and the model is used to calculate the load rating.

2.3.2 Bridge Monitoring and Traffic Detection

Although a field load test allows an engineer to understand the structural behavior and predict the capacity of the bridge, there are limitations: (1) some level of traffic control during testing is needed, (2) the test setup takes time, and (3) the measured data represent only a snapshot in time.

In the past 20 years, significant advancements have been made in the fields of nondestructive testing, electronic instrumentation, and data acquisition. These new technologies provide an opportunity to collect adequate data to obtain a comprehensive understanding of a bridge's behavior. Much work has been conducted that aims to develop an in-service monitoring system to collect the desired data for a bridge evaluation assignment, including bridge load rating.

Aktan et al. (2000) envisioned that future structural health monitoring systems in the field of transportation will take advantage of integrated information systems and will permit officials and engineers to access, review, and analyze legacy and recent data and information in addition to real-time data. The next-generation system will take advantage of a high-speed fiber-optic local area network for collecting data from sensor clusters distributed throughout a bridge. The WIM and weather monitor systems will maintain wireless communication with a bridge data server. Integrated streams of data and images will be transmitted from the bridge data server through the internet for remote control of data acquisition, viewing, processing, and archival.

In-service monitoring has the following advantages: (1) does not require traffic control during monitoring, (2) records the response due to ambient traffic, thereby proving statistical information about actual response, and (3) allows the response to be tracked over time (Chajes et al. 2000). However, as the researchers pointed out, the limitation of in-service monitoring is that the weight and classification of the truck loadings are not specifically known, which poses challenges for explicitly evaluating bridge parameters. One solution for collecting detailed data on the weight and classification of trucks is to utilize a WIM system.

Traditional WIM systems use pavement-based sensors installed on a roadway. The major drawbacks of these sensors include the following: (1) surrounding pavement conditions can greatly affect their performance; (2) truck operators can discover the locations of sensors and take steps to avoid them; and (3) roadway closures are required to install the pavement-based sensors.

Moses (1979) suggested using a bridge as a scale with strain gauges installed to estimate the weight of trucks crossing the bridge. This concept is commonly called a bridge WIM (BWIM) system. BWIM systems are undetectable to truck drivers and do not require road closures for installation. Over the years, research has been conducted on developing BWIM systems, and many improvements have been made, including (1) separation of multiple lane loads, (2) separation of sequential truck loads, (3) measurement of axial weight and spacing, (4) preliminary identification of the vehicle's classification, and (5) detection of lightweight or small vehicles.

Cardini and DeWolf (2009) indicated that many different methods exist for implementing BWIM systems, and each method has its advantages and disadvantages. The factors that need to be taken into consideration before selecting a BWIM method include pavement smoothness, calibration procedure, superstructure type, span and support conditions, and bridge geometry. However, further research is still necessary, and much is ongoing, to allow BWIM systems to capture more accurate and detailed truck information and classification (Cardini and DeWolf 2009, Moses and Ghosn 1983, Wall et al. 2009).

Although further improvements are still needed to BWIM systems, this concept has been used as an in-service monitoring system for bridge load rating. To overcome challenges in the development of a BWIM system, advanced technology in other fields has been adopted and evaluated. For example, Zaurin and Catbas (2009) and Catbas et al. (2012) presented a damage index to determine the change in structural behavior by using both images and sensor data, especially for bridge-type structures.

Images and responses are correlated and used to create a series of unit influence lines to be used as an index for structural evaluation. The background subtraction method is used to detect the type of vehicle and the magnitude and location of the loads transmitted to the structure through the wheels. Pixels in the current frame that deviate significantly from the model are considered to be moving objects and to belong to the foreground. In addition, the number of wheel axles is identified by using an additional camera located perpendicular to the traffic flow direction.

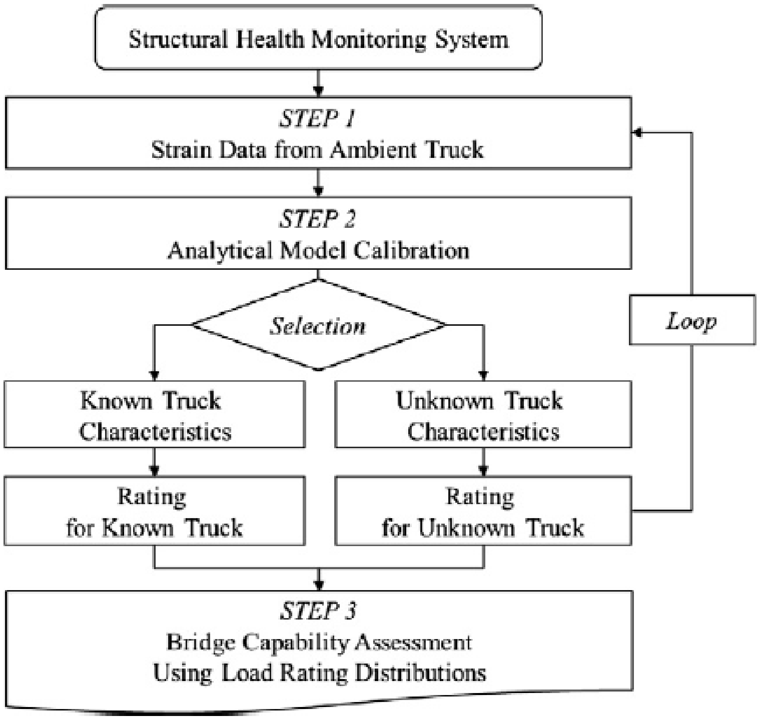
Zaurin and Catbas present a methodology where unit influence lines are extracted from synchronized video and sensor data. This approach was validated in an experimental test and a field demonstration test to obtain upper and lower bounds for bridge load rating and to warrant the condition of the bridge using load tests. However, many limitations and uncertainties in the experimental process that may lead to errors were identified and are summarized as follows:

- Uncertainty in synchronizing time with distance
- Uncertainty in the straight path of the truck
- Uncertainty in data filtering to remove ambient effects and system noise from the static data

- Uncertainty in the weight per axle that may lead to a different unit influence line
- Uncertainty in the assumption of linear bridge behavior
- Uncertainties due to environmental effects on the stiffness and behavior of a bridge

Hou et al. (2019) developed a data-driven load rating approach based on data collected from a highway corridor with bridge monitoring systems, traffic cameras, and WIM stations linked together in a cohesive cyber-physical system (CPS) architecture. The CPS architecture is designed to capture and track trucks in the corridor so that bridge excitations can be attributed to measured truck weight parameters. Computer vision algorithms, and namely convolutional neural networks, are embedded with traffic cameras to identify the trucks. This allows a bridge's responses to a given truck to be conclusively linked to truck weight parameters measured by a WIM station that is not collocated with the bridge. All data collected (i.e., bridge strains, camera frames, and WIM records) within the same data collection cycle are automatically uploaded to a server hosted in the cloud. When uploading is completed, a program on the CPS sever automatically detects and synchronizes truck events between the different types of data at each location, after which each detected truck event is segmented from the original dataset as a set of truck images plus either the bridge monitoring data or truck weight data. Based on truck weight and bridge strain response data, essential load rating parameters, such as the dynamic load allowance, are estimated and investigated under various loading scenarios. This can lead to more accurate load ratings specific to the monitored bridge. The study showed that it is feasible to link measured bridge responses to truck axle weights measured using a WIM station by identifying the truck through computer vision.

Seo et al. (2013) developed a nonregulatory protocol to estimate the load rating distributions for bridges from the measured response to ambient trucks. The critical regions of the bridge were instrumented using strain sensors to measure the real-time strain time history resulting from ambient trucks. Strain time history data and the truck characteristics obtained from weigh stations located near the target bridge were used in the model calibration. A flowchart of the procedure is shown in Figure 2.



Seo et al. 2013, © 2012 Elsevier Ltd. All rights reserved. Used with permission from Elsevier

Figure 2. Flowchart to estimate load rating distributions

The first step is to randomly select sets of actual strain data from the target bridge loaded by ambient trucks. The second step, which focuses on model calibration with ambient strain data, has two critical sub-steps: model calibration and rating calculation.

Two possible scenarios were tried for the first sub-step: (1) known and (2) unknown truck characteristic selections. In the first scenario, ambient truck characteristics were identified by investigating strain time history patterns obtained from the deck bottom sensors. These patterns allowed for the identification of ambient truck configurations, including axle numbers and spacing. The truck characteristics that closely matched the features were identified and then used for model calibration.

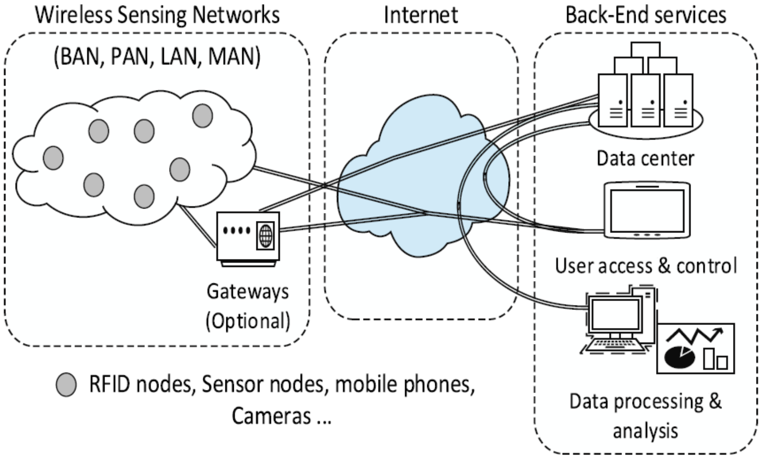
For the second scenario, to account for more variability in the configurations than the first scenario, a number of unknown trucks were randomly selected from the weigh station and then used to calibrate the models. The calibrated models, along with standard HS20-44 loading following the AASHTO LFR method, were used to calculate load rating factors. This protocol was then validated against that obtained from a rating package used by the Iowa DOT.

The results from Seo et al. indicated that the rating factors obtained from the proposed method were 24 percent and 27 percent for known and unknown truck selections, respectively, greater than the values obtained from the Iowa DOT rating package. Generally, the higher load ratings can be attributed to field tested bridges exhibiting better load distribution characteristics than conventional rating methods.

2.3.3 Connectivity and Communication Technology

Due to the large size of the existing bridge inventory, it can be difficult to widely deploy conventional technologies to monitor performance. The rapid development of sensing technologies, data transmission, and communication technologies has provided many alternatives for collecting the data in a more efficient way at a lower cost. Many new technologies have been used to improve the connectivity and communication between the sensors and the data acquisition systems; a few commonly used technologies include internet of things (IoT), wireless sensor networks (WSNs), and RFID.

IoT is a global system based on an internet protocol (IP) suite in which objects equipped with sensors, tags, or barcodes have a unique identity, operate in a smart environment, and are seamlessly integrated into the information network by using intelligent interfaces. Tokognon et al. (2017) provides a flowchart (Figure 3) to illustrate the use of IoT in a structural health monitoring system, which could be a part of a next-generation bridge load rating system.



Tokognon et al. 2017, © 2017 Institute of Electrical and Electronics Engineers (IEEE), used with permission

Figure 3. Use of IoT in structural health monitoring

To date, one of the greatest challenges in deploying a WSN is the power consumption of the sensors and field-installed data acquisition system. The power consumed by the wireless sensing unit is a function of the voltage and the amount of electrical current supplied to each component. A common practice for a bridge monitoring system in a city has been to get power from a nearby ground line. For highway bridges, solar panels are commonly used to supply power to the monitoring system. However, both methods require wires to directly connect each sensor, which reduces the benefits of the wireless sensing system.

To eliminate wires in a bridge monitoring system, wireless sensing units can instead employ batteries that have a limited supply of energy for the near future. Batteries are not feasible in the short-term because current power harvesting techniques cannot yet provide a reliable, convenient, and low-cost solution for powering typical wireless structural sensors (Churchill et al. 2003, Roundy 2003, Sodano et al. 2004). Zhou and Yi (2013) pointed out that wireless sensing technology is still in its infancy, and much work remains before this promising technology can fulfill the requirements for complex bridge monitoring and evaluation. The power source, which is responsible for providing stable energy to the sensing interface, computing core, and wireless transceiver, commonly employs batteries. Therefore, to date, a major effort in the field of wireless-based SHM involves the development of high-performance wireless sensors.

2.3.4 Intelligent Transportation Systems and Technology

An ITS integrates traffic information with a bridge monitoring system to evaluate the effect of traffic operational conditions on a bridge structure. ITS devices usually include roadway traffic monitoring sensors, such as loop detectors, WIM stations, digital traffic monitoring cameras, etc. (Khan et al. 2016).

A few successful uses of ITS have been seen in the field of bridge engineering. For example, ITS has been used to investigate the response of bridges subjected to normal traffic flow. Zaurin and Catbas (2009) used data collected from both ITS and SHM sensors and synchronized the data to construct unit influence lines. Catbas et al. (2012) used a computer vision process to analyze images and understand the images' content. Using data derived from strain gauges and video cameras, the authors experimentally performed a load rating analysis to calculate a bridge structure's load carrying capacity.

Other applications have involved evaluating the response of a bridge to critical events and the development of bridge management systems. Khan et al. (2016) indicated that an intelligent bridge management system consists of the following four components: (1) information acquisition, (2) data management, (3) evaluation and decision making, and (4) application service.

An ITS employs RSE and OBE systems. The U.S. DOT's Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) Technology Test Bed provides a V2V and V2I communication system that researchers can use to test and demonstrate traveler services through applications that interface within this framework.

For example, the V2V and V2I Technology Test Bed includes a number of features that support in-vehicle signage (the display of messages to drivers), including RSE, that broadcasts vehicle messaging data to vehicles and OBE that receives the data, stores messages in a queue of messages that should be displayed when a vehicle enters a geographic area, and tracks the vehicle's position to display messages at appropriate locations. If an incident occurs, this type of application could transmit information about that incident to the V2V and V2I Technology Test Bed back office servers, which would then push that information to the appropriate RSE and, from there, to OBE-equipped vehicles. The vehicles would then display information about the incident.

A similar concept was explored in work conducted by Judd et al. (2017). When a vehicle traverses the highway with a tag inside the vehicle, the transponder at the bridge detects the approaching RFID tag and triggers the data acquisition system to release the response (strain) data from a sensor interrogator through a microcontroller to a network portal.

2.3.5 Digital Asset Maintenance, Stewardship, and Governance

Research to develop infrastructure information management systems for field monitoring and inspection activities has been ongoing. For example, a complex bridge maintenance management system was developed by Ni and Wong (2012). This system integrates SHM and a maintenance management system for condition-based maintenance (CBM) of in-service bridges. This system was designed to fulfill eight main functions, as follows:

1. Inspection, through visual inspection with a systematic inventory and structural condition rating system
2. Monitoring, though an on-structure instrumentation system with appropriate data processing, analysis, and reporting software tools
3. Evaluation, through routine field-calibrated finite element models and appropriate analytical methods
4. Rating, through codified requirements of design and rehabilitation with programming tools
5. Maintenance, through maintenance strategies, options, priorities, and availability of resources
6. Enquiry, through data buffer and network security tools
7. Management, through management of data and information with a data warehouse management system and online analytical processing tools
8. Display, through the display wall system

The capabilities of this system include but are not limited to monitoring structural and durability health conditions under the performance thresholds at the serviceability limit state, evaluating structural and durability safety when the serviceability limit state thresholds are exceeded, and rating the inspection, monitoring, and evaluation results based on codified or designated criteria for inspection prioritization of structural components.

Another method to generate and manage data during an infrastructure's lifecycle is BIM (Lee et al. 2006), which was previously discussed regarding its use in conjunction with RFID. BIM is a digital representation of the physical and functional characteristics of a facility. It allows for the definition, storage, sharing, and maintenance of applicable information. BIM covers geometry, spatial relationships, geographic information, quantities, and the properties of structural components. BIM can achieve improvements in data management by modeling representations of the actual components of the structure. Several technology providers provide such professional services (Ackerman et al. 2017, Shim et al. 2017).

Following the introduction of BIM, Al-Shalabi et al. (2015) implemented Bridge Information Modeling (BrIM) technology for bridge inspections and compared it to the conventional approach of using paper checklists. The software environment includes a 3D representation of the infrastructure and allows the integration of inspection data, such as the presence, type, severity, and localization of damage and previous maintenance decisions.

2D drawings and previous inspection and maintenance data from two bridges in Iowa were modeled using Revit. Both models were synced using cloud-based solutions so that the models could be accessed from tablet computers on-site. Then, the technology was tested by Iowa DOT engineers and bridge inspectors, who confirmed that BrIM can be used to automatically query, sort, evaluate, and send information to decision makers. The results indicated that this methodology can substantially improve bridge assessment and maintenance operations, resulting in a reduction in the costs associated with bridge assessment (of which bridge load rating is a component) and improvements in structural resiliency by enabling more effective maintenance and repair operations.

2.3.6 Digital Twin Concept

Many research activities have been conducted to implement the digital twin concept in bridge engineering. These activities provide a primer as to what can be possible in a next-generation bridge load rating system.

The digital twin concept has been widely used in vehicle and aerospace engineering (Mayani et al. 2018) with the interaction and convergence between the physical and cybernetic aspects of manufacturing attracting increased attention, as the digital twin concept paves the way to cyber-physical integration.

The practice of digital twinning involves the creation of virtual, digital models for physical objects to simulate their behaviors. The virtual models can capture the state of the physical entities through sensor data to predict, estimate, and analyze dynamic changes to the objects (Qi and Tao 2018).

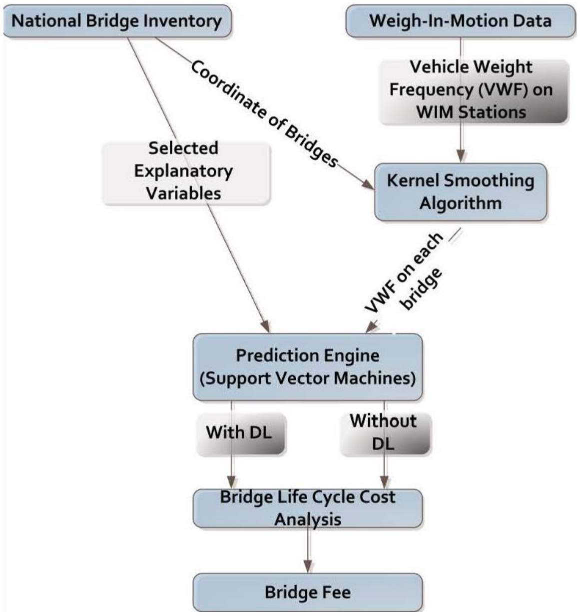
Dang et al. (2018) proposed 3D digital twin models of typical bridge structures for the next generation of bridge maintenance systems. 3D geometric models are created through a combination of 3D scanning and alignment-based parametric modeling. The 3D digital twin models include information for analysis and the basic attributes of the design and construction parameters. Damage records are linked to the structural members of a bridge and have unique code numbers. Environmental conditions, including temperature, humidity, loading history, and monitoring data, provide essential information for predicting the future performance of a bridge’s structural members. Deterioration of or damage to a structure changes the structural parameters in the model for future analysis. The digital model is updated with each new inspection result and as new monitoring data are added.

This approach was implemented on a prestressed concrete bridge and cable-supported bridges by Shim et al. (2019a, 2019b). The results showed that the maintenance tasks on the bridges were significantly enhanced due to the models, and more possibilities to use recent technologies were found through the initial application. However, the implementation revealed three major challenges: automated data capturing and BIM creation, the timely updating and completeness of maintenance information, and controlling for uncertainty in the data.

2.3.7 Automation and System Integration

Automated permitting systems have been used by many State DOTs to provide efficient service for truck drivers requesting permits for overweight trucks. The details of these systems were previously presented. In addition to the applications described, automated systems have been developed to estimate and charge overweight vehicle fees.

Gungor et al. (2018) developed a fully data-driven framework for computing overweight vehicle fees that combines historical bridge data from the NBI and WIM data. In this framework, information regarding vehicle weight distribution on bridges is obtained using Gaussian mixture model-based interpolation. Using this interpolation approach, the vehicle weight distribution on each bridge can be estimated from WIM data based on location. These estimated distributions are then combined with the NBI data to develop a machine learning-based prediction model that takes bridge characteristics (e.g., age and traffic) as inputs and outputs deck condition. The model is employed to calculate expected bridge service life under two scenarios to compute a reduction in bridge life per damaging loads. Finally, a bridge life-cycle cost analysis is conducted to convert the calculated service life difference into a fee. A flowchart of the developed framework is illustrated in Figure 4.



Al-Qadi et al. 2017, Illinois Center for Transportation, used with permission

Figure 4. Automated overweight vehicle fee estimation system

CHAPTER 3. STATE DOT SURVEY AND REVIEW OF SELECT STATE DOT PROGRAMS

3.1 Survey Overview

Based on the findings from the desk scan and literature search for this project, a subset of State agencies was selected for further in-depth information collection. The information of interest included current practices for load ratings as well as the documentation for the technologies used. The purpose of this survey was two-fold.

First, the survey aimed to gather information on load rating practices from the States that appear to have initiated the implementation of advanced ideas, concepts, and technologies. Second, the survey would help to identify States that warranted an even more comprehensive review of polices, manuals, procedures or practices, and use of advanced technologies.

The survey was sent to nine State DOTs that were selected from the desk scan results, literature search, and discussion with the technical advisory panel. These nine States were Arizona, California, Indiana, Iowa, Kansas, Michigan, Ohio, Pennsylvania, and Wyoming.

3.1.1 Survey Development

The survey was developed with nine major sections. Figure 5 shows the form.

State of Practices: Bridge Load Rating

State		**Date**	
1. Bridge rating process			
1.1 What software is being used to perform load ratings for the following types of structures?			
Prestressed concrete beam			
Steel girder			
Steel truss			
Curved/complex			
Concrete box culvert			
Post tensioned structures			
Metal culverts under fill			
Concrete arches under fill			
1.2 How many bridges in your state have you built computer analysis and load rating models that can be reused? State Bridges_____% and Local Bridges _____%			
1.3 How is bridge deterioration being incorporated into your load rating models, and how is it communicated to other systems that the load rating model includes deterioration?			
1.4 What quality assurance/quality control (QA/QC) procedures are used for load rating?			
2. Automated bridge rating system			
2.1 Are weigh-in-motion (WIM) devices used for load rating or posting enforcement? If so, how is the WIM device used and how is the WIM data relayed to maintenance operations systems to ensure posting. Describe the success of this performance.			
2.2 Is the concept of a digital twin being used in bridge load rating, bridge reliability assessment and/or safety performance management? If so, please explain how it is incorporated and comment on the performance.			
2.3 Are any of the following concepts being used? If so, please comment on the respective performance. (Internet of Things [IoT], V2X [i.e. vehicle to bridge], dedicated short range communication [DSRC], radio-frequency identification [RFID], geofencing, intelligent [digital, smart, connected] bridges, Intelligent transportation system [ITS])			
2.4 Is any automated rating software being used?			

3. Integrated infrastructure data storage
3.1 How are the bridge load rating, geospatial, building information modeling (BIM) data and structural analysis models being exchanged within any integrated system(s)? (e.g., cloud computing services, software services)
3.2 How are the bridge load rating data and bridge analysis models being maintained and updated?
4. Permitting system
4.1 How are digital bridge assets being synchronized into the overweight permitting system?
4.2 How does a carrier determine a route for an overweight truck using the automated permitting system?
4.3 Are you making load rating data and permitting systems readily available to local agencies to assess posting needs and impacts of overweight permits on bridges?
4.4 Are you using any specific techniques for enforcement within the overweight permitting system?
4.5 Are you utilizing weigh station data to update bridge/load models used in the load rating process? If so, how are these data being used to establish protocols to update load rating procedures?
5. Bridge structural monitoring system
5.1 Is a bridge monitoring system (e.g., SHM) being used for load rating purposes? If so, what system and how does this system benefit the load rating process?
5.2 In what ways is this system being utilized?
6. Are you developing automated mechanisms to conduct parametric studies on new load models and assess impacts on highway corridors?

7. Can you use the bridge and load models to assess pavements, dynamic load allowance and model deterioration in bridge decks and superstructures?
8. Are there “experimental” systems or ongoing related research projects in progress for the purpose of doing/helping/enhancing load rating? If yes, could you please provide any details on this work?
9. How do you rate the level of automation for Load Rating and Permitting in your state? ______ Level 1 – No automation; all manual. No or small percent load rating can be easily updated or reused. Level 2 – Mixed computer analysis models and paper (hard copy, spreadsheet) calculations. The computer models can be updated manually and re-run. Level 3 – Predominant (almost all) computer analysis models. The computer models can be updated manually and re-run. Level 4 – All computer analysis models (digital twins). The computer models can be updated quasi-automatically and re-run. Level 5 – All computer analysis models (digital twins). Fully automated updating and rating.

Comments: ____

____

Figure 5. Survey form

3.1.2 Survey Results

The survey results are summarized in Table 3 through Table 8 for each individual section or group of sections.

Table 3 shows the results from the Section 1 bridge rating process part of the survey (skipping the detailed results for questions 1.1 and 1.2 in the table to not include commercial software specifics in this report). The results for question 1.1 of the survey did indicate diversity in software usage by States to complete the bridge load rating process. The Kansas DOT (KDOT), for example, indicated the software that KDOT uses could cover all the structures listed for question 1.1 of the survey.

All of the surveyed DOTs considered deterioration of individual bridge elements, global deterioration, or both by changing the element level capacity using one or more of the following: condition factor reduction, cross-sectional property reduction, material property reduction. One State indicated that its bridge management approach was to not let deterioration occur to reduce structural capacity and deterioration was therefore not a factor in changing load ratings. A common approach for determining the deterioration level and its impact on the load rating is to rely on bridge inspection results. However, no automated approaches or prescriptive methods were found to be used in this process.

The results indicated that more than 50 percent of the bridges have been load rated using software with computer models that can be re-used. However, the percentage of local bridges that have been load rated utilizing reusable computer models was less than that for State-owned bridges. For example, Iowa and Kansas had 15 percent and 25 percent of local bridges load rated with computer models, respectively, at the time of the survey.

Based on the survey results from the nine States, QA/QC is usually completed by having two or more qualified engineers complete and review the load rating process or results. The survey results also showed that many of the States have a standard checklist to follow as the engineer is completing the calculations and process. No DOT reported the use of an automated approach that can aid in the QA/QC process.

Table 3. Survey results summary for Section 1 bridge rating process

State	1.3 How is bridge deterioration being incorporated into your load rating models, and how is it communicated to other systems that the load rating model includes deterioration?
Arizona	N/A
California	Through element level capacity reduction or global condition factor reduction. Load rating summaries are archived in a database and contain plain language descriptions of modeled deterioration/capacity reduction when applicable.
Indiana	Depending on the structure type and deterioration, strands may be removed or debonded from prestressed members, a reduced cross-section or cross-section element may be used for steel or concrete beams, concrete properties may be adjusted to reflect testing results. Members that have been modified for deterioration are identified in a manner to communicate to the end user (permitting, inspection, etc.) that the load rating results do not reflect pristine condition. In situations where applicable, the appropriate LRFR Condition Factor is applied within the analysis.
Iowa	As NBIS inspections are being complete, condition changes are documented and provided to Load Rating Section and bridge models are updated accordingly.
Kansas	Deterioration is being incorporated based on a formula that KDOT has developed. Load ratings are reduced based on structural health index. For bridges with major deterioration, those will be modeled by the Bridge Load Rating Engineer.
Michigan	The appropriate member (i.e., steel web, flange, rebar) in the computer model is reduced by either a percentage or by entering the remaining section measurement. Broken or severed prestressing strands are removed from the model or debonded as appropriate. MDOT uses a spreadsheet to analyze steel beam end capacity and gusset plate capacity. Bridge decks are evaluated for punching shear capacity.
Ohio	All bridges in Ohio are field inspected at least once in 12 months. Based on the field inspection reports, the bridge models are revised to incorporate the deterioration of state bridges. Comments are added in the rating models and rating summary sheet (BR100) to indicate that the deteriorations have been incorporated.
Pennsylvania	Bridge safety inspection captures the deterioration. This deterioration is communicated to the District Load Rating Engineer and the analysis files are updated accordingly.
Wyoming	Reduced section properties are used for capacity calculations. Increased wheel fractions are used to account for ineffective structural members (i.e., broken or cracked timber beams).

N/A: Information not available

Table 3. Survey results summary for Section 1 bridge rating process (continued)

State	1.4 What quality assurance/quality control (QA/QC) procedures are used for load rating?
Arizona	After a model created by an engineer, it is checked (QC) by another professional engineer and a QA done by team leader.
California	Every bridge load rating model and/or hand calculation is fully reviewed/checked by a load rating check engineer. Final review of every bridge load rating is conducted by a Senior Bridge Engineer, Supervisor. A QC checklist is utilized in the load rating process and includes initial signatures from the load rating engineer/load rating checker/senior engineer. Finally, a senior level engineer will randomly sample and review completed load ratings for QA.
Indiana	Load rating models are to be created and reviewed by separate individuals. The final load rating model and documentation is certified by a registered Indiana Professional Engineer. Following submittal to INDOT, an overall review of the submitted model is performed. This review confirms the integration into INDOT's system of working models and load rating documentation.
Iowa	When load ratings require review based on the Load Rating Evaluation Form in the Structure Inventory and Inspection Management System (SIIMS), checks are performed by an engineer qualified to do load rating.
Kansas	New load rating models are created by a design engineer. A separate load rating model of the same bridge is made by the design checker. The agreed upon model is then sent to the Bridge Load Rating Engineer for a final check. For older structures, the Bridge Load Rating Engineer will check any modifications to a structure that needs to be done. These modifications will sometimes also be checked or verified by the Bridge Evaluation Engineer.
Michigan	All load ratings are reviewed by a second engineer. In addition, MDOT has a bridge inspection and load rating consultant contract to perform QA/QC reviews on 10% of each selected agency's bridge inventory annually. We have 7 geographic regions and currently include 2 regions (MDOT and all local agencies within the region) in this contract annually.
Ohio	In-house reviews by a PE.
Pennsylvania	We follow standard checking practice of checking engineering computations.
Wyoming	Each load rating is performed by an engineer & undergoes a check by a second engineer & is stamped by a PE when complete. Approximately 10% of the year's load ratings are reviewed for accuracy of the structural capacity and loads.

N/A: Information not available

Table 4 summarizes the results from Section 2 of the survey related to the use of an automated bridge load rating system.

The results indicated only three of the nine State DOTs use automated technologies in their load rating system.

The Wyoming DOT (WYDOT) uses an in-house application (BRASS-ROUTE) that temporarily updates truck and other loading information in existing BRASS-GIRDER data files on a proposed route and uses BRASS-GIRDER to compute an operating rating and determine applicable restrictions for each structure on the route. The application returns the load rating data file to its original state.

The Indiana DOT (INDOT) has an extensive ITS, managed by Traffic Management, to which WIM files and virtual WIM (VWIM) files are connected. However, INDOT does not currently use its ITS in a way that relates to bridges beyond the potential for OS/OW enforcement. Even though this use of their ITS is not specific to load rating, it was indicated in their survey response as something that may provide benefit to Indiana’s bridges due to potentially reducing illegal OS/OW movement.

Caltrans, on the other hand, has developed automated software in-house to rerun models.

Table 4. Survey results summary for Section 2 automated bridge rating system

State	2.1 Are weigh-in-motion (WIM) devices used for load rating or posting enforcement? If so, how the WIM device is used and how is the WIM data relayed to maintenance operations systems to ensure posting. Describe the success of this performance.	2.2 Is the concept of a digital twin being used in bridge load rating, bridge reliability assessment and/or safety performance management? If so, please explain how it is incorporated and comment on the performance.
Arizona	No.	No.
California	WIM devices are utilized in the State, but the WIM data is rarely utilized in the course of routine bridge load ratings, and no instance where it is utilized for posting enforcement.	No.
Indiana	Currently, WIMs are not used for bridge load rating or posting enforcement. In Indiana, WIMs and VWIMS (virtual weigh-in-motion, basically a WIM with one or more cameras) are currently used for the following purposes: Road Classification – over the years, several traffic counting devices across the State have been replaced with WIMs. Screening tools for OSOW enforcement – Indiana State Police (ISP) can log in to INDOT's ITS and access the WIMs in real time. This allows ISP to target trucks that read overweight on the WIMs. However, there is currently no direct enforcement from the WIMs. INDOT, Indiana State Police, and the State Budget Agency are currently piloting VWIMs for OSOW direct enforcement.	No.
Iowa	No.	No.
Kansas	KDOT does not use WIM devices.	No.
Michigan	No.	No.
Ohio	No.	No.
Pennsylvania	No.	No.
Wyoming	WIM devices are not used for automated load rating or posting enforcement.	For overweight load (OWL) analysis, WYDOT uses an in-house application (BRASS-ROUTE) that temporarily updates truck and other loading information in existing BRASS-GIRDER data files on a proposed route and uses BRASS-GIRDER to compute an operating rating and determine applicable restrictions for each structure on the route. The application returns the load rating data file to its original state.

Table 4. Survey results summary for Section 2 automated bridge rating system (continued)

State	2.3 Are any of the following concepts being used? If so, please comment on the respective performance. (Internet of Things [IoT], V2X [i.e. vehicle to bridge], dedicated short range communication [DSRC], radio-frequency identification [RFID], geofencing, intelligent [digital, smart, connected] bridges, Intelligent transportation system [ITS])	2.4 Is any automated rating software being used?
Arizona	No.	No.
California	No.	We developed automated software to rerun models. The software was developed in-house using the Python programming language.
Indiana	INDOT has an extensive ITS system, managed by Traffic Management, which our WIMs and VWIMs are connected to. However, INDOT does not currently use ITS in a way that relates to bridges beyond the potential for OSOW enforcement. Even though this use of ITS is not specific to load rating, reducing illegal OSOW movement does provide benefit to Indiana's bridges.	Indiana does not use any automated load rating software at this time.
Iowa	Currently only in research.	Not in a current production
Kansas	None of these concepts are being used at KDOT.	Load ratings are done manually by the Bridge Load Rating Engineer or Bridge Evaluation Engineer.
Michigan	No.	No.
Ohio	We post bridges which cannot carry legal loads. Posting signs are installed on each end of the bridge. Early warning signs are also installed near the closest intersection on either side of the bridge.	Yes
Pennsylvania	No.	No, except for permit evaluation.
Wyoming	No, these concepts are not used.	No automated rating software is used.

Table 5 presents the results from Section 3 of the survey on integrated infrastructure data storage.

The results indicated that most of the State DOTs store the load rating data or models on a secure server or commercial cloud service. Some DOTs indicated they have an automated exchange of the bridge rating data within their integrated system.

For example, INDOT stores all load rating and posting values within the Bridge Rating Application Database of Indiana (BRADIN). The load rating and posting data are pushed nightly to the Bridge Inventory and Appraisal System (BIAS).

The Michigan DOT (MDOT) uses an internally developed program (MiBRIDGE) to update the inventory, view or report inventory data, and store bridge plans and relevant load rating data, including the XML files. However, a separate database is used to store the completed models. MDOT plans to switch from MiBRIDGE to commercially available software to store all bridge model files within the revised interface.

The Pennsylvania DOT (PennDOT) uses an interface called Engineering Dataset Manager that links the load rating analysis datasets to the analysis program to perform the load rating computations. The datasets are also linked to the PennDOT Automated Permit Analysis system to allow for the consideration of overweight permit requests.

WYDOT uses the routing application in the BRASS-ROUTE software to select a route, connect to a separate database to select the structures on the route, select data files from those on the network, and then runs BRASS-GIRDER to analyze the structures for given loads.

Table 5. Survey results summary for Section 3 integrated infrastructure data storage

State	3.1 How are the bridge load rating, geospatial, building information modeling (BIM) data and structural analysis models being exchanged within any integrated system(s)? (e.g., cloud computing services, software services)
Arizona	Not available or not being performed at this time.
California	There is no current exchange with any integrated system.
Indiana	The majority of INDOT's bridges have load rating models stored. In addition to storing models, all files for in-service models are also stored individually in INDOT's Archives - Bridge File Documents. Load rating models are updated in response to inspectors' reporting of completion of construction or condition change. Outdated load rating models are manually replaced in the data source with the updated models that reflect the in-service condition of the bridge. During this process, a new load rating report is created in the Bridge Rating Application Database of Indiana (BRADIN) that contains the updated load rating values. A PDF of the load rating summary report and the load rating model is also saved to Archives - Bridge File Documents at this time. All load rating and posting values are stored within INDOT's BRADIN application. The load rating and posting data is pushed nightly to INDOT's Bridge Inventory and Appraisal System (BIAS), called AssetWise Asset Reliability Inspections, and is available read only within AssetWise. INDOT's Bridge Management System (BMS) and Pavement Management System (PMS) are processed with the network optimization software, which pulls data from Assetwise and from INDOT's Pavement Inventory System, called Roads and Highways (R&H). Data are also pulled from INDOT's contracting software, which provides currently committed contract information, such as work type, cost, and programmed year.
Iowa	Currently being tested in an initial test project.
Kansas	All bridge load rating results are saved into a database and then imported to display load ratings, structural health, and other information for bridge management.
Michigan	No.
Ohio	The load rating information (rating factors) and NBI data are stored in bridge inventory system, which is then shared with other systems within the department. The enterprise data warehouse gets updated with the bridge information every night.
Pennsylvania	Some data is stored in our Bridge Management system, PennDOT geo-spatial system called OneMap, and as described in question 3.2, our Engineering Dataset Manager. We are working towards BIM, but that is a few years away.
Wyoming	Our BRASS-ROUTE software uses a routing application to select a route, connects to our database to select the structures on the route, selects data files from on our network, and then runs BRASS-GIRDER to analyze the structures for given loads.

Table 5. Survey results summary for Section 3 integrated infrastructure data storage (continued)

State	3.2 How are the bridge load rating data and bridge analysis models being maintained and updated?
Arizona	All data is stored as a PDF report and on a dedicated server (all rating models).
California	Summary load rating data is being maintained in database format. Full rating detail output is being archived on a secure server. Models are stored in a 'main' database. Updates are currently done on an as-needed basis, but as described in 2.4, we have begun automated analysis updates.
Indiana	Load rating data is being updated in BRADIN by the engineers responsible for submitting the load ratings. The data source is manually maintained by replacing out of date load rating models with updated models. Manual comparisons are routinely made between the data source and AssetWise inventory data to ensure the load rating models are the best representation of INDOT’s assets.
Iowa	As bridge inspections are being complete, they will be assigned to Load Rating Section for review if there is a change in condition. The load rating model will be updated based on the inspection report.
Kansas	Bridge analysis models are maintained and updated by the Bridge Load Rating Engineer or Bridge Evaluation Engineer. This is done by manually updating the analysis model.
Michigan	MDOT currently uses an internally developed program (MiBRIDGE) to update the inventory, view/report inventory data, and store bridge plans and relevant load rating data, including the XML file. We also maintain a separate database where we store the completed models. This is separate from the database used to update and create the models. We plan to switch from MiBRIDGE to commercially available software sometime in the next couple of years. The intention is to be able to store all bridge model files within the revised interface. MDOT load ratings are updated by MDOT employees or via consultant contract.
Ohio	The load rating information (rating factors) and NBI data are stored in bridge inventory system. The load rating data and models are updated on need basis.
Pennsylvania	The load rating analysis datasets are stored electronically. We have an interface called Engineering Dataset Manager that links the datasets to the PennDOT analysis program to perform the load rating computations. Also, the datasets are linked to our Automated Permit Analysis system to load rating overweight permit requests.
Wyoming	BRASS-GIRDER & BRASS CULVERT data files are stored in a read-only file and are updated as necessary when loading or capacity conditions change.

Table 6 shows the results from Section 4 of the survey related to permitting systems.

Among the nine State DOTs surveyed, four States—California, Indiana, Michigan, and Wyoming—indicated they are able to automatically synchronize their digital bridge assets into their overweight permit system.

With respect to the determination of the route for the overweight vehicle, two approaches are reported: user-defined route or a system-generated route. The survey results indicated that most DOTs surveyed generate the route automatically, and the carrier needs to only input the origin, destination, and truck information. These States included California, Indiana, Iowa, Kansas, Ohio, and Pennsylvania.

The survey results also indicated that, in all the surveyed States, local agencies do not have access to the permitting system built by their State DOT. In addition, mobile and portable weight scales are sometimes used to enforce overweight permits; however, the scale data (either portable or from a weigh station) are not reported back to the load rating office for the use in future load rating applications or processes.

Table 6. Survey results summary for Section 4 permitting system

State	4.1 How are digital bridge assets being synchronized into the overweight permitting system?	4.2 How does a carrier determine a route for an overweight truck using the automated permitting system?	4.3 Are you making load rating data and permitting systems readily available to local agencies to assess posting needs and impacts of overweight permits on bridges?	4.4 Are you using any specific techniques for enforcement within the overweight permitting system?	4.5 Are you utilizing weigh station data to update bridge/load models used in the load rating process? If so, how are these data being used to establish protocols to update load rating procedures?
Arizona	Not practicing at this time.	Commercial software.	Not at this time.	We use escorts (provided by enforcement department with MVD) as required.	Not at this time.
California	The Office of Traffic Operations combines digital bridge asset information from several sources for vertical/horizontal clearances and weight capacities. Traffic Operations utilizes an automated permit routing system for the vast majority of permit requests. Superloads or trucks weighing over 800kip +/- are reviewed on a case-by-case basis by a senior bridge engineer.	The vast majority of the permit requests are processed through the automated system. The carrier submits the request, and the automated system determines the appropriate route. See the Traffic Operations website for more information: https://dot.ca.gov/programs/traffic-operations/transportation-permits.	We provide current summary load rating data that can be used for permit routing to all but one county in the state. We do not provide permit routing systems or support.	Large trucks may be weighed. State police force may be utilized to escort trucks and assure compliance to any permit restrictions.	No.
Indiana	Nightly feeds of the data source, Bridge Inventory data, and Roadway Inventory data is being provided to the automated permitting application for daily updates.	The carrier inputs origin and destination, then the automated permitting system reviews all state bridges for clearance, construction restrictions, and load rating capacity to determine alternate route options for the carrier to select from.	Local agencies are able to view load rating data in a system. At this time, the local agencies do not have access to the permitting system.	Not at this time.	Indiana is not using WIM data to update bridge load rating models.

Table 6. Survey results summary for Section 4 permitting system (continued)

State	4.1 How are digital bridge assets being synchronized into the overweight permitting system?	4.2 How does a carrier determine a route for an overweight truck using the automated permitting system?	4.3 Are you making load rating data and permitting systems readily available to local agencies to assess posting needs and impacts of overweight permits on bridges?	4.4 Are you using any specific techniques for enforcement within the overweight permitting system?	4.5 Are you utilizing weigh station data to update bridge/load models used in the load rating process? If so, how are these data being used to establish protocols to update load rating procedures?
Iowa	Once the load ratings are updated, a transfer file is created to manually send to our permitting system.	The system automatically generates a route that is approved for the carrier. The carrier has the option to try to adjust the route and the system will check the adjusted route.	No. Local public agencies do not have the files needed to utilize the permitting system.	No.	No.
Kansas	An entire copy of the bridge analysis models is sent to the company that developed and maintains the permitting/routing software for KDOT. The set is used to load rate bridges on a permitted route.	The carrier provides the dimensions and axle weights and spacing along with an origin and destination. The system will determine a route based on restrictions and bridge load ratings.	The permitting system is not available for local routes. The Bureau of Local Projects has been working with local entities to complete their load rating data. Local agencies are not permitted to route roads under the state's jurisdiction unless defined in a City-State agreement. KDOT will not route on a road not under the jurisdiction of the Secretary of Transportation.	All vehicles over 10,000 pounds are required to stop at weigh stations for inspection. Law enforcement has access to the permitting system to revoke permits if they are acting in a way contrary to what is allowed by the permit.	No.
Michigan	Bridge data currently must be manually updated in the permit software by an MDOT database administrator. Our Transport Permits Unit is currently reviewing new permitting and routing software programs and the intention is for the new software to connect to the NBI database, with real-time or daily inventory updates.	Currently, carriers must choose their own route and submit it for approval in the permitting system. The ability for routes to be recommended/generated by the automated permitting system is being evaluated as part of the process to choose a new permitting and routing software program.	MDOT does not issue permits for local agency routes/bridges.	No.	No.

Table 6. Survey results summary for Section 4 permitting system (continued)

State	4.1 How are digital bridge assets being synchronized into the overweight permitting system?	4.2 How does a carrier determine a route for an overweight truck using the automated permitting system?	4.3 Are you making load rating data and permitting systems readily available to local agencies to assess posting needs and impacts of overweight permits on bridges?	4.4 Are you using any specific techniques for enforcement within the overweight permitting system?	4.5 Are you utilizing weigh station data to update bridge/load models used in the load rating process? If so, how are these data being used to establish protocols to update load rating procedures?
Ohio	Bridge inventory data is uploaded/refreshed periodically into the overweight permitting system.	We use software that determines a clear route for an overweight/oversize hauler based on the origin and destination information provided by the hauler. The bridges on the routes get analyzed using the Rating Tool and rating models in software.	ODOT only issues permit on the state-owned routes. Ohio Turnpike, Ohio counties, and cities use their own load permitting processes.	Multiple techniques are used for enforcement, such as mobile and portable weighing scales, State Highway Patrol, private escort services, etc.	We are currently not using weigh station data to load rate bridges or update bridge models.
Pennsylvania	We have engineering datasets for permit vehicle analysis.	Two methods, using a user-defined route or a system-generated route. The system-generated route accounts for posted bridges, vertical restrictions, constructions restrictions, etc.	Load rating analysis is made available to local agencies. Locals do not have access to our automated permit system.	No.	No.
Wyoming	See answer to 3.1.	WYDOT does not currently have an automated permitting system for overweight loads. Carriers currently submit a route, and the Bridge Section analyzes the route and provides restrictions to the office of overweight loads (OWL). This process is repeated until an acceptable route is determined.	Load rating summaries are provided to local authorities for them to make decisions.	We are not aware of any.	WYDOT has had a couple of research projects that used WIM data to investigate the impacts of truck loading on the I-80 corridor. The research resulted in updating the design loading for bridges on that corridor.

Table 7 presents the results from Section 5 of the survey, which sought information on the use of structural bridge monitoring systems.

Generally, structural monitoring information has not been used in State's load rating programs. However, two State DOTs (the Iowa DOT and KDOT) report research activities on the implementation of structural monitoring into their load rating systems. The most mature of these research activities are from Iowa, which is currently in the implementation phase.

Table 7. Survey results summary for Section 5 bridge structural monitoring system

State	5.1 Is a bridge monitoring system (e.g., SHM) being used for load rating purposes? If so, what system and how does this system benefit the load rating process?	5.2 In what ways is this system being utilized?
Arizona	No.	No.
California	No.	No.
Indiana	Indiana’s structural health monitoring system (SHM) is not currently used to help or enhance load rating.	INDOT has structural health monitoring (SHM) that is used for bridge hit notification for specific bridges. At this time, SHM is not being used for load rating purposes.
Iowa	No. This is a current research topic that we are working on implementing. The Bridge Engineering Condition Assessment System (BECAS) we are working on developing completes the load rating, but this has not been integrated into our load rating program and asset management program.	Bridge Engineering Condition Assessment System (BECAS) provides SHM summary data, load rating, ADT, load rating histograms, and condition changes. In the future, we would like to integrate the data collected into our asset management program.
Kansas	N/A	N/A
Michigan	No.	No.
Ohio	No.	No.
Pennsylvania	We have not used SHM for load rating purposes. We have an active contract that we have SHM on 10 bridges throughout the Commonwealth.	See previous answer.
Wyoming	The University of Wyoming did a research project investigating the use fiber optic strain sensors for a SHM system. WYDOT has not implemented any of these systems to date.	These have not been implemented yet.

N/A: Information not available

Table 8 summarizes the results from Section 6 through Section 9 of the survey.

The results indicated that no surveyed DOT has implemented a fully automated mechanism to conduct parametric studies on their load rating models. However, MDOT reported that a research project is being conducted to perform parametric studies to compare the load effects of various load models (such as specialized hauling vehicles [SHVs] and EVs) to the load effects of Michigan legal loads, while this work is not automated.

In addition, WYDOT reported that BRASS-ROUTE can be used as a preliminary analysis tool to check for posting implications for a special truck on many structures at one time.

A few States have funded research projects related to bridge load ratings. However, all of the projects cited in the survey (aside from the Iowa work previously mentioned) are from a structural perspective. The only efforts to develop automated technologies or approaches for load rating was the work by Iowa.

In the last section of the survey form, each State DOT was asked to rate the level of automation for load rating and permitting within their States. The five levels were defined as follows:

Level 1 – No automation; all manual. Either no or small percentage of load ratings can be easily updated or reused.

Level 2 – Mixed computer analysis models and paper (hard copy, spreadsheet) calculations. The computer models can be updated manually and re-run.

Level 3 – Predominant (almost all) computer analysis models. The computer models can be manually updated and re-run.

Level 4 – All computer analysis models (digital twins). The computer models can be quasi-automatically updated and re-run.

Level 5 – All computer analysis models (digital twins). Fully automated updating and rating.

Seven of the nine States responded to this question. Four of the DOTs rated themselves as Level 3 and two rated themselves as Level 2. WYDOT rated themselves with the highest level of automation between Level 3 and Level 4.

Table 8. Survey results summary for Section 6 though 9

State	6 Are you developing automated mechanisms to conduct parametric studies on new load models and assess impacts on highway corridors?	7 Can you use the bridge and load models to assess pavements, dynamic load allowance and model deterioration in bridge decks and superstructures?
Arizona	No.	No.
California	No.	No.
Indiana	Indiana does not have automated mechanisms to conduct parametric studies at this time. Manual evaluation is performed using the data generated through commercial software.	At this time, load rating models are only used to assess deterioration in bridge superstructures. The automated permitting application, currently being developed, will provide load rating values that take into consideration variable dynamic load allowance.
Iowa	As the state law changes legal loads, we use our permitting system as a screen tool for bridges that may need a refined analysis, restriction, or posting.	No, current research topic.
Kansas	Not at the current time.	KDOT can manually change or alter dynamic load allowance in the analysis models. Deterioration has to be added manually to the model by section loss or an approved method of the Bridge Load Rating Engineer or Bridge Evaluation Engineer. KDOT does not load rate bridge decks or pavement.
Michigan	MDOT has a contract with the Center for Technology and Training (CTT) at Michigan Tech University. As part of this contract, CTT has conducted parametric studies to compare the load effects of various load models (such as SHVs and EVs) to the load effects of Michigan legal loads. However, this process is not automated. CTT created models for various span lengths & configurations and developed a script to automatically pull the shear and moment load effects from these models into an Excel spreadsheet for comparison to Michigan legal load effects.	No.
Ohio	No.	No such study is being conducted within the department.
Pennsylvania	No.	No.
Wyoming	The use of BRASS-ROUTE as described in Section 2.2 above can be used as a preliminary analysis tool to check for posting implications for a special truck and many structures at one time.	No, not at this time.

Table 8. Survey results summary for Section 6 through 9 (continued)

State	8 Are there "experimental" systems or ongoing related research projects in progress for the purpose of doing/helping/enhancing load rating? If yes, could you please provide any details on this work?	9 How do you rate the level of automation for Load Rating and Permitting in your state?
Arizona	Not at this time.	Level 2.
California	One on-going research focuses on studying end connection eccentricity and load rating analysis for truss bridges.	Level 2.
Indiana	INDOT is supporting several research projects to assist with load ratings. The current project topics in progress are: 1. Improved Live Load Distribution Factors for Use in Load Rating of Older Slab and T-Beam Reinforced Concrete Bridges 2. Shear and Bearing Capacity of Corroded Steel Beam Bridges and Effects on Load Rating 3. Use of LRFR Methodology for Load Rating of INDOT Steel Bridges 4. Legal and Permit Loads Evaluation for Indiana Bridges 5. Concrete Box Beam Risk Assessment and Mitigation Several of these on-going research projects are intended to provide guidance on evaluating observed deterioration.	N/A
Iowa	Yes, new research proposals: (1) Evaluation of the Use of IRI Data to Estimate Bridge Impact Factor; (2) SHM Data Utilization.	Level 3.
Kansas	Not at the current time.	Level 3.
Michigan	No.	N/A
Ohio	No.	Level 3.
Pennsylvania	Yes, we have a research project with University of Pittsburgh to evaluate and validate the results of the SHM contract addressed in question 5.	Level 3.
Wyoming	See sections 4.4 and 5.1 above.	Between Level 3 and Level 4.

N/A: Information not available

3.2 Comprehensive Review

A further in-depth assessment of the State DOT practices on the implementation of automated technology in the bridge load rating program was conducted on select DOTs. The objective of this effort was to collect more information from the DOTs that identified considerable experience with the application of automated technology in the bridge load rating program but were not able to present all of the details in the survey.

Based on the findings from the survey, follow-up discussions were scheduled with California, Iowa, Indiana, and Kansas. This consisted of a meeting with State representatives to discuss their practices on the application of automatic technology in their bridge load rating program. The findings from these meetings are presented here, separated by State.

3.2.1 California

Based on the initial survey results, the researchers followed up through additional discussions with Caltrans about how automation is incorporated into load rating models and the integration of deterioration into the load rating process.

1. Caltrans has approximately 25,000 bridges, split relatively evenly between State and locally owned bridges. Uniquely, the load rating group at Caltrans does the load rating for all of these bridges, including locally owned bridges. There was a load rating Plan of Corrective Action to complete all the updated bridge load ratings that were needed. The software that is used was selected largely due to its ability to perform LRFR ratings. Additionally, an in-house tool was created to take existing models and add SHV, EV2, and EV3 vehicles to them in an automated fashion. This automated tool was mostly utilized to catch up on load rating and was not currently used on a regular basis. It could be used again in the future, or some updated version of it, if updates are needed. The goal for Caltrans is to have a model for every bridge in the State such that they can be updated on a bi-annual basis for load rating needs.

2. In general, when an inspector finds deterioration or damage, the preferred course of action is to fix the issue rather than adjusting the load factor or giving a lower rating. This somewhat stems from a desire to not have State load postings on the highway system due to limited enforcement resources and other factors. This leads to a more aggressive repair program that can incorporate temporary restrictions or reductions in the rating. If a repair isn't made, and an inspector finds something in the field, they would send a work request to the load rating group. The load rater would then go into the model and manually update the capacity to reflect what was seen in the field. This process is not automated and involves teamwork between the inspector and load rater to ensure that the model is accurate.

3.2.2 Iowa

The focus of the Iowa DOT follow-up interview was on the DOT’s use of structural modeling for the purpose of load rating. The Iowa DOT invested heavily in the development of an integrated and automated monitoring system known as the Bridge Engineering Condition Assessment System (BECAS), which was developed with the Bridge Engineering Center at Iowa State University. BECAS load rating captures bridge response to ambient traffic and uses that response to calibrate an analytical model that can be used to perform automated load rating calculations.

The Iowa DOT has installed BECAS on multiple bridges with plans to install more in the next 12 months as part of a statewide implementation plan. The goal with implementation is to use the monitoring system as a tool for the enhanced management of Interstate bridges.

3.2.3 Indiana

The focus of the Indiana follow-up interview was on the integration of several different systems within the State DOT. INDOT has recently launched an automated permitting system that uses the stored load rating results via documented bridge load ratings as well as through software models (which have been created for approximately 5,200 of the approximately 6,000 Indiana State-owned bridges). This automated permitting system determines a route for the user based on their vehicle type rather than the user inputting their chosen route and being told whether or not they can use that selected route.

The output from this automated system is a report that shows the origin and destination that the user requested, as well as an approved route. That report also shows which bridges did not pass for the vehicle, as well as the truck configuration. The information is being pulled from the models for the given truck configuration, using generated influence surfaces for quick analysis purposes. This process includes only State-owned bridges.

A load rating request application is an internal tool that allows inspectors to essentially flag bridges that need a load rating evaluation to be performed. This process is not automated and instead manually relies on the inspectors. There is also an input in the form to note if the load rating included deterioration considerations.

At INDOT, the load rating group is within bridge design office, not bridge inspection, as is common for other States.

3.2.4 Kansas

Discussions with a KDOT representative focused on integration of deterioration into the load rating process and how to incorporate health monitoring into the program.

1. When significant deterioration happens to a bridge (when a bridge has been hit and significant damage or section loss has occurred, for example), a bridge model is developed to model the section loss as best as possible. For standard deterioration over time (i.e., not due to one significant event), KDOT has developed a formula that incorporates a structural health index to lower the load rating. The condition of the various components of the bridge are input to calculate the health index, which was developed by KDOT. A typical health index is approximately 90–95, which does not greatly change the load rating. Changes to the load rating typically happen when the health index approaches 75. Note that these health index values do not directly correlate to a percentage of deterioration. In other words, a health index of 75 does not indicate that 75 percent of the bridge is deteriorated. The health index has many different weights associated with various aspects of the bridge such that some elements have a more drastic effect on the overall health index.

2. KDOT does not currently incorporate health monitoring data into the load rating process.

3.2.5 Summary of Interview Findings

In general, there is an overall push to incorporate automation into the load rating and permitting processes. However, very few States have rolled out a program that achieves that goal as of yet. As more and more bridges have computer models available, these data will inherently allow for more integration within the processes.

3.3 NBI Data Mining

An analysis was performed on NBI data from 2009 and 2019 to assess how bridge load rating has evolved over that 10-year period. The goal of this was to assess general technological or conceptual advancement readiness via an assessment of how States have implemented new approaches and advances.

First, all data were analyzed in terms of engineering metrics and the impact of those metrics on bridge management. Second, all data were statistically analyzed with the goal of identifying statistically significant changes from 2009 to 2019. to achieve these objectives, the following process was followed:

Step 1: Data download and filtering
Step 2: Data overview
Step 3: Data analysis

3.3.1 Data Download and Filtering

The 2009 and 2019 NBI data were downloaded from the FHWA Bridges & Structures website at https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm. The original data files included information for 713,115 items for 2009 and 617,084 items for 2019.

Both 2009 and 2019 data were filtered to include only the data with Item 5A=1, which indicated that the structure carried the route (ON record). The other items, which do not carry the route (UNDER record), were removed from the dataset. In addition, the culvert and non-culvert structures were separated so that they could be considered independently. The resulting number of structures for each category is listed in Table 9.

Table 9. Number of structures plotted in each bar chart

Year	Culvert	Non-Culvert	Total
2009	131,698	476,721	608,419
2019	141,722	475,362	617,084

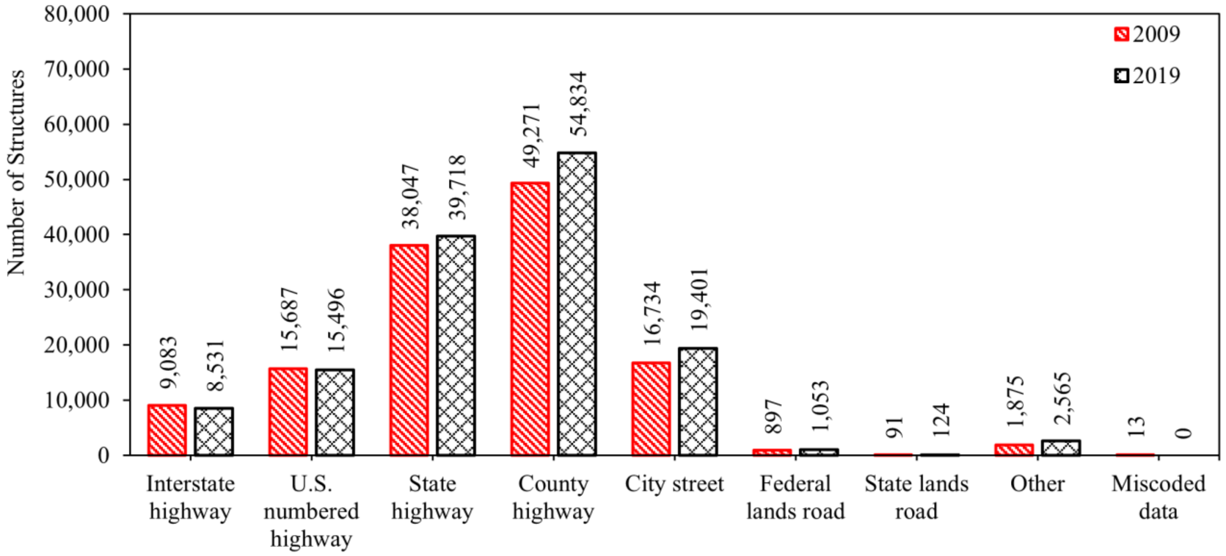
3.3.2 Data Overview

The data were compared for the following items:

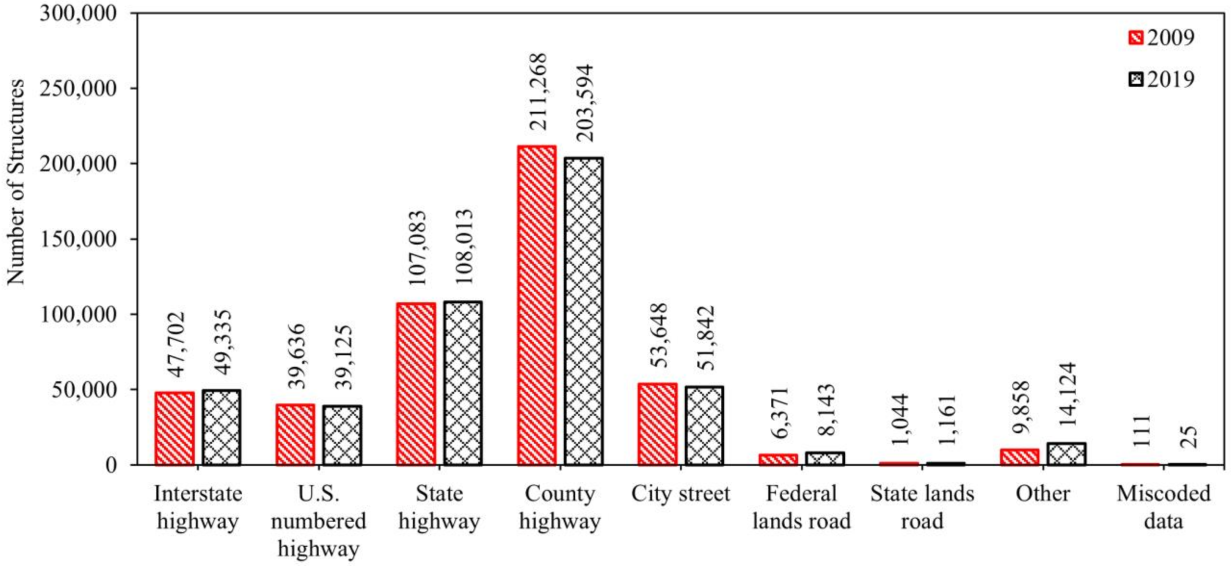
- Item 27: Year Built
- Item 31: Design Load
- Item 41: Structure Open, Posted, or Closed to Traffic
- Item 59: Superstructure Condition Ratings
- Item 62: Culvert Condition Rating
- Item 63: Method used to Determine Operating Rating
- Item 65: Method used to Determine Inventory Rating

To provide a direct overview of the comparison of the data from 2009 and 2019, the authors created a group of bar charts, and the charts are included on the following pages. These charts were formulated from two perspectives: those showing the actual number of structures and those showing the percentage of structures. This was done to better highlight any changes in trends over the 10-year period of data in the NBI.

Figure 6 shows the number of structures versus Item 5B: Record Signing Prefix for Inventory Route, and Figure 7 shows the percentage distribution on Item 5B: Record Signing Prefix for Inventory Route.

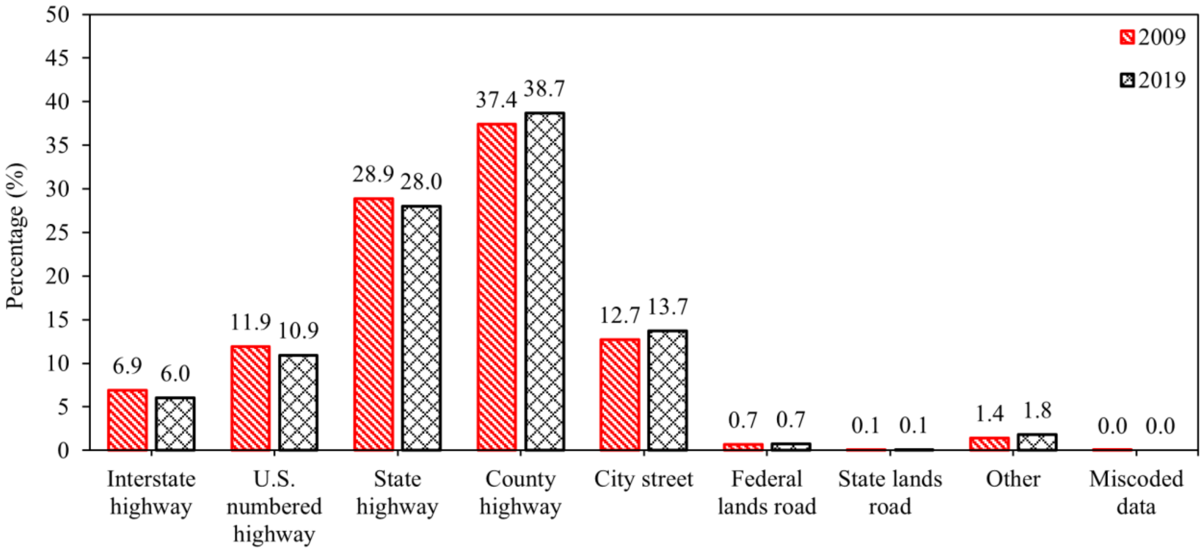


(a) Culvert Structures

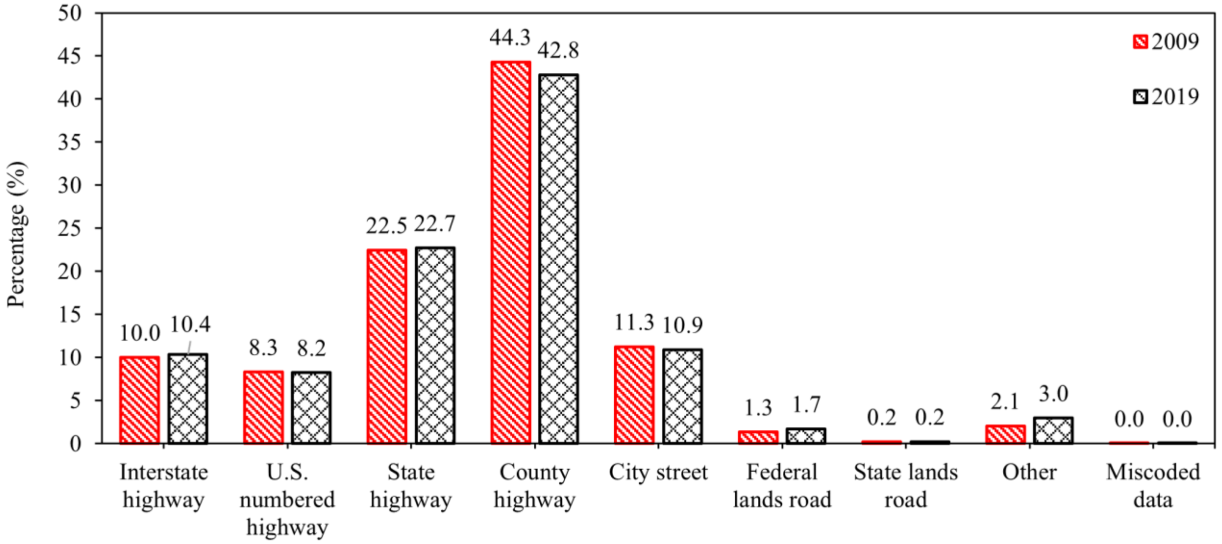


(b) Non-Culvert Structures

Figure 6. Number of bridges vs. Item 5B: Record Signing Prefix for Inventory Route



(a) Culvert Structures

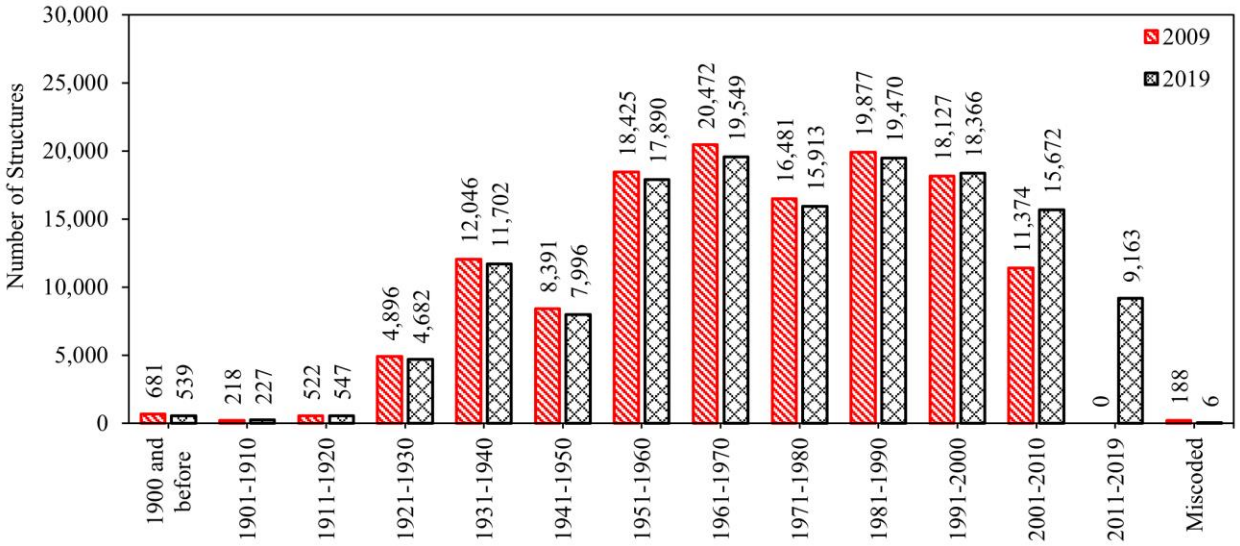


(b) Non-Culvert Structures

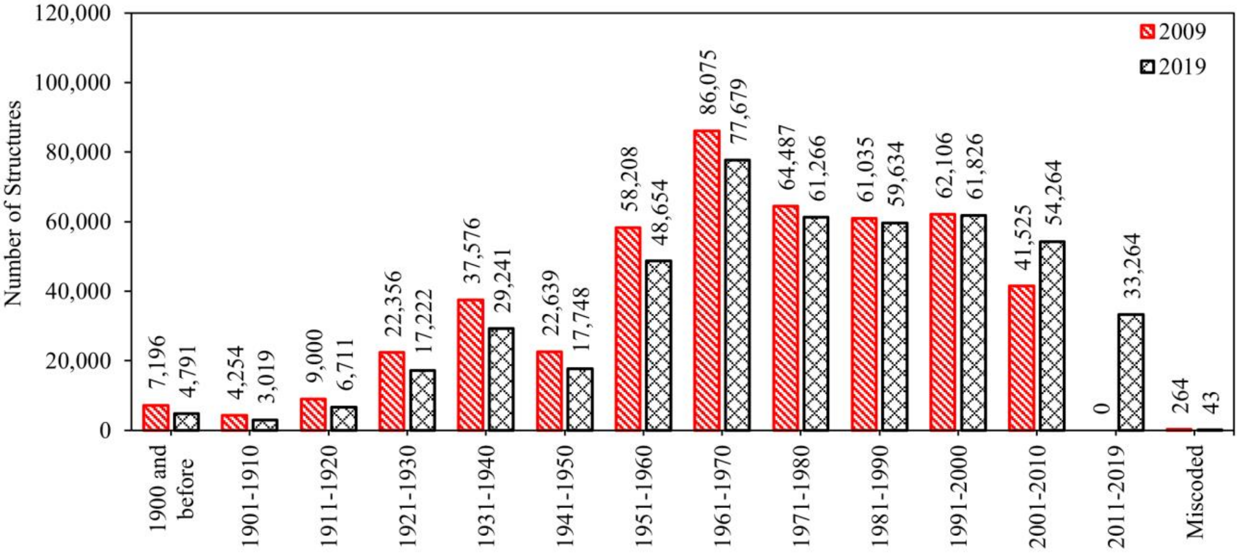
Figure 7. Percentage distribution on Item 5B: Record Signing Prefix for Inventory Route

Both figures indicated that the majority of the culvert and non-culverts were built on county and State highways. Comparing the data from 2009 to those from 2019, there were no remarkable differences or trends.

Figure 8 and Figure 9 show the number and percentage, respectively, of structures built in each decade.

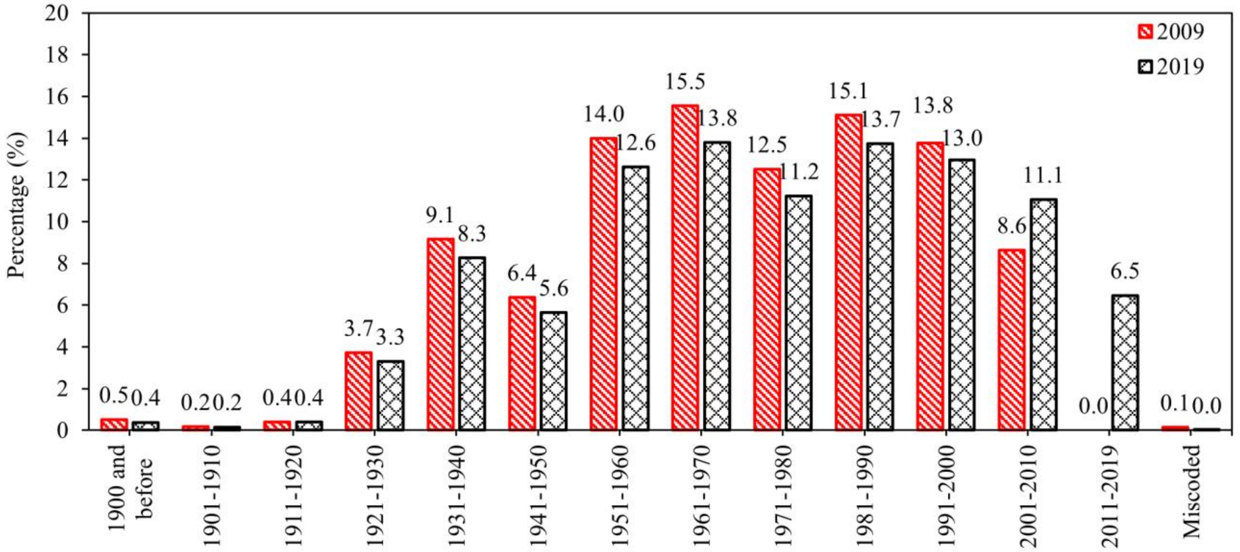


(a) Culvert Structures

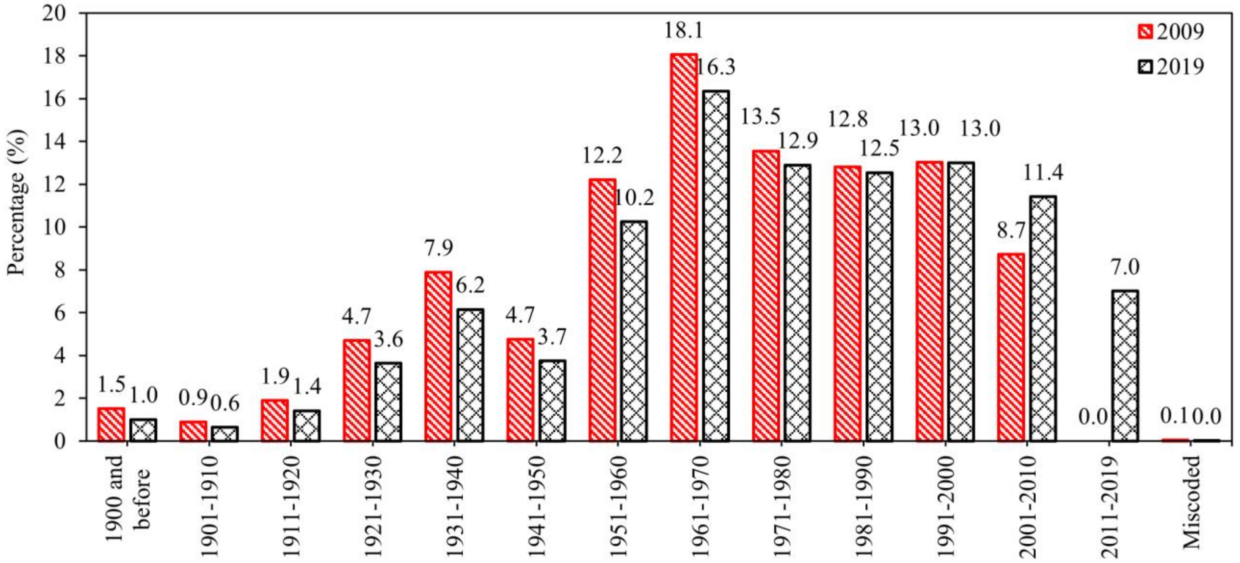


(b) Non-Culvert Structures

Figure 8. Number of bridges vs. Item 27: Year Built



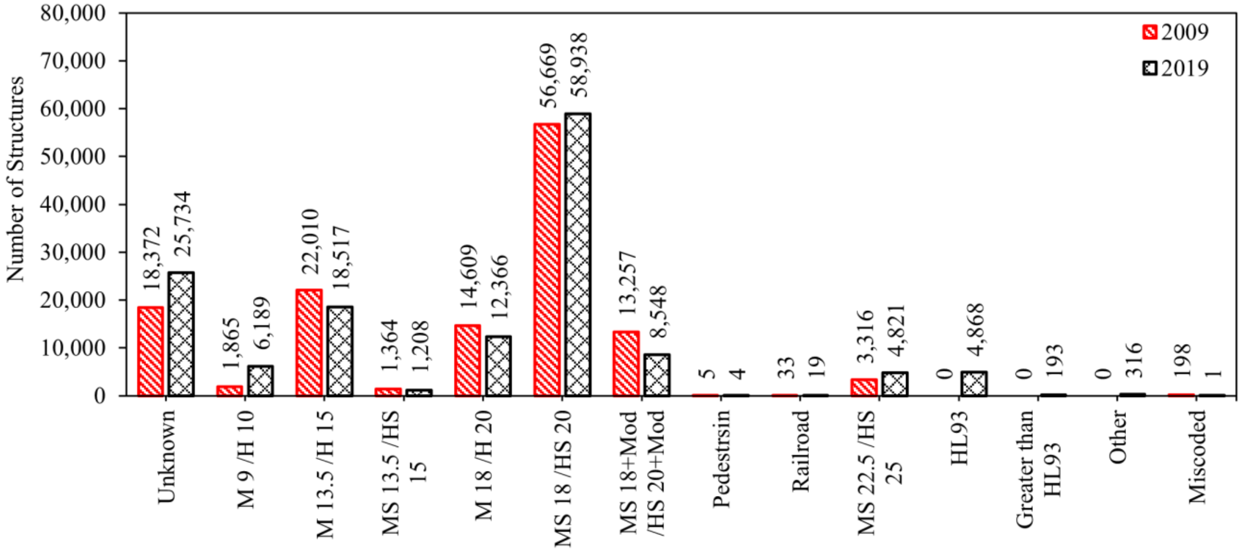
(a) Culvert Structures



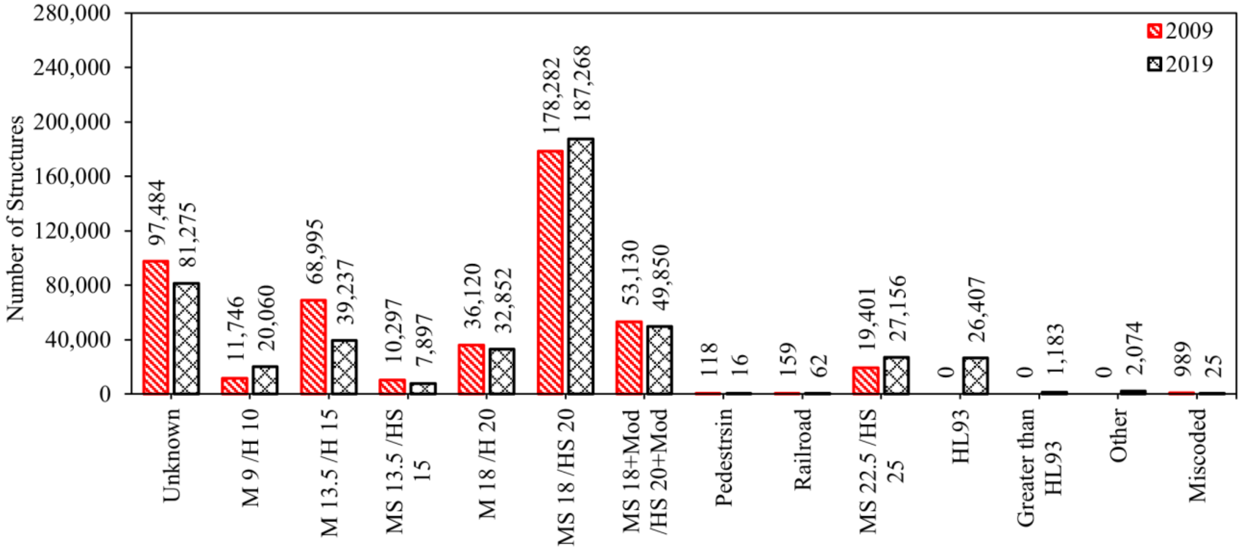
(b) Non-Culvert Structures

Figure 9. Percentage distribution on Item 27: Year Built

Figure 10 and Figure 11 show the distribution of design load type.

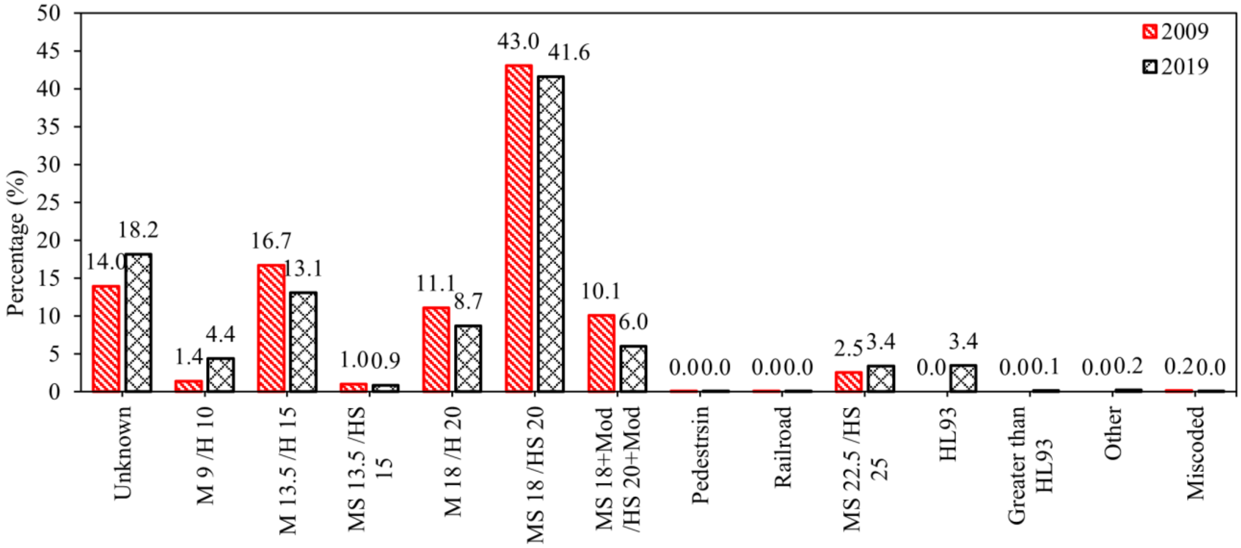


(a) Culvert Structures

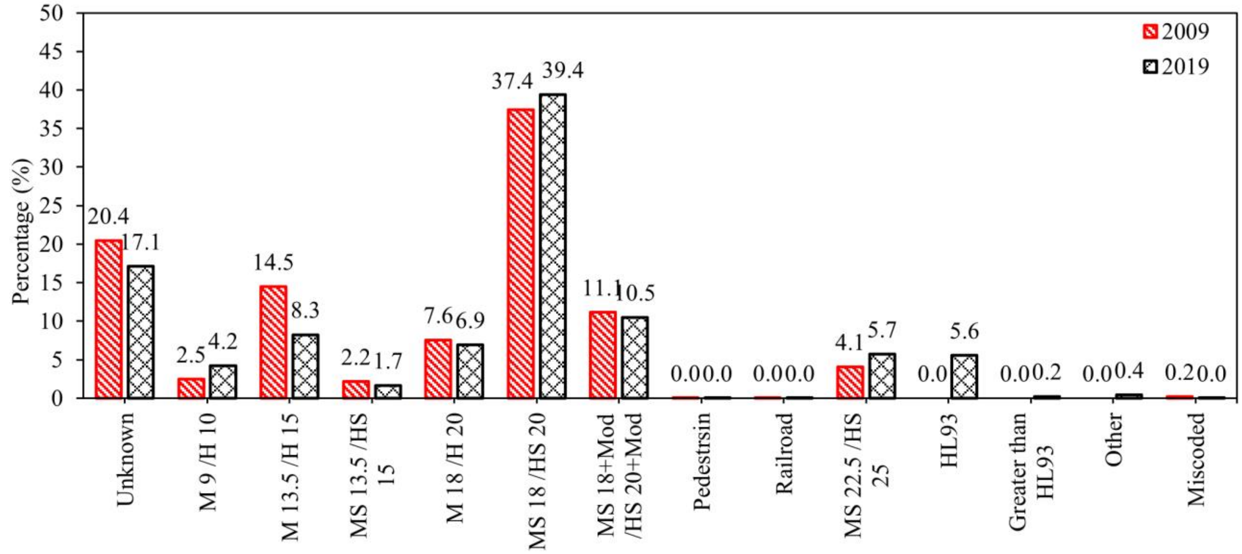


(b) Non-Culvert Structures

Figure 10. Number of bridges vs. Item 31: Design Load



(a) Culvert Structures

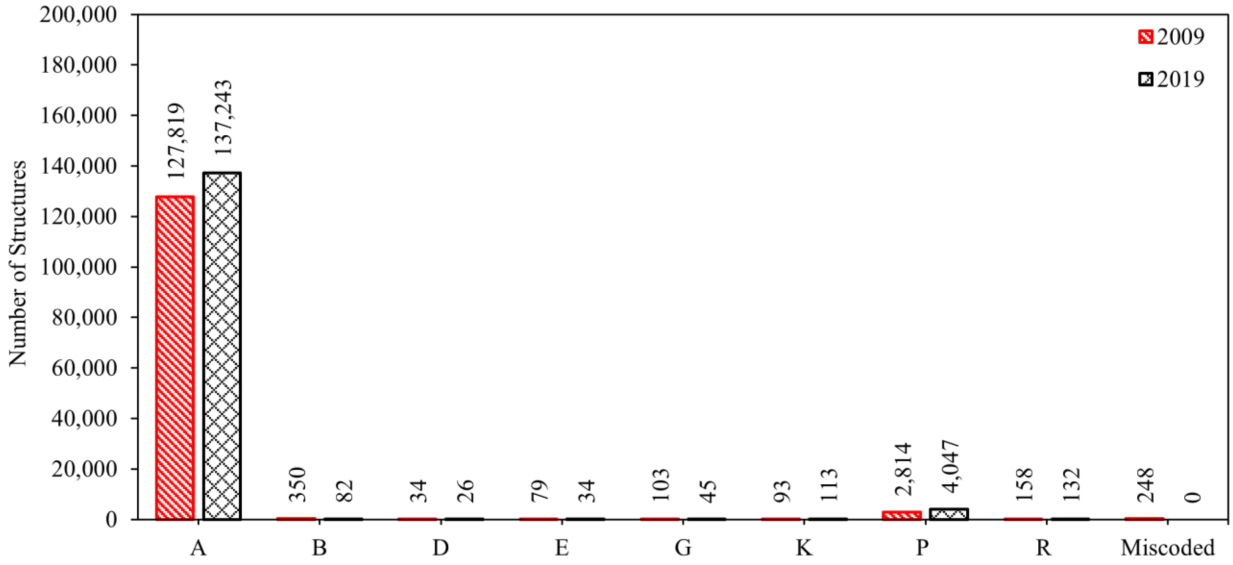


(b) Non-Culvert Structures

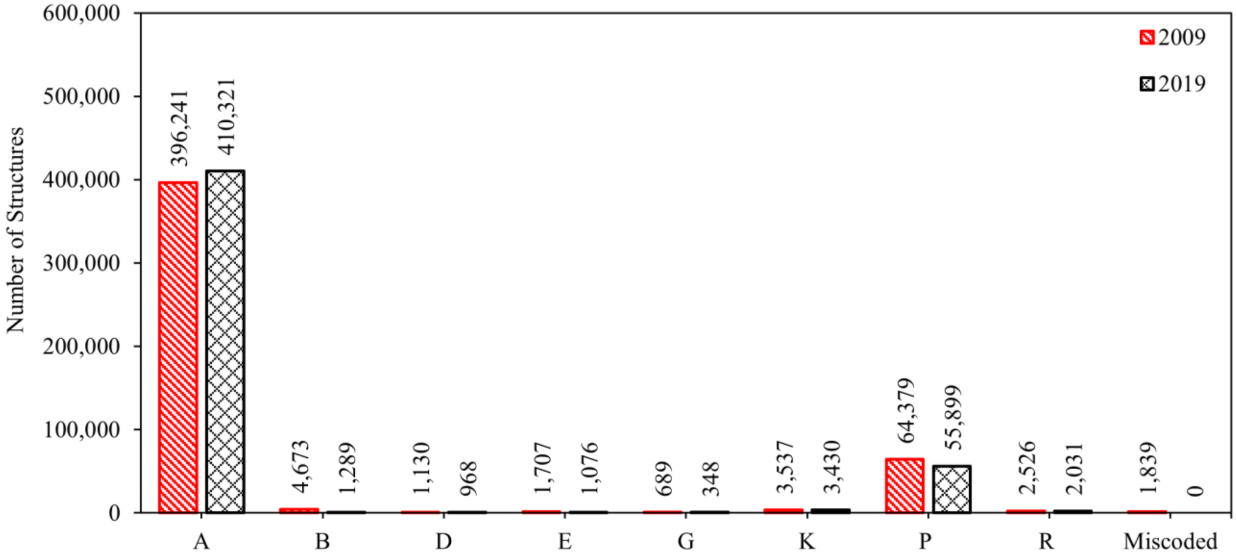
Figure 11. Percentage distribution on Item 31: Design Load

The results indicated that the most commonly used design load is the MS18/HS20. Comparing the data from 2009 and 2019, the number of structures designed based on the MS18/HS20 load increased. Other commonly used design loads include M13.5/H15, M18/H20, and MS18+Mod/HS20+Mod. While comparing the data from 2009 and 2019, the number of structures designed based on these three design loads is decreasing. Note that there were approximately 27,590 (5.8%) bridges designed by LRFD for HL-93 or greater live loading added into the national inventory from 2009 to 2019.

Figure 12 and Figure 13 show the distributions for Item 41: Bridge Open/Posted/Closed.



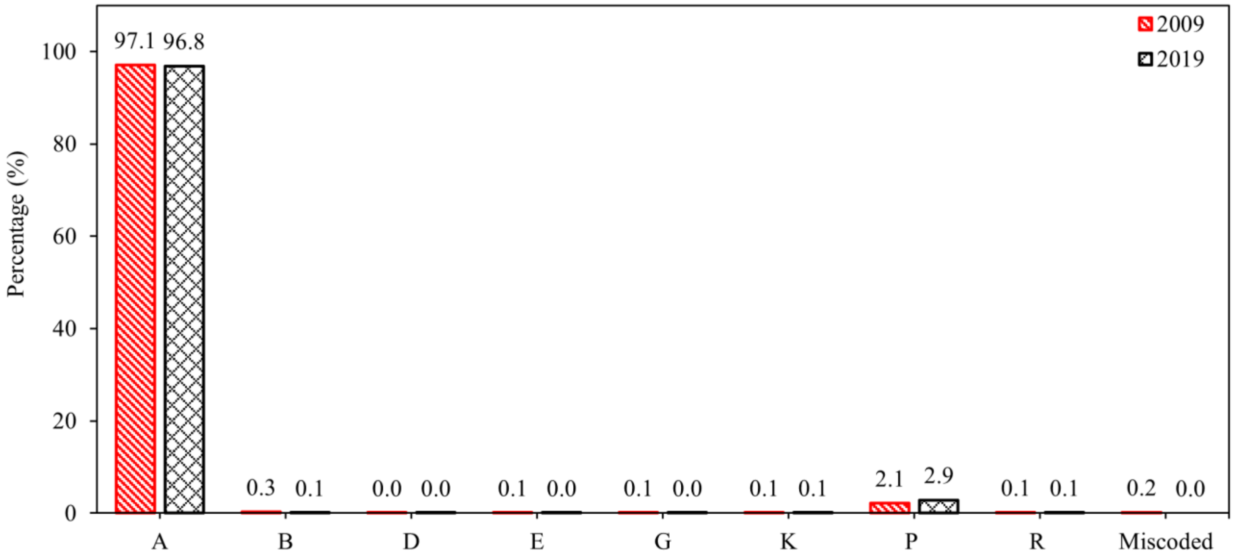
(a) Culvert Structures



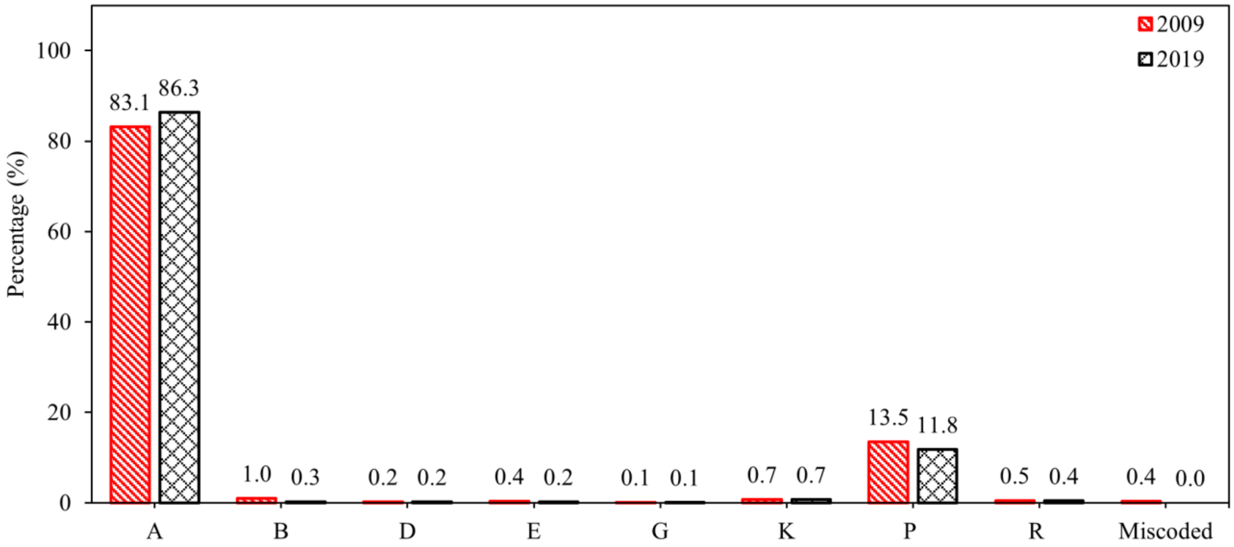
(b) Non-Culvert Structures

A: Open, no restriction; B: Open, posting recommended but not legally implemented; D: Open, would be posted or closed except for temporary shoring, etc. to allow for unrestricted traffic; E: Open, temporary structure in place to carry legal loads while original structure is closed and awaiting replacement or rehabilitation; G: New structure not yet open to traffic; K: Bridge closed to all traffic; P: Posted for load; R: Posted for other load-capacity restriction; 99: Miscoded data

Figure 12. Number of bridges vs. Item 41: Bridge Open/Posted/Closed



(a) Culvert Structures



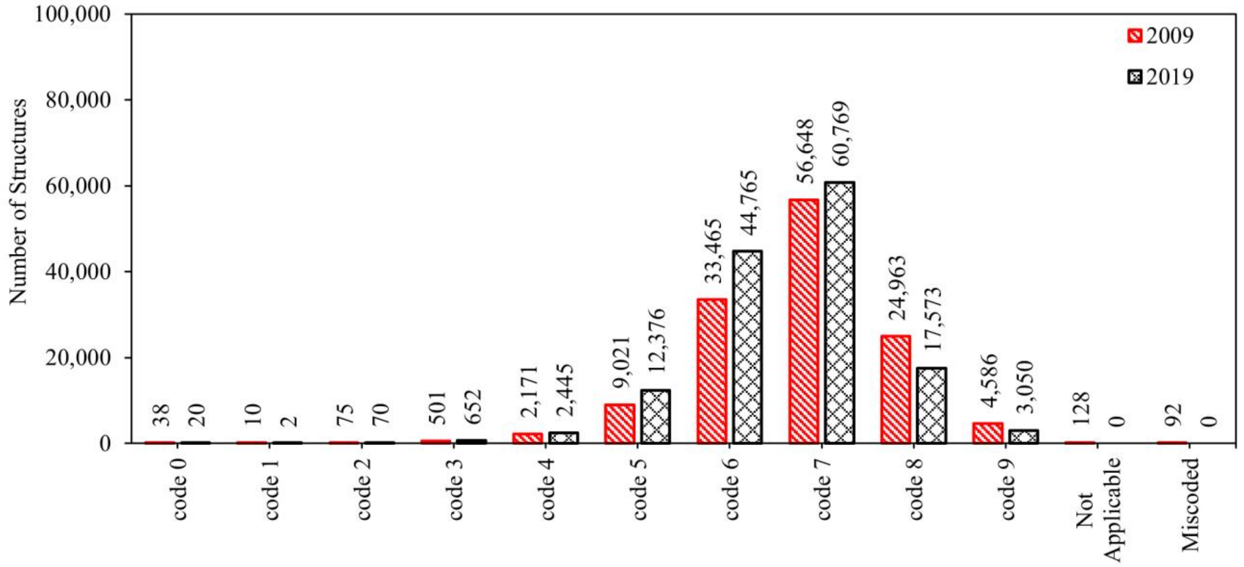
(b) Non-Culvert Structures

A: Open, no restriction; B: Open, posting recommended but not legally implemented; D: Open, would be posted or closed except for temporary shoring, etc. to allow for unrestricted traffic; E: Open, temporary structure in place to carry legal loads while original structure is closed and awaiting replacement or rehabilitation; G: New structure not yet open to traffic; K: Bridge closed to all traffic; P: Posted for load; R: Posted for other load-capacity restriction; 99: Miscoded data

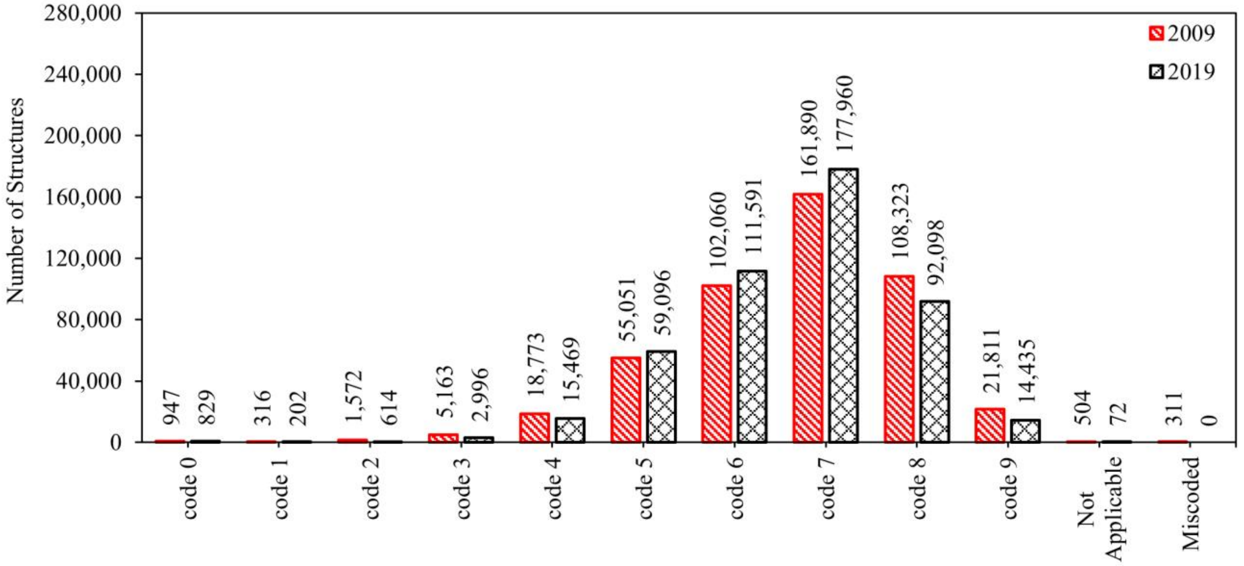
Figure 13. Percentage distribution on Item 41: Bridge Open/Posted/Closed

The results indicated that the majority of the structures are classified as A: Open with no restriction. Nearly 100,000 non-culvert structures were miscoded in the 2009 dataset, but most were well classified in the 2019 dataset. No significant other difference was seen between the 2009 and 2019 data.

Figure 14 and Figure 15 show the number of bridges versus Item 59: Bridge Superstructure Condition. Since the culvert structures do not have superstructures, all of them were classified as NOT APPLICABLE.



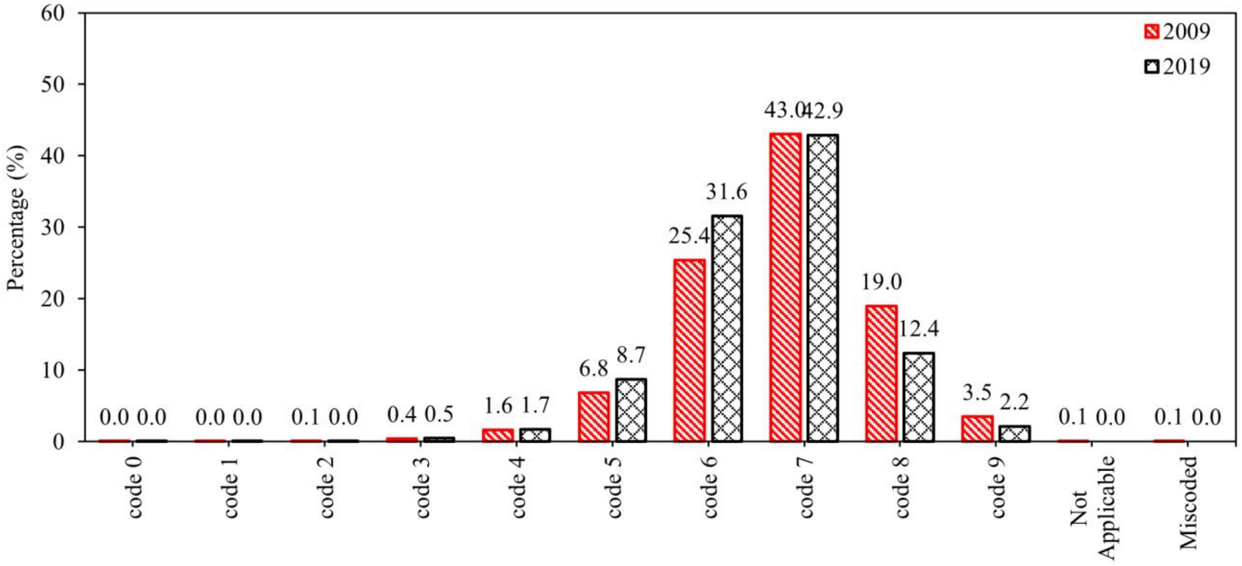
(a) Number of Culvert Structures vs. Item 62: Culvert Condition



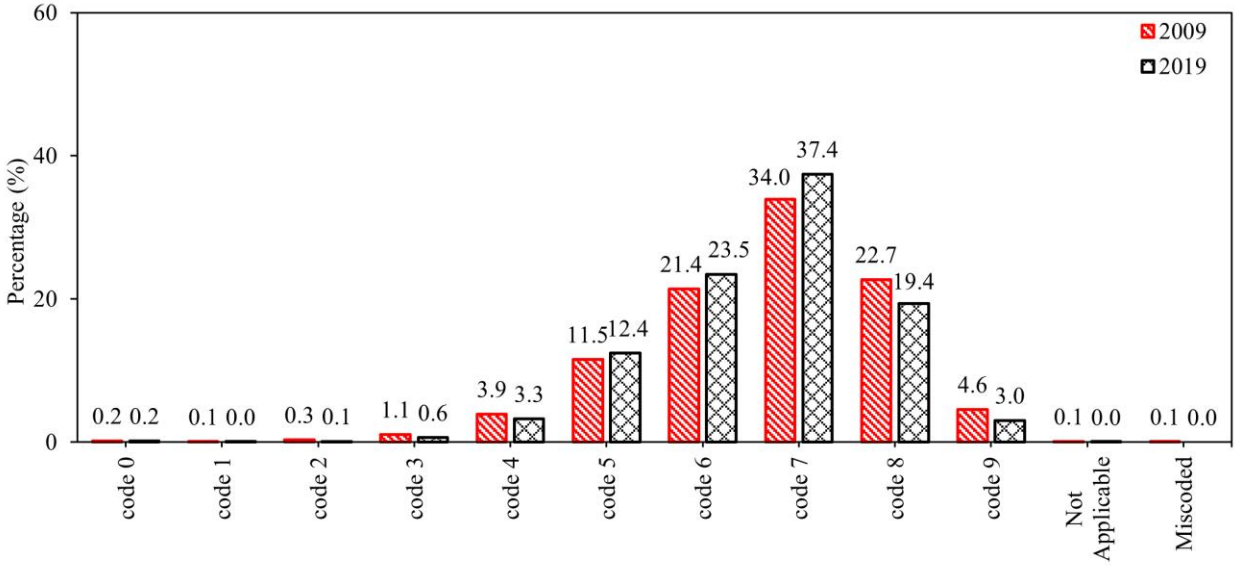
(b) Number of Non-Culvert Structures vs. Item 59: Bridge Superstructure Condition

N: NOT APPLICABLE; Code 9: EXCELLENT CONDITION; Code 8: VERY GOOD CONDITION; Code 7: GOOD CONDITION; Code 6: SATISFACTORY CONDITION; Code 5: FAIR CONDITION; Code 4: POOR CONDITION; Code 3: SERIOUS CONDITION; Code 2: CRITICAL CONDITION; Code 1: "IMMINANT" FAILURE CONDITION; Code 0: FAILED CONDITION; Code 99: Miscoded data

Figure 14. Number of bridges vs. Item 59 and Item 62: structural condition



(a) Culvert Structures



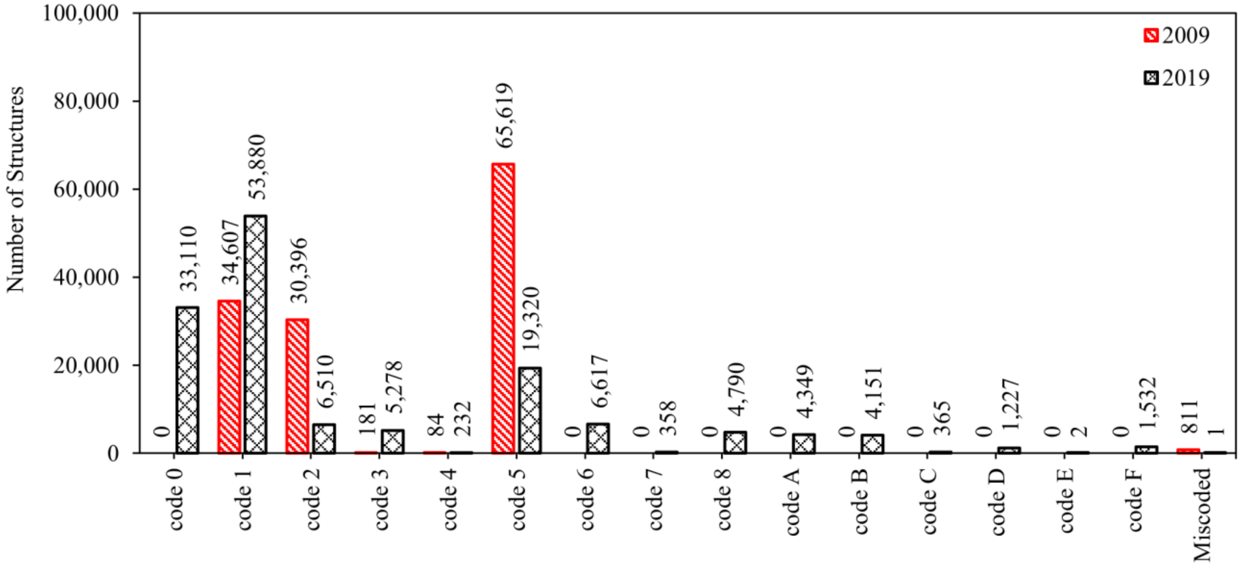
(b) Non-Culvert Structures

N: NOT APPLICABLE; Code 9: EXCELLENT CONDITION; Code 8: VERY GOOD CONDITION; Code 7: GOOD CONDITION; Code 6: SATISFACTORY CONDITION; Code 5: FAIR CONDITION; Code 4: POOR CONDITION; Code 3: SERIOUS CONDITION; Code 2: CRITICAL CONDITION; Code 1: "IMMINANT" FAILURE CONDITION; Code 0: FAILED CONDITION; Code 99: Miscoded data

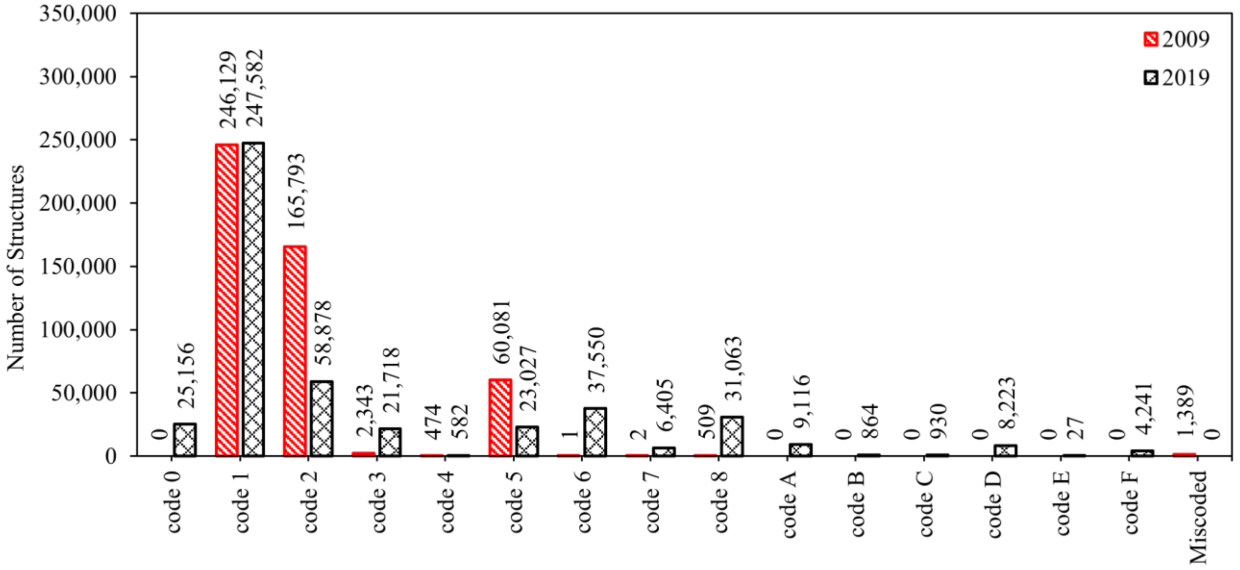
Figure 15. Percentage distribution on Item 59 and Item 62: structural condition

The results of the non-culvert structure data indicate a bell-curve distribution, such that most of the superstructure conditions are classified into codes 6, 7, and 8. The number of structures in codes 3, 4, 8, and 9 decreased and increased in codes 5, 6, and 7 when comparing to the 2009 and 2019 data in Figure 14. This indicates that the superstructures in the U.S. tend to be in FAIR to GOOD condition. It also indicates that a small proportion of structures are classified below FAIR condition.

Figure 16 through Figure 19 show the rating method distribution for the Operating rating and Inventory rating.



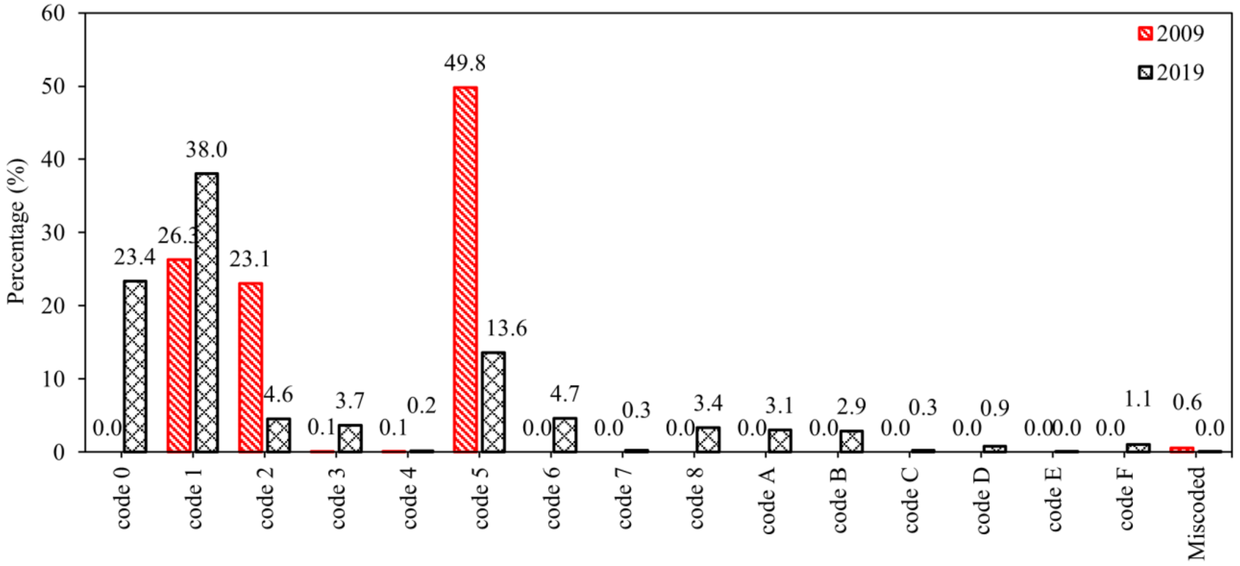
(a) Culvert Structures



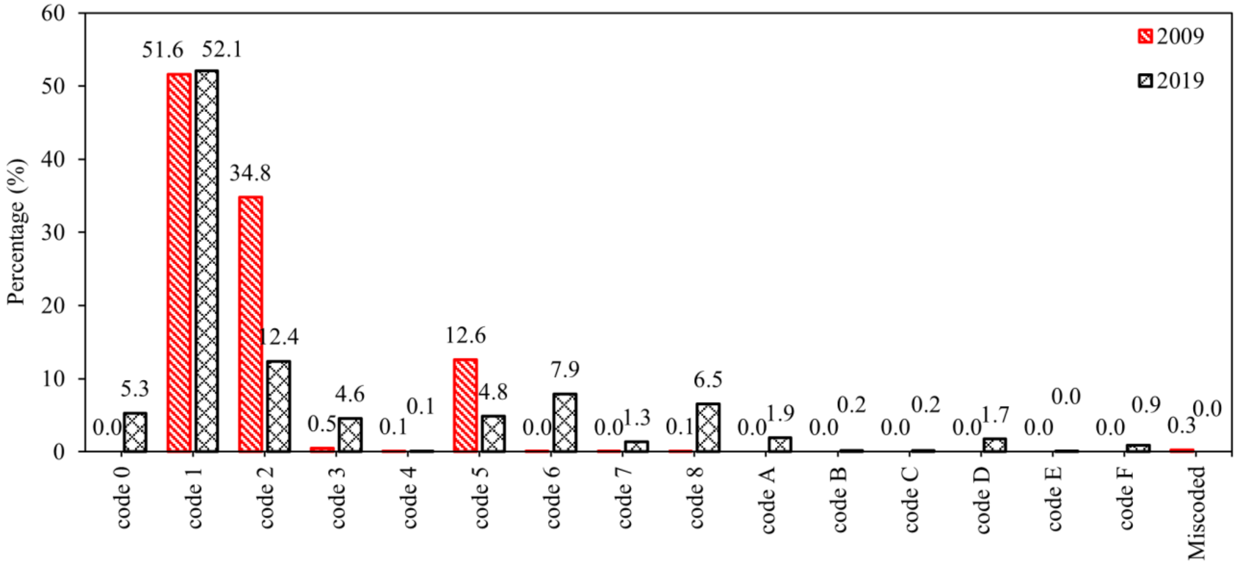
(b) Non-Culvert Structures

Code 0: Field evaluation and documented engineering judgment; Code 1: Load Factor (LF); Code 2: Allowable Stress (AS); Code 3: Load and Resistance Factor (LRFR); Code 4: Load Testing; Code 5: No rating analysis or evaluation performed; Code 6: Load Factor (LF) rating reported by rating factor (RF) method using MS18 loading; Code 7: Allowable Stress (AS) rating reported by rating factor (RF) method using MS18 loading; Code 8: Load and Resistance Factor Rating (LRFR) rating reported by rating factor (RF) method using HL-93 loadings; Code 9: Assigned rating based on Load Factor Design (LFD) reported in metric tons; Code B: Assigned ratings based on Allowable Stress Design (ASD) reported in metric tons; Code C: Assigned ratings based on Load and Resistance Factor Design (LRFD) reported in metric tons; Code D: Assigned rating based on Load Factor Design (LFD) reported by rating factor (RF) using MS18 loading; Code E: Assigned ratings based on Allowable Stress Design (ASD) reported by rating factor (RF) using MS18 loadings; Code F:Assigned ratings based on Load and Resistance Factor Design (LRFD) reported by rating factor (RF) using HL-93 loadings

Figure 16. Number of bridges vs. Item 63: Bridge OPR Rating Method



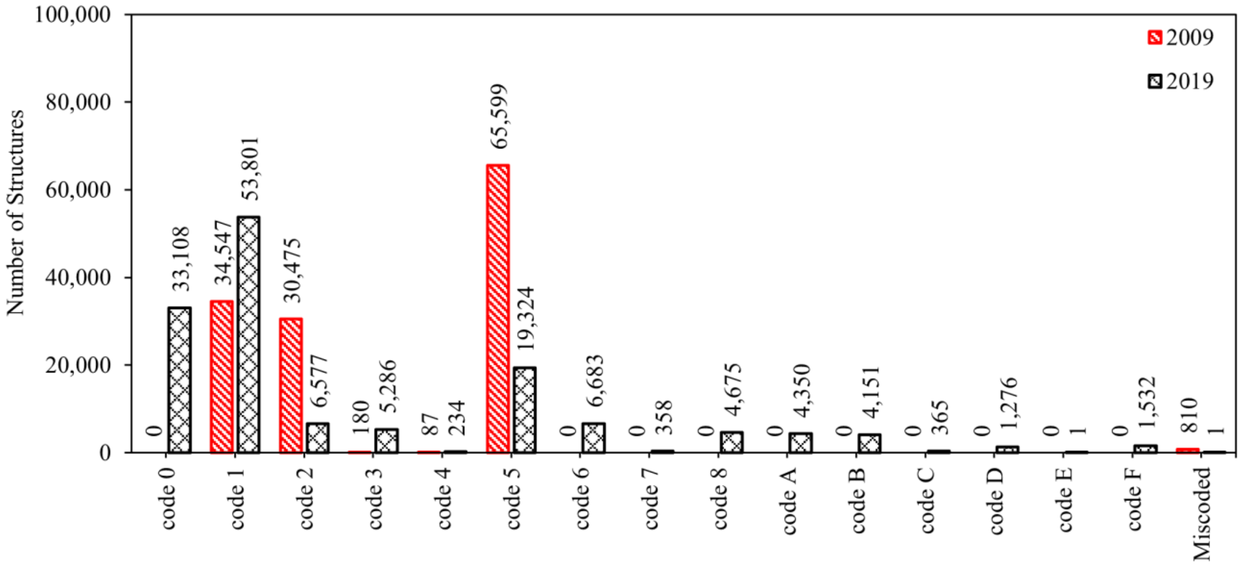
(a) Culvert Structures



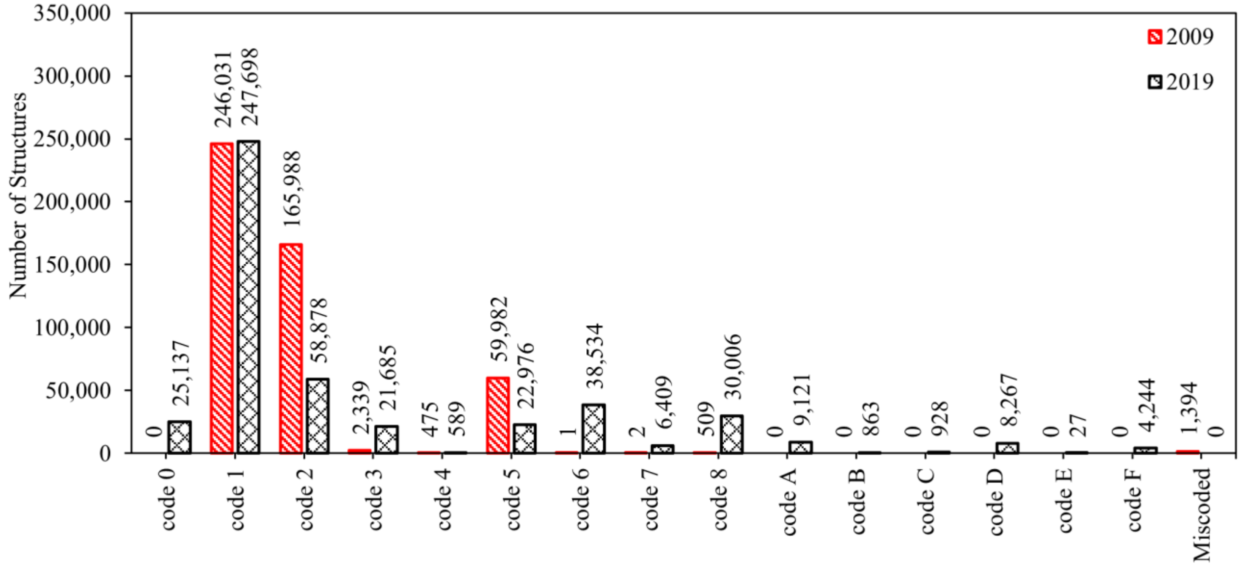
(b) Non-Culvert Structures

Code 0: Field evaluation and documented engineering judgment; Code 1: Load Factor (LF); Code 2: Allowable Stress (AS); Code 3: Load and Resistance Factor (LRFR); Code 4: Load Testing; Code 5: No rating analysis or evaluation performed; Code 6: Load Factor (LF) rating reported by rating factor (RF) method using MS18 loading; Code 7: Allowable Stress (AS) rating reported by rating factor (RF) method using MS18 loading; Code 8: Load and Resistance Factor Rating (LRFR) rating reported by rating factor (RF) method using HL-93 loadings; Code 9: Assigned rating based on Load Factor Design (LFD) reported in metric tons; Code B: Assigned ratings based on Allowable Stress Design (ASD) reported in metric tons; Code C: Assigned ratings based on Load and Resistance Factor Design (LRFD) reported in metric tons; Code D: Assigned rating based on Load Factor Design (LFD) reported by rating factor (RF) using MS18 loading; Code E: Assigned ratings based on Allowable Stress Design (ASD) reported by rating factor (RF) using MS18 loadings; Code F:Assigned ratings based on Load and Resistance Factor Design (LRFD) reported by rating factor (RF) using HL-93 loadings

Figure 17. Percentage distribution on Item 63: Bridge OPR Rating Method



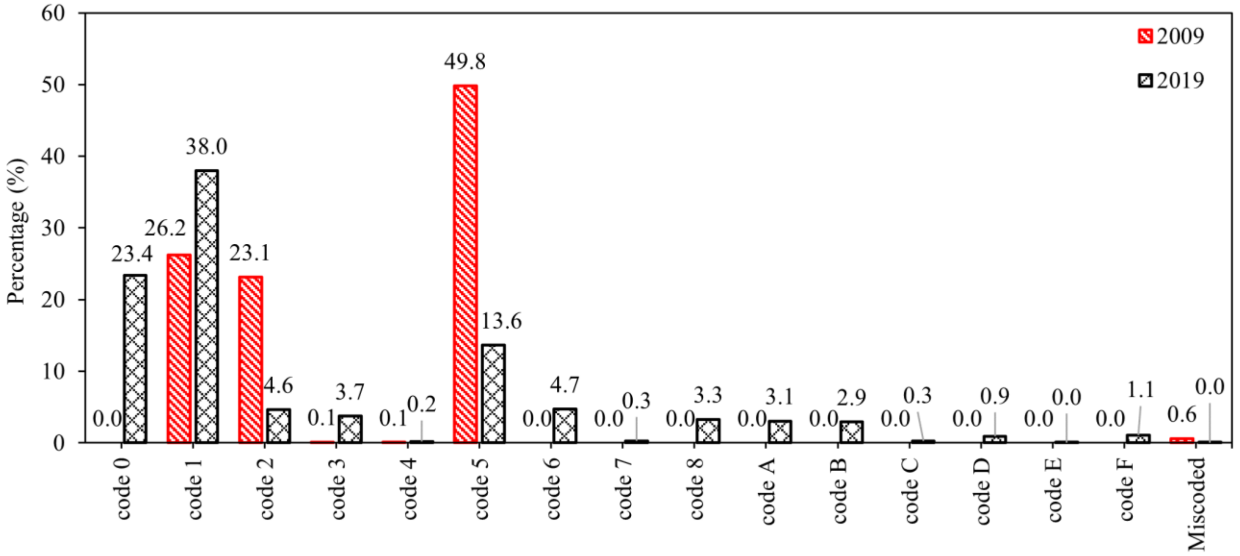
(a) Culvert Structures



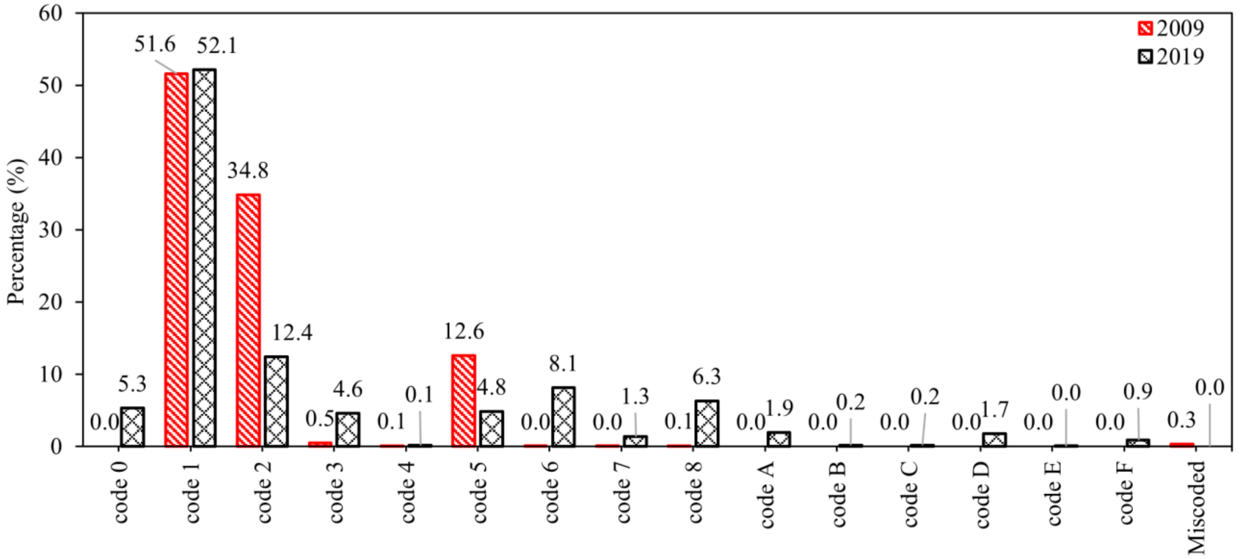
(b) Non-Culvert Structures

Code 0: Field evaluation and documented engineering judgment; Code 1: Load Factor (LF); Code 2: Allowable Stress (AS); Code 3: Load and Resistance Factor (LRFR); Code 4: Load Testing; Code 5: No rating analysis or evaluation performed; Code 6: Load Factor (LF) rating reported by rating factor (RF) method using MS18 loading; Code 7: Allowable Stress (AS) rating reported by rating factor (RF) method using MS18 loading; Code 8: Load and Resistance Factor Rating (LRFR) rating reported by rating factor (RF) method using HL-93 loadings; Code 9: Assigned rating based on Load Factor Design (LFD) reported in metric tons; Code B: Assigned ratings based on Allowable Stress Design (ASD) reported in metric tons; Code C: Assigned ratings based on Load and Resistance Factor Design (LRFD) reported in metric tons; Code D: Assigned rating based on Load Factor Design (LFD) reported by rating factor (RF) using MS18 loading; Code E: Assigned ratings based on Allowable Stress Design (ASD) reported by rating factor (RF) using MS18 loadings; Code F:Assigned ratings based on Load and Resistance Factor Design (LRFD) reported by rating factor (RF) using HL-93 loadings

Figure 18. Number of bridges vs. Item 65: Bridge INV Rating Method



(a) Culvert Structures



(b) Non-Culvert Structures

Code 0: Field evaluation and documented engineering judgment; Code 1: Load Factor (LF); Code 2: Allowable Stress (AS); Code 3: Load and Resistance Factor (LRFR); Code 4: Load Testing; Code 5: No rating analysis or evaluation performed; Code 6: Load Factor (LF) rating reported by rating factor (RF) method using MS18 loading; Code 7: Allowable Stress (AS) rating reported by rating factor (RF) method using MS18 loading; Code 8: Load and Resistance Factor Rating (LRFR) rating reported by rating factor (RF) method using HL-93 loadings; Code 9: Assigned rating based on Load Factor Design (LFD) reported in metric tons; Code B: Assigned ratings based on Allowable Stress Design (ASD) reported in metric tons; Code C: Assigned ratings based on Load and Resistance Factor Design (LRFD) reported in metric tons; Code D: Assigned rating based on Load Factor Design (LFD) reported by rating factor (RF) using MS18 loading; Code E: Assigned ratings based on Allowable Stress Design (ASD) reported by rating factor (RF) using MS18 loadings; Code F:Assigned ratings based on Load and Resistance Factor Design (LRFD) reported by rating factor (RF) using HL-93 loadings

Figure 19. Percentage distribution on Item 65: Bridge INV Rating Method

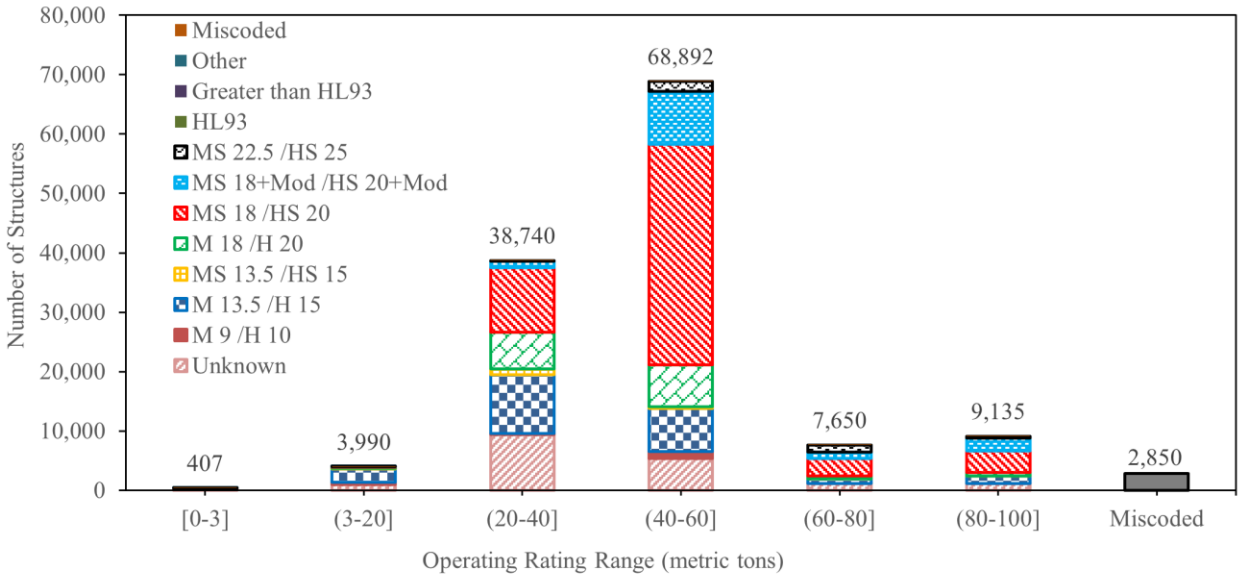
In general, these data show that most of the currently used structures were rated using the load factor (LF) method. Comparing the data from 2009 and 2019, the results indicate that more structures are being rated utilizing the LRFR method. However, comparing to the total number of structures, this portion of structures rated by LRFR is still very small, even in the 2019 dataset. This indicates a slow speed of adoption with respect to the newest rating method. This is because many States continue to report and load rate using LFR since their permitting systems are not capable of performing or using LRFR analysis.

For both culvert and non-culvert structures, the number of structures rated by the allowable stress (AS) method experienced a significant decrease from 2009 to 2019. From 2009 to 2019, the number of structures with no rating analysis or evaluation performed was reduced significantly, which indicates an improvement on the bridge rating work nationwide.

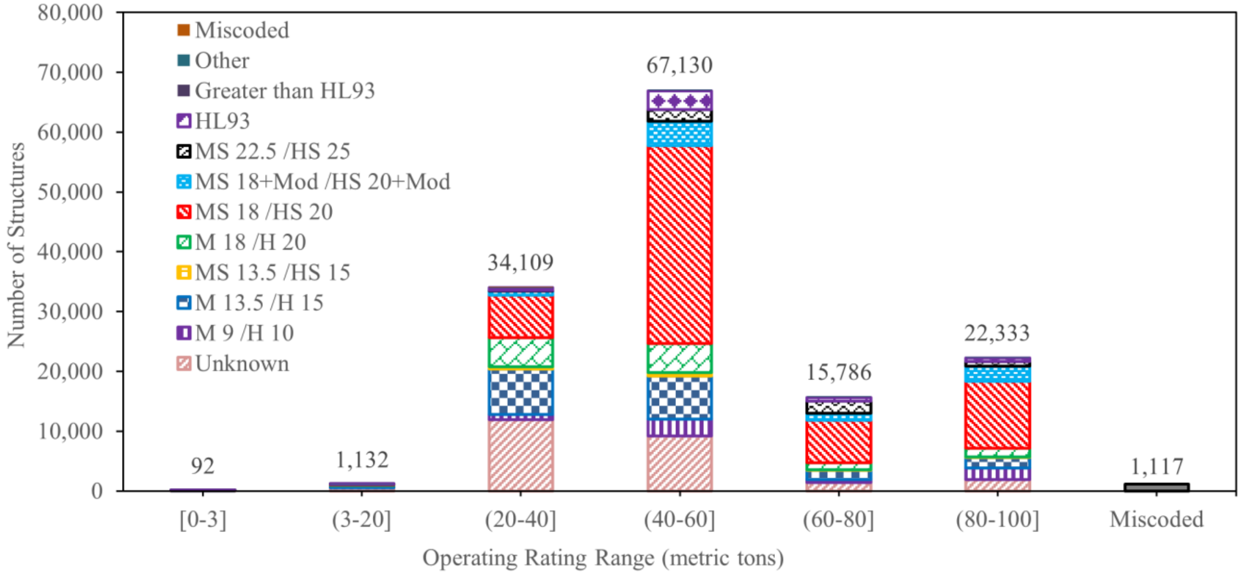
3.3.3 Data Analysis

The NBI data were further analyzed to investigate the relationship between multiple items. Stacked bar charts were used to present the results.

Figure 20 through Figure 23 present the relationship between Item 64 (66): Operating (Inventory) Rating results and Item 31: Design Load.

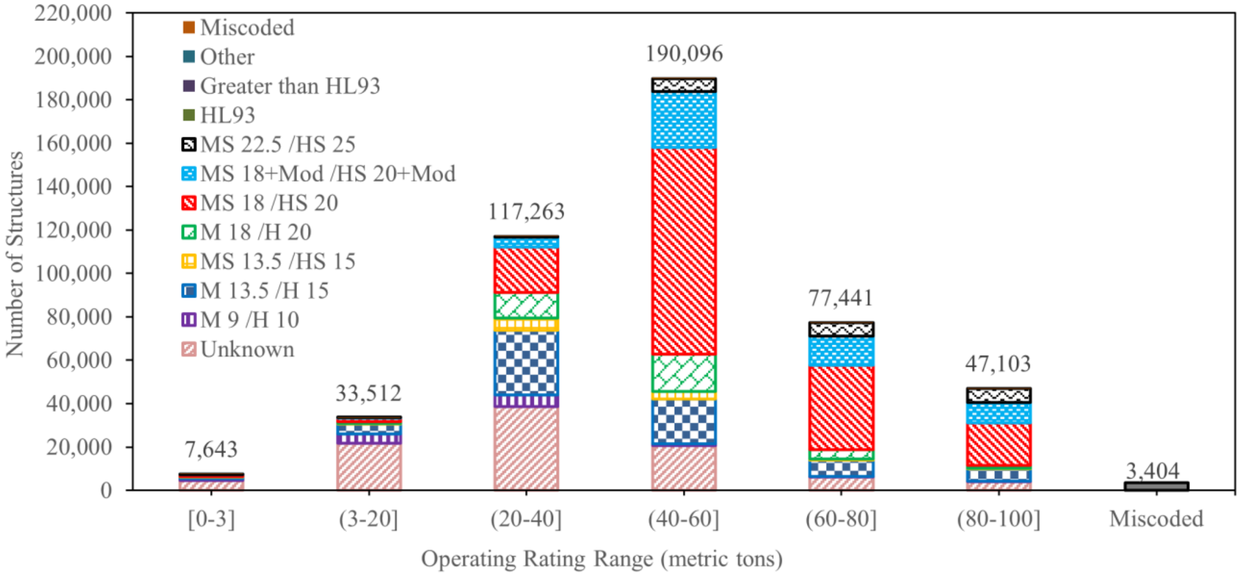


(a) 2009 data

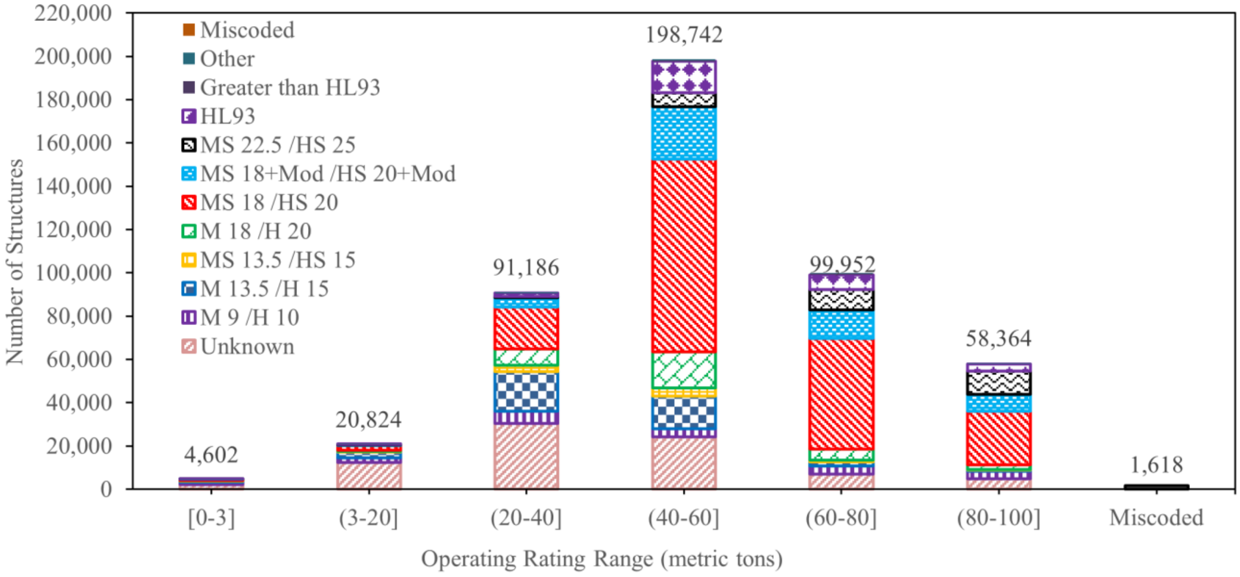


(b) 2019 data

Figure 20. Number of structures vs. Item 64: Operating Rating Result and Item 31: Design Load for culvert structures

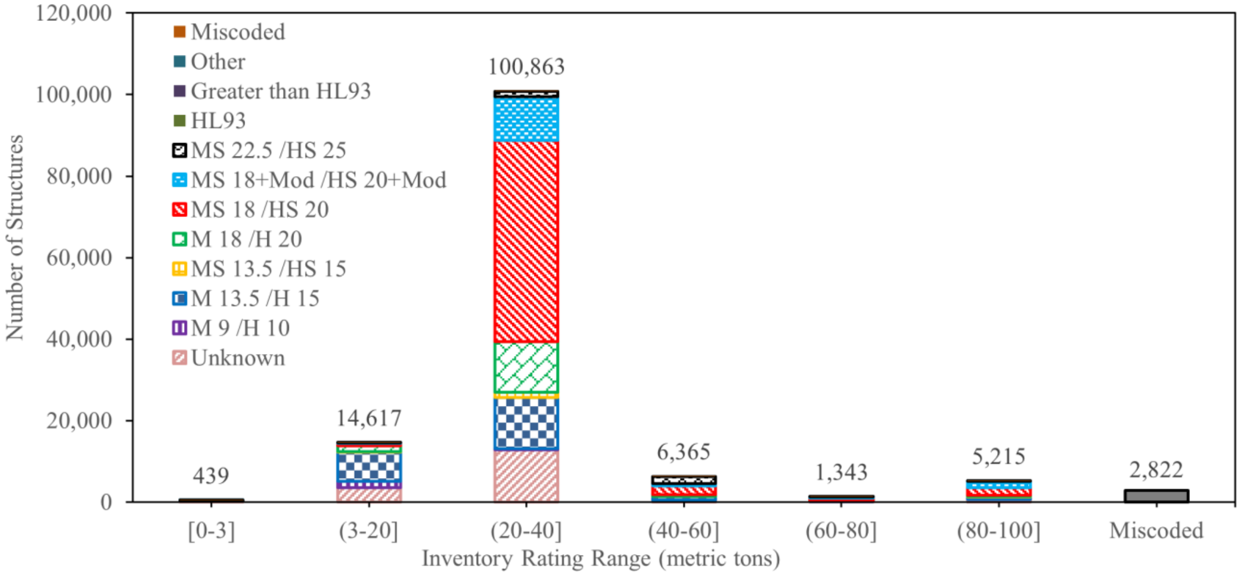


(a) 2009 data

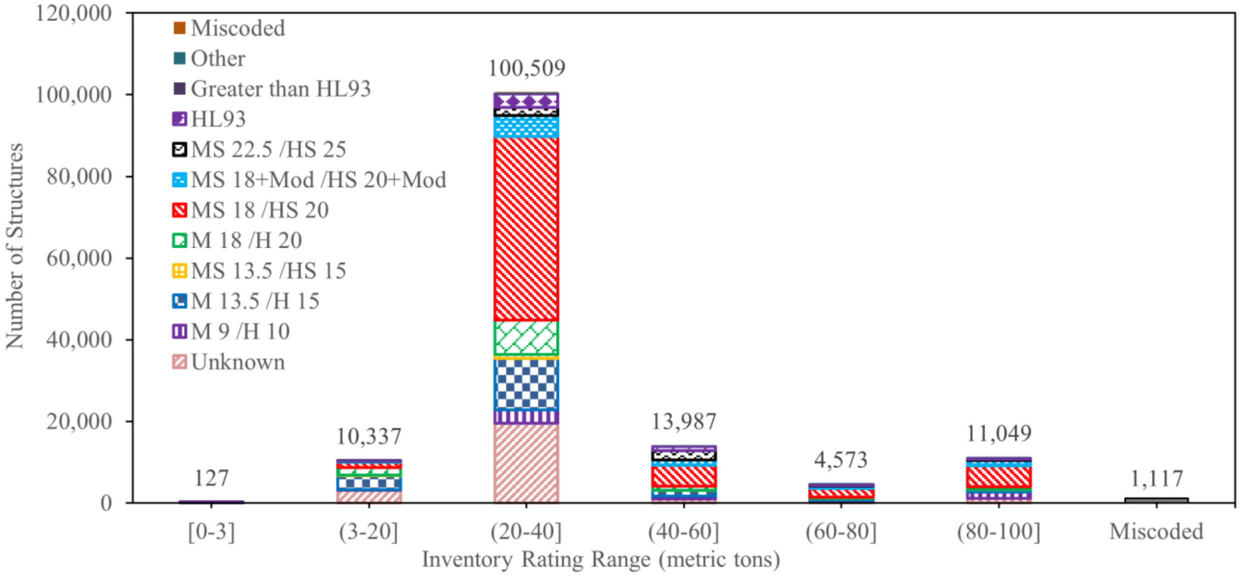


(b) 2019 data

Figure 21. Number of structures vs. Item 64: Operating Rating Result and Item 31: Design Load for non-culvert structures

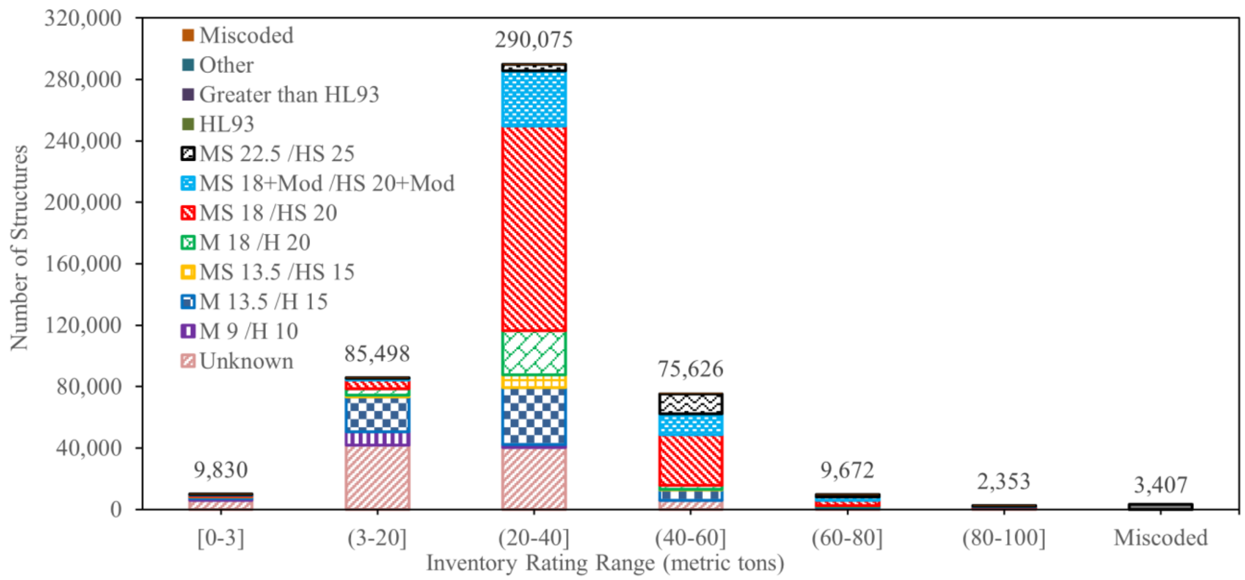


(a) 2009 data

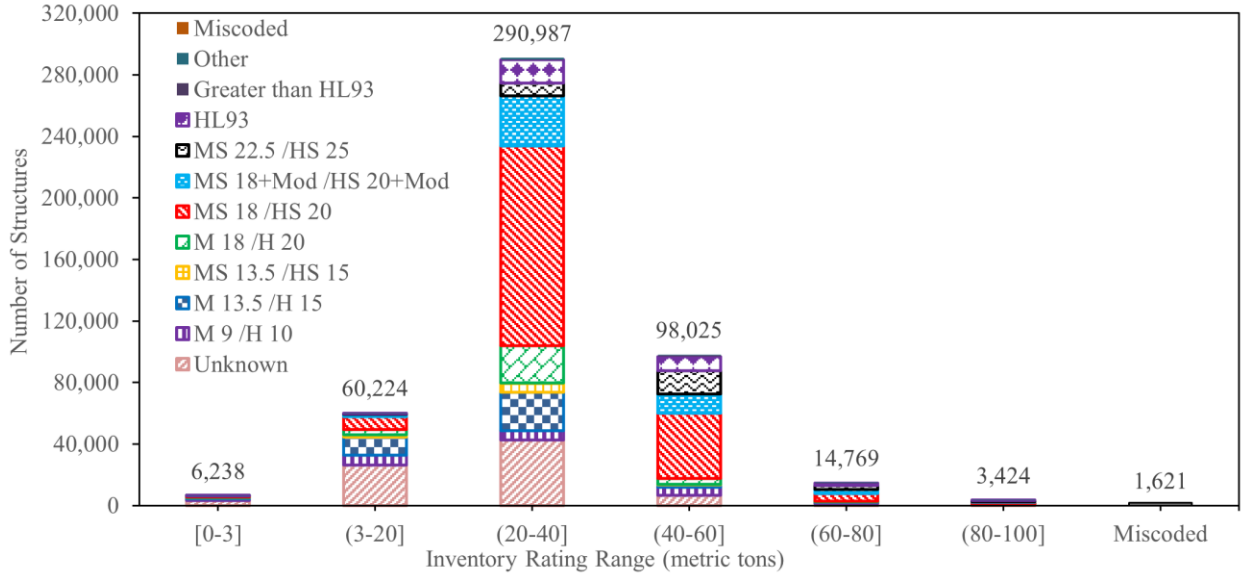


(b) 2019 data

Figure 22. Number of structures vs. Item 66: Inventory Rating Result and Item 31: Design Load for culvert structures



(a) 2009 data



(b) 2019 data

Figure 23. Number of structures vs. Item 66: Inventory Rating Result and Item 31: Design Load for non-culvert structures

Operating ratings are the absolute maximum permissible load level to which each structure may be subjected for the vehicle type used in the rating. The rating represents the total mass of the entire vehicle, measured in metric tons. The inventory rating is a load that can safely utilize an existing structure for an indefinite period of time. A structure coded as 999, according to the FHWA *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (1995), indicates that the live load is insignificant with respect to structure load capacity.

Figure 20 and Figure 21 show that the majority of the structures have an operating rating from 40 to 60 metric tons with an inventory rating in the range of 20 to 40 metric tons. Comparing Figure

20 and Figure 21 to Figure 22 and Figure 23, MS18/HS20 was the most commonly used design load for structures with an operating capacity greater than 40 metric tons and with an inventory capacity greater than 20 metric tons.

Table 10 through Table 13 show the detailed breakdown on the number of structures used to plot the previous Figure 20 through Figure 23.

Table 10. Operating rating results for culverts (Item 64)

Type	Year	Rating Result Range					
		0–3	3–20	20–40	40–60	60–80	80–100
Unknown	**2009**	210	924	9,400	5,368	1,148	1,104
	2019	42	546	11,967	9,189	1,433	1,944
M 9/H 10	**2009**	4	377	215	1,215	17	33
	2019	3	17	831	2,880	500	1,957
M 13.5/H 15	**2009**	21	2,338	9,828	7,243	760	1,246
	2019	8	337	7,620	7,160	1,534	1,726
MS 13.5/HS 15	**2009**	6	12	1,005	242	57	42
	2019	1	11	396	541	141	118
M 18/H 20	**2009**	17	220	6,143	7,121	482	578
	2019	8	80	4,826	4,945	1,095	1,411
MS 18/HS 20	**2009**	95	99	10,920	37,117	2,924	3,644
	2019	22	106	7,079	33,071	7,094	11,234
MS 18+Mod/HS 20+Mod	**2009**	11	14	1,103	8,928	1,037	2,158
	2019	2	20	738	4,056	1,203	2,519
Pedestrian	**2009**	0	0	0	3	1	1
	2019	0	0	0	0	2	2
Railroad	**2009**	2	2	3	13	2	7
	2019	0	0	3	9	4	3
MS 22.5/HS 25	**2009**	33	4	110	1,639	1,208	314
	2019	1	9	110	1,895	2,010	791
HL-93	**2009**	0	0	0	0	0	0
	2019	5	5	401	3,200	658	577
Greater than HL-93	**2009**	0	0	0	0	0	0
	2019	0	0	7	73	69	43
Other	**2009**	0	0	0	0	0	0
	2019	0	1	133	120	49	13
Miscoded	**2009**	10	2	16	19	17	16
	2019	0	0	1	0	0	0

Table 11. Operating rating results for non-culverts (Item 64)

Type	Year	Rating Result Range					
		0–3	3–20	20–40	40–60	60–80	80–100
Unknown	**2009**	4,513	21,793	38,619	20,789	6,218	4,173
	2019	2,154	12,313	30,422	24,303	6,980	4,742
M 9/H 10	**2009**	916	4,369	5,447	795	135	68
	2019	1,073	2,236	5,651	3,749	3,767	3,571
M 13.5/H 15	**2009**	886	4,494	29,726	20,562	7,524	5,629
	2019	642	2,641	18,385	14,886	1,942	673
MS 13.5/HS 15	**2009**	76	302	5,545	3,445	686	228
	2019	51	236	2,905	3,763	752	178
M 18/H 20	**2009**	144	745	11,820	17,352	4,226	1,517
	2019	129	722	7,568	16,837	5,253	2,164
MS 18/HS 20	**2009**	763	1,581	21,121	95,138	38,901	19,581
	2019	447	2,134	19,380	89,026	50,913	24,860
MS 18+Mod/HS 20+Mod	**2009**	89	159	4,362	25,673	13,404	9,388
	2019	42	299	4,191	24,308	13,396	7,585
Pedestrian	**2009**	55	23	10	7	3	3
	2019	1	4	2	3	2	1
Railroad	**2009**	11	13	26	57	21	30
	2019	0	2	5	25	11	18
MS 22.5/HS 25	**2009**	239	54	486	6,117	6,099	6,377
	2019	23	47	675	6,263	9,314	10,737
HL-93	**2009**	0	0	0	0	0	0
	2019	24	114	1,455	14,513	6,804	3,397
Greater than HL-93	**2009**	0	0	0	0	0	0
	2019	0	1	18	427	520	212
Other	**2009**	0	0	0	0	0	0
	2019	17	81	536	667	311	245
Miscoded	**2009**	17	15	137	225	248	142
	2019	0	0	0	0	0	0

Table 12. Inventory rating results for culverts (Item 66)

Type	Year	Rating Result Range					
		0–3	3–20	20–40	40–60	60–80	80–100
Unknown	2009	227	3,582	12,865	606	155	720
	2019	59	3,088	19,501	1,004	349	1,119
M 9/H 10	2009	4	1,530	285	21	11	10
	2019	3	160	3,353	719	366	1,587
M 13.5/H 15	2009	27	7,199	12,583	810	204	618
	2019	11	3,428	12,593	1,346	412	595
MS 13.5/HS 15	2009	6	71	1,207	52	15	13
	2019	2	108	906	120	32	40
M 18/H 20	2009	19	1,439	12,417	294	70	323
	2019	11	1,924	8,470	940	308	712
MS 18/HS 20	2009	101	659	49,461	2,152	589	1,858
	2019	30	1,295	44,971	5,127	2,157	5,027
MS 18+Mod/HS 20+Mod	2009	12	117	10,625	689	257	1,551
	2019	5	247	5,083	1,281	558	1,364
Pedestrian	2009	0	0	3	2	0	0
	2019	0	0	4	0	0	0
Railroad	2009	2	5	13	2	2	5
	2019	0	1	11	4	1	2
MS 22.5/HS 25	2009	33	9	1,397	1,721	36	112
	2019	1	33	2,008	2,329	167	278
HL-93	2009	0	0	0	0	0	0
	2019	5	47	3,271	1,025	201	297
Greater than HL-93	2009	0	0	0	0	0	0
	2019	0	1	67	79	22	23
Other	2009	0	0	0	0	0	0
	2019	0	6	285	17	1	7
Miscoded	2009	10	11	23	20	6	10
	2019	0	0	1	0	0	0

Table 13. Inventory rating results for non-culverts (Item 66)

Type	Year	Rating Result Range					
		0–3	3–20	20–40	40–60	60–80	80–100
Unknown	**2009**	5,974	41,970	40,471	5,818	1,250	625
	2019	3,114	26,230	42,780	6,579	1,500	712
M 9/H 10	**2009**	1,143	8,693	1,735	129	19	11
	2019	1,213	6,471	6,042	5,490	748	83
M 13.5/H 15	**2009**	1,166	22,614	37,200	6,716	859	262
	2019	893	11,968	24,711	1,339	190	68
MS 13.5/HS 15	**2009**	98	1,299	8,393	450	25	17
	2019	73	1,186	6,112	443	66	5
M 18/H 20	**2009**	184	4,008	28,456	2,749	297	109
	2019	186	3,632	24,246	3,942	518	149
MS 18/HS 20	**2009**	886	5,582	133,437	32,902	3,605	673
	2019	607	8,245	129,855	42,166	4,895	990
MS 18+Mod/HS 20+Mod	**2009**	117	1,121	35,808	13,633	2,022	374
	2019	71	1,586	32,475	12,501	2,559	629
Pedestrian	**2009**	57	24	15	3	2	0
	2019	2	5	5	1	0	0
Railroad	**2009**	14	19	56	50	9	11
	2019	0	3	29	19	6	4
MS 22.5/HS 25	**2009**	246	133	4,281	12,871	1,563	278
	2019	30	249	8,534	15,045	2,709	492
HL-93	**2009**	0	0	0	0	0	0
	2019	32	343	14,981	9,399	1,291	259
Greater than HL-93	**2009**	0	0	0	0	0	0
	2019	0	2	286	691	175	24
Other	**2009**	0	0	0	0	0	0
	2019	19	312	965	430	118	13
Miscoded	**2009**	16	78	294	358	32	4
	2019	0	0	0	0	0	0

Furthermore, some structures were assigned as exactly 32.4 metric tons. While it is possible that a bridge could rate at exactly 32.4 metric tons, a rating of 32.4 metric tons likely represents an estimation of the rating based on engineering judgment rather than an actual load rating based on codified procedures. A summary of the data for these is shown in Table 14.

Table 14. Number of bridges rated as exactly 32.4 metric tons

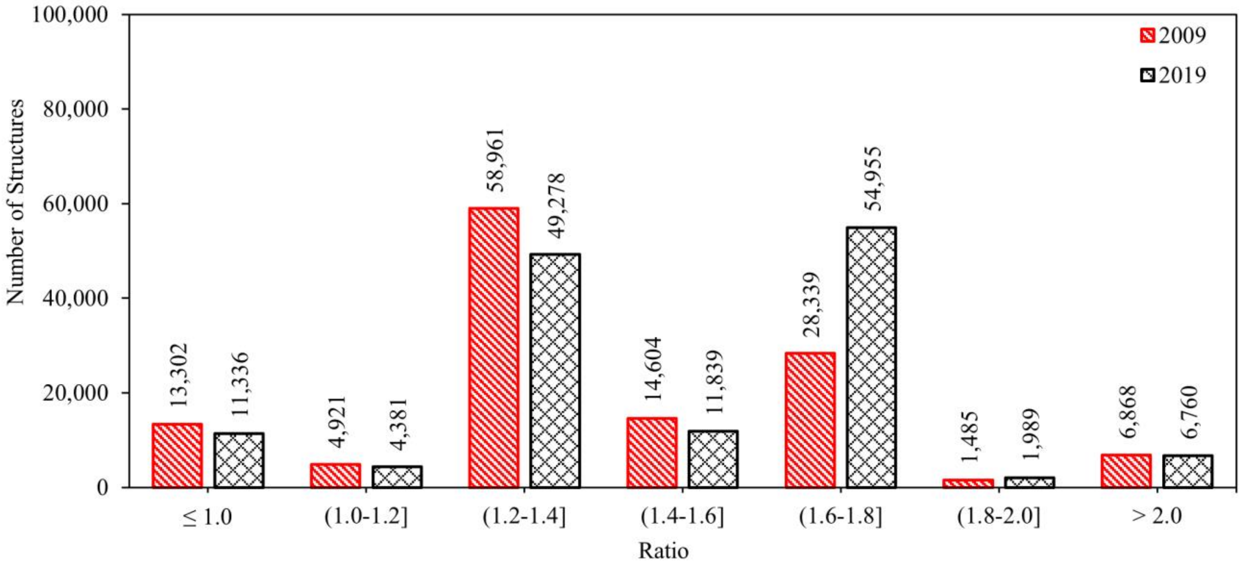
	Item 64: Operating Rating		Item 66: Inventory Rating	
Type	2009	2019	2009	2019
Culvert	10,794	1,175	37,131	19,849
Non-Culvert	13,017	2,386	72,176	41,178

Table 15 shows number of bridges grouped by the ratio of Item 64: Operating Rating to Item 66: Inventory Rating.

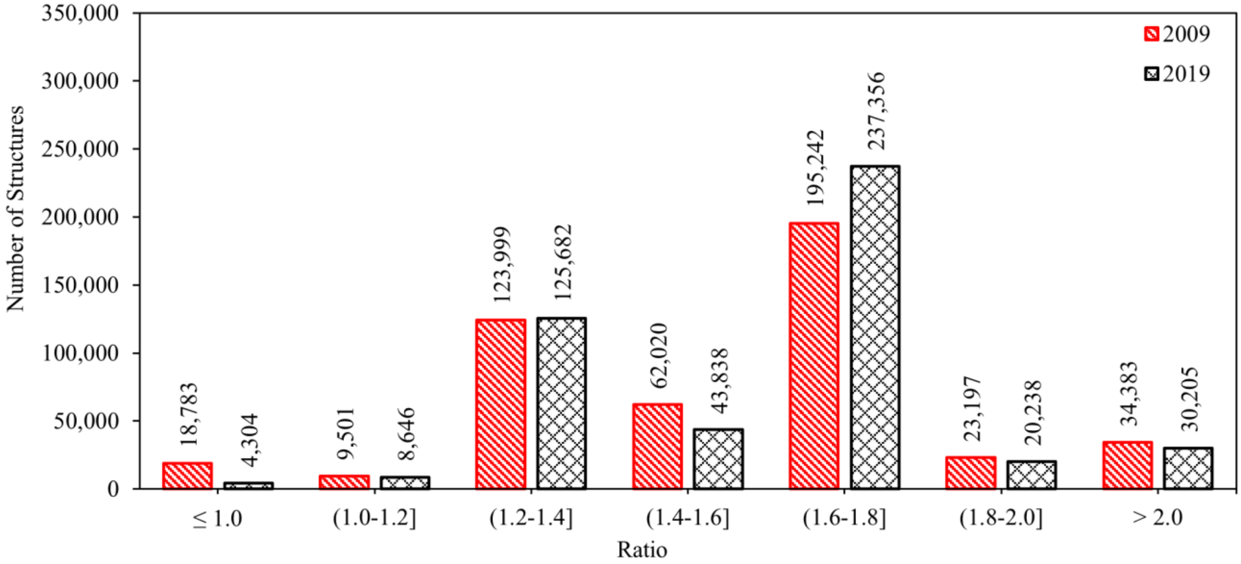
Table 15. Number of bridges grouped by the ratio of Item 64: Operating Rating to Item 66: Inventory Rating

Year	Type	Operating Rating / Inventory Rating						
		≤1.0	1.0 – 1.2	1.2 – 1.4	1.4 – 1.6	1.6 – 1.8	1.8 – 2.0	>2.0
2009	**Culvert**	13,302	4,921	58,961	14,604	28,339	1,485	6,868
	Non-Culvert	18,783	9,501	123,999	62,020	195,242	23,197	34,383
2019	**Culvert**	11,336	4,381	49,278	11,839	54,955	1,989	6,760
	Non-Culvert	4,304	8,646	125,682	43,838	237,356	20,238	30,205

Figure 24 shows the data in Table 15 graphically.



(a) Culvert Structure



(b) Non-Culvert Structure

Figure 24. Number of bridges grouped by the ratio of Item 64: Operating Rating to Item 66: Inventory Rating

The results indicated that most of the structures showed a ratio of 1.2 to 1.4 and 1.6 to 1.8. Comparing 2009 and 2019 data, the number of structures that showed a ratio of 1.6 to 1.8 increased significantly for both culvert and non-culvert structures.

to see the change in load rating, the mean value was calculated for both 2009 and 2019 data. Before calculating the mean value, the data were filtered to remove structures that had an empty cell for Item 64 or Item 66. The resulting total number of structures is listed in Table 16.

Table 16. Total number of structures used to calculate the mean value

Type	Year	Operating rating results			Inventory rating results		
		Used Data	Filtered/Removed Data	Total Data	Used Data	Filtered/Removed Data	Total Data
Culvert	**2009**	128,848	2,850	131,698	128,876	2,822	131,698
	2019	140,605	1,117	141,722	140,605	1,117	141,722
Non-Culvert	**2009**	473,317	3,404	476,721	473,314	3,407	476,721
	2019	473,744	1,618	475,362	473,741	1,621	475,362

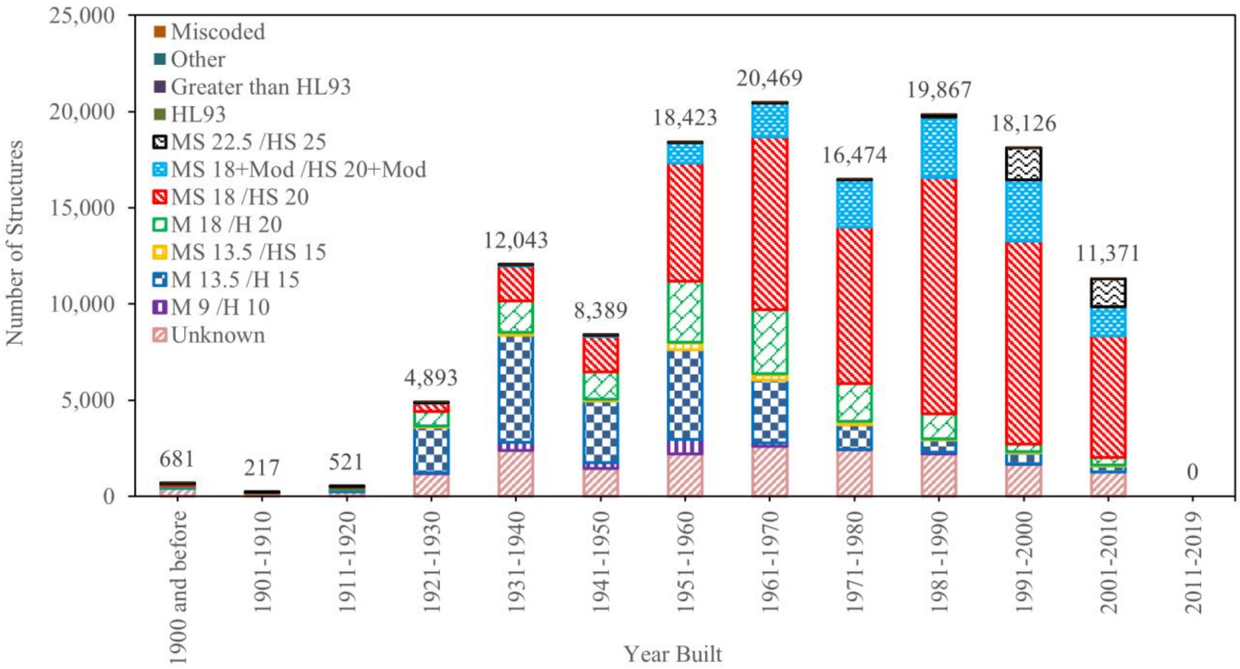
The mean values for culvert and non-culvert structures are presented and compared in Table 17.

Table 17. Bridge load rating mean values (metric tons)

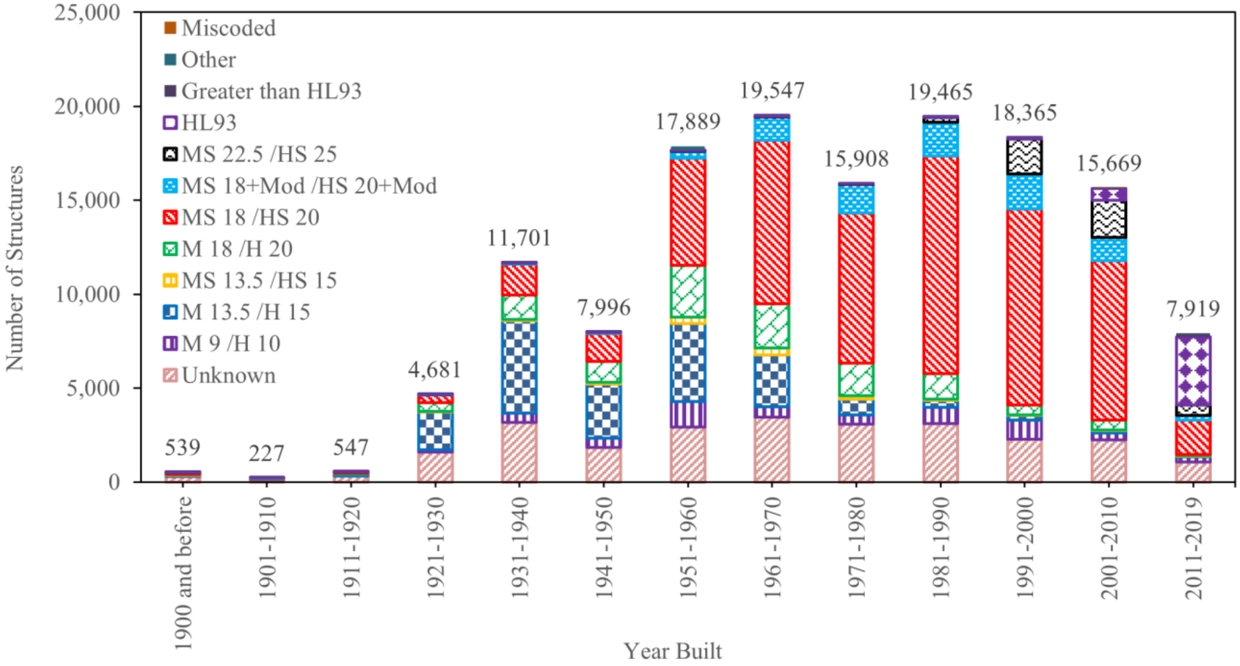
Type	Data Results	2009	2019	Increase by (%)
Culvert	**Operating Rating**	45.72	53.54	17.10
	Inventory Rating	32.48	37.27	14.75
Non-Culvert	**Operating Rating**	48.25	52.91	9.66
	Inventory Rating	30.66	33.43	9.03

The results indicated that the mean value of the reported load ratings of bridge and culvert structures in the United States increased from 2009 to 2019. The culvert structures increased by 17.1 percent for operating rating and 14.75 percent for inventory rating. The non-culvert structures increased by 9.66 percent for operating rating and 9.03 percent for inventory rating.

Figure 25 and Figure 26 show the relationship between Item 27: Year Built and Item 31: Design Load for culvert and non-culvert structures, respectively.

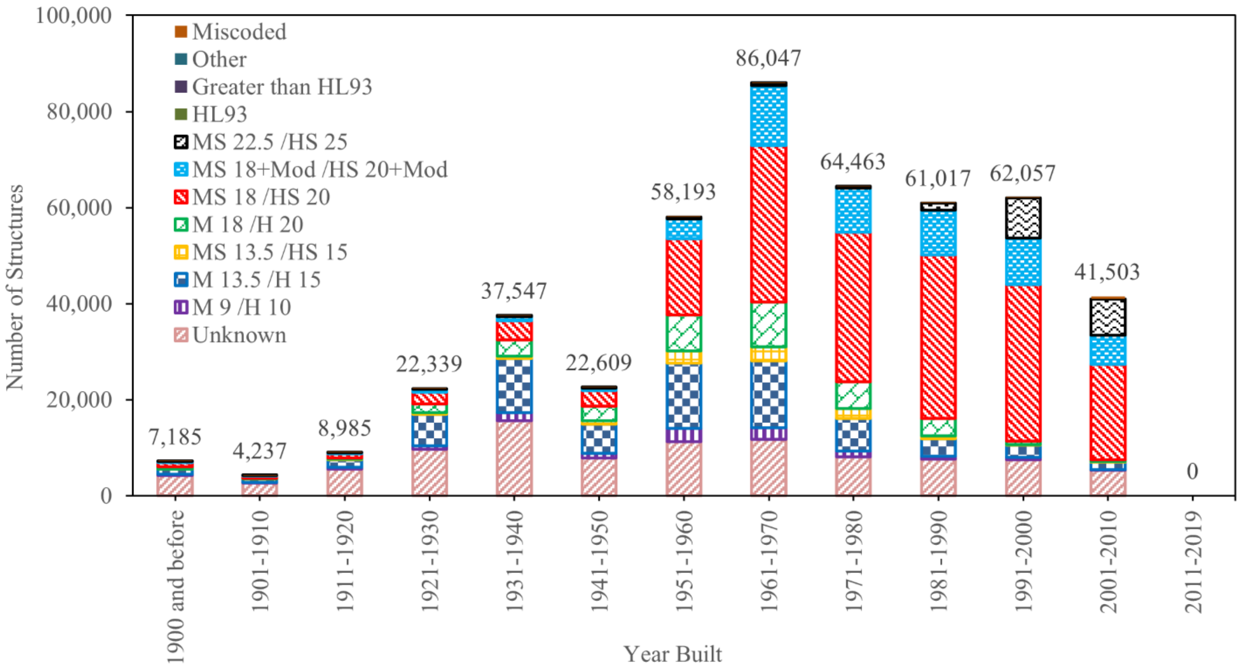


(a) 2009 data

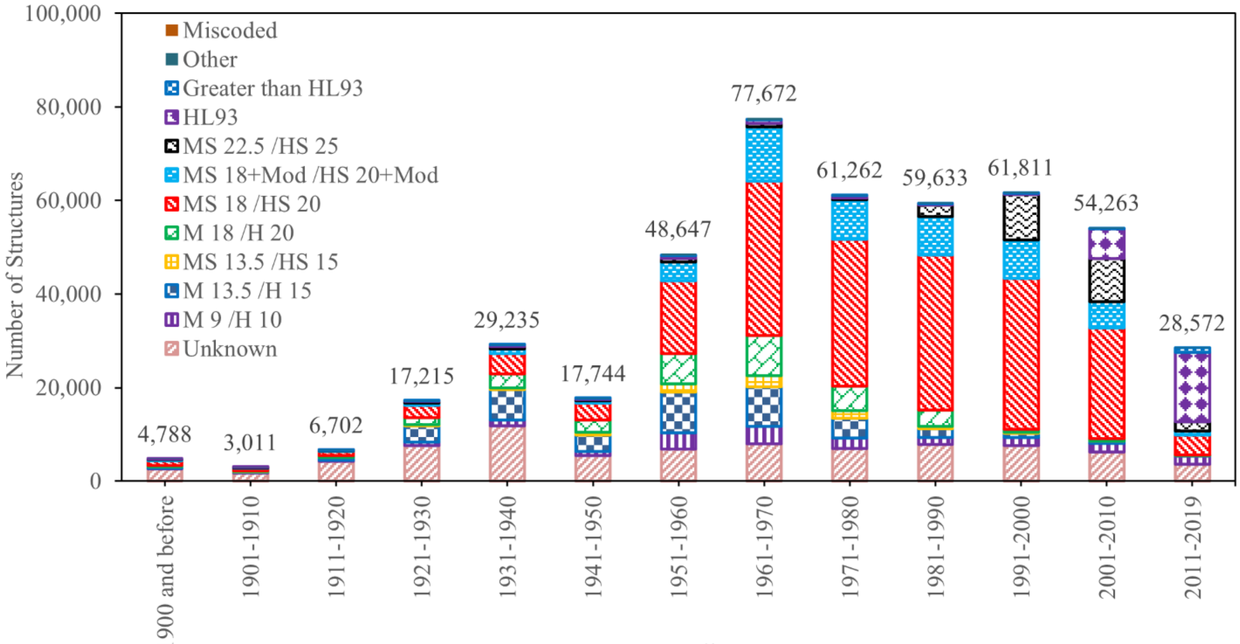


(b) 2019 data

Figure 25. Number of structures vs. Item 27: Year Built and Item 31: Design Load for culvert structures



(a) 2009 data

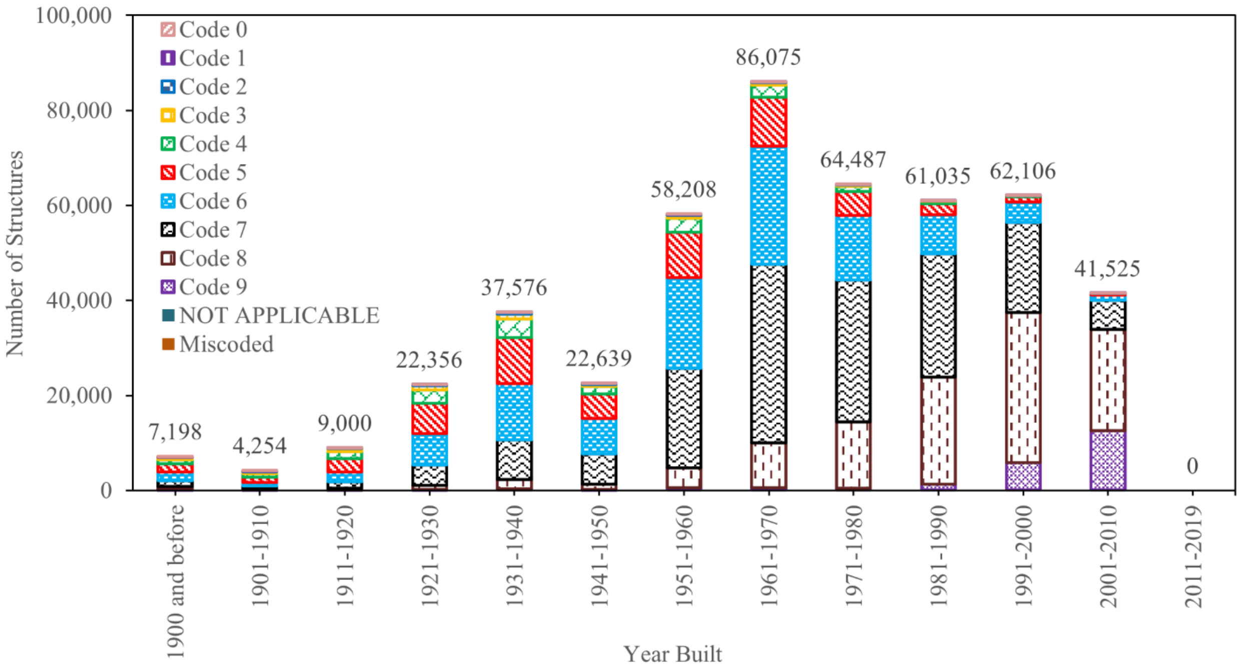


(b) 2019 data

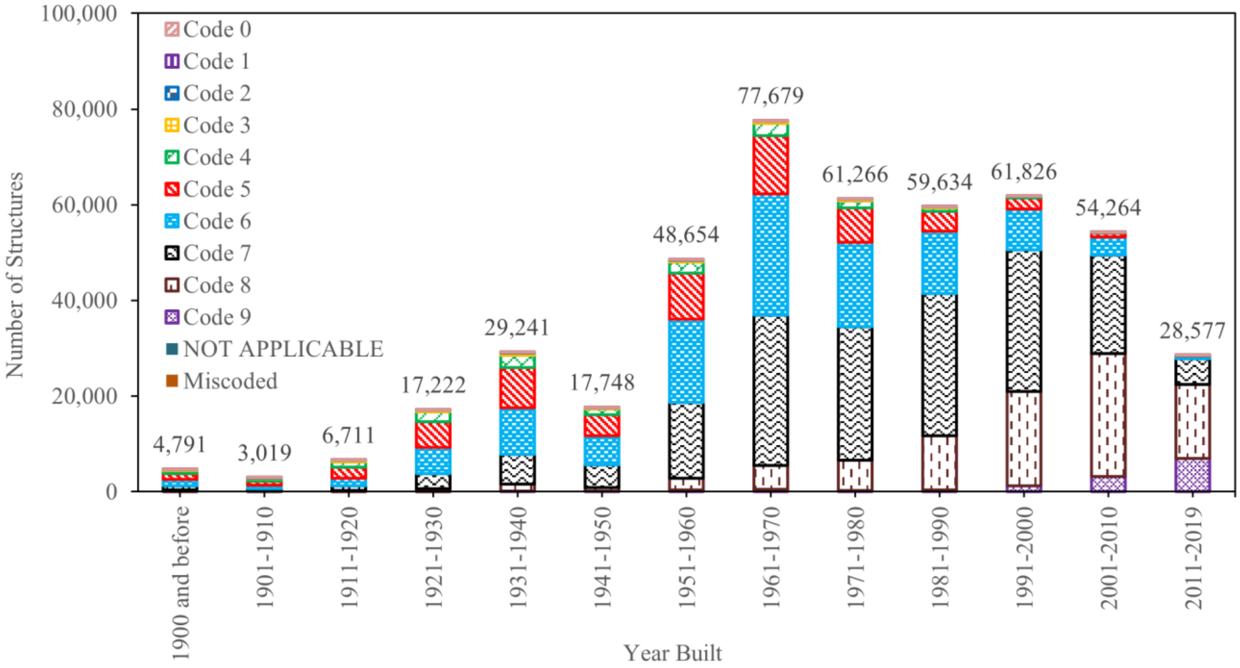
Figure 26. Number of structures vs. Item 27: Year Built and Item 31: Design Load for non-culvert structures

Both figures indicate that larger design loads were used for a higher proportion of structures as time went on. For example, in Figure 25, the M13.5/H 15 design load was used for nearly half of the total structures built during the 1920s, 1930s, and 1940s. After that, the use of the MS18/HS20 design load started to increase and replace the M13.5/H15 design load as a commonly used design load for the majority of new structures in the 1960s and beyond. During the past 30 years (1990 through 2019), the proportion of total newly constructed structures designed utilizing the larger design load (e.g., MS 22.5/HS 25, HL-93 or larger) increased.

Figure 27 shows the relationship between Item 27: Year Built and Item 59: Superstructure Condition for non-culvert structures.



(a) 2009 data



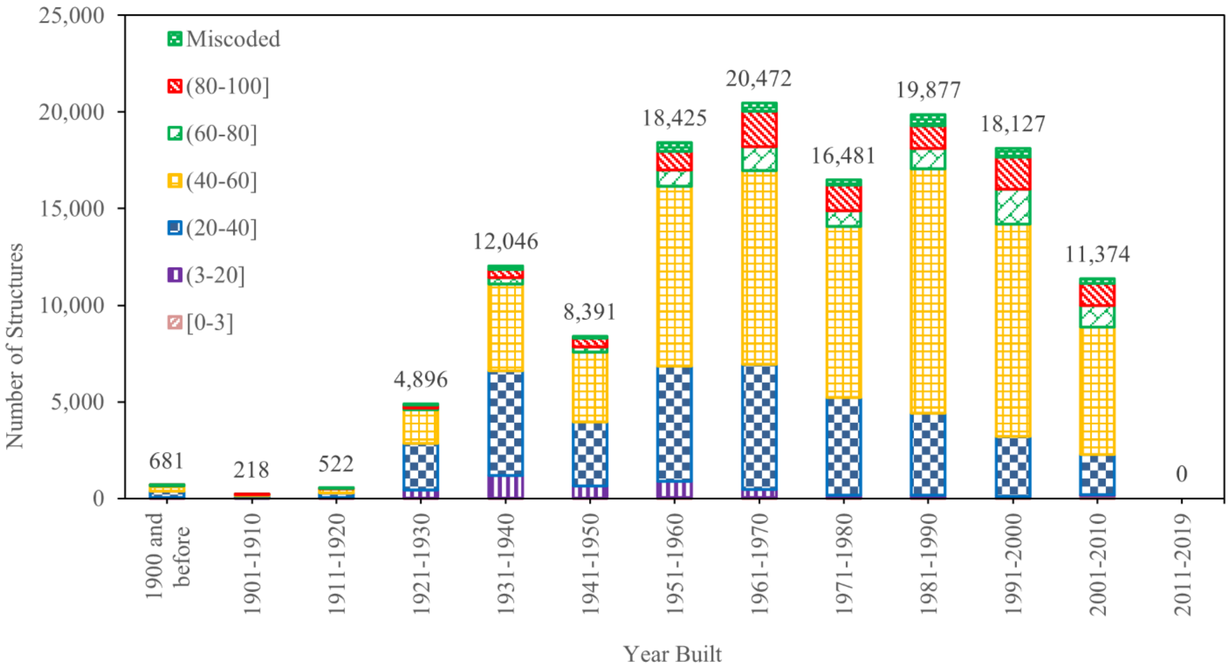
(b) 2019 data

N: NOT APPLICABLE; Code 9: EXCELLENT CONDITION; Code 8: VERY GOOD CONDITION; Code 7: GOOD CONDITION; Code 6: SATISFACTORY CONDITION; Code 5: FAIR CONDITION; Code 4: POOR CONDITION; Code 3: SERIOUS CONDITION; Code 2: CRITICAL CONDITION; Code 1: "IMMINANT" FAILURE CONDITION; Code 0: FAILED CONDITION; Code 99: Miscoded data

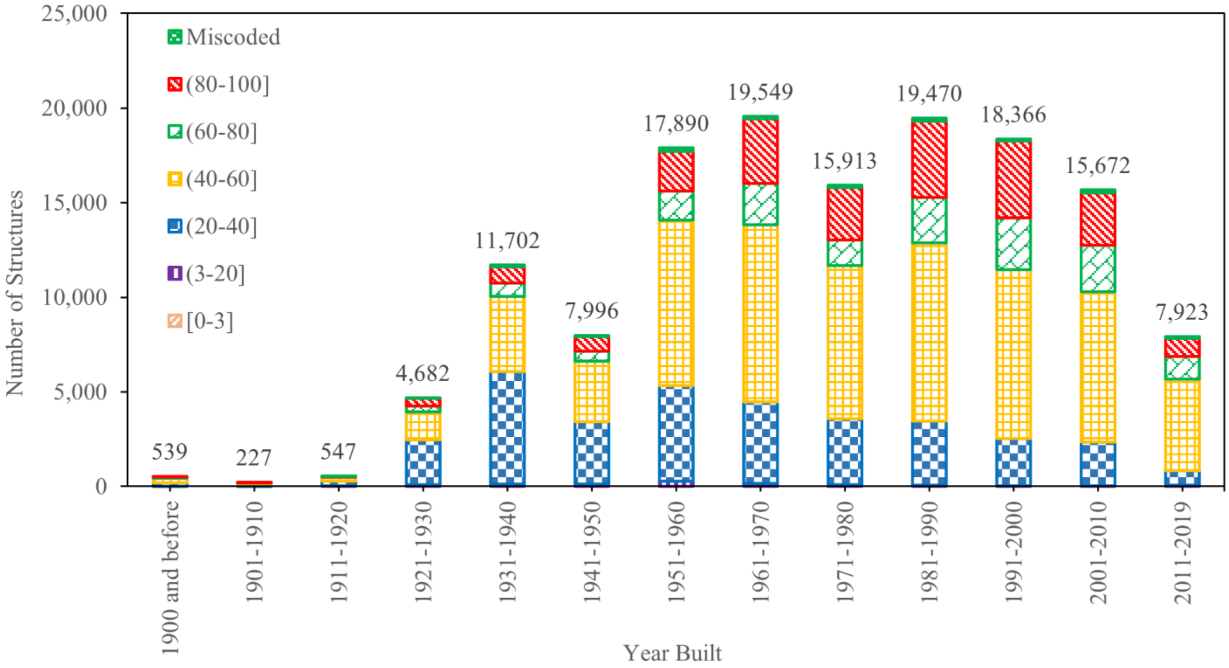
Figure 27. Number of structures vs. Item 27: Year Built and Item 59: Superstructure Condition for non-culvert structure

A higher code number indicates a better structure condition (see the previous section for detailed descriptions of each code number). The results confirmed that, in general, newer structures have a better condition and older structures have a worse condition.

Figure 28 through Figure 31 show the relation between Item 27: Year Built and Item 64: Operating Rating (or Item 66: Inventory Rating). The results indicate that the newer bridges have higher live load capacities.

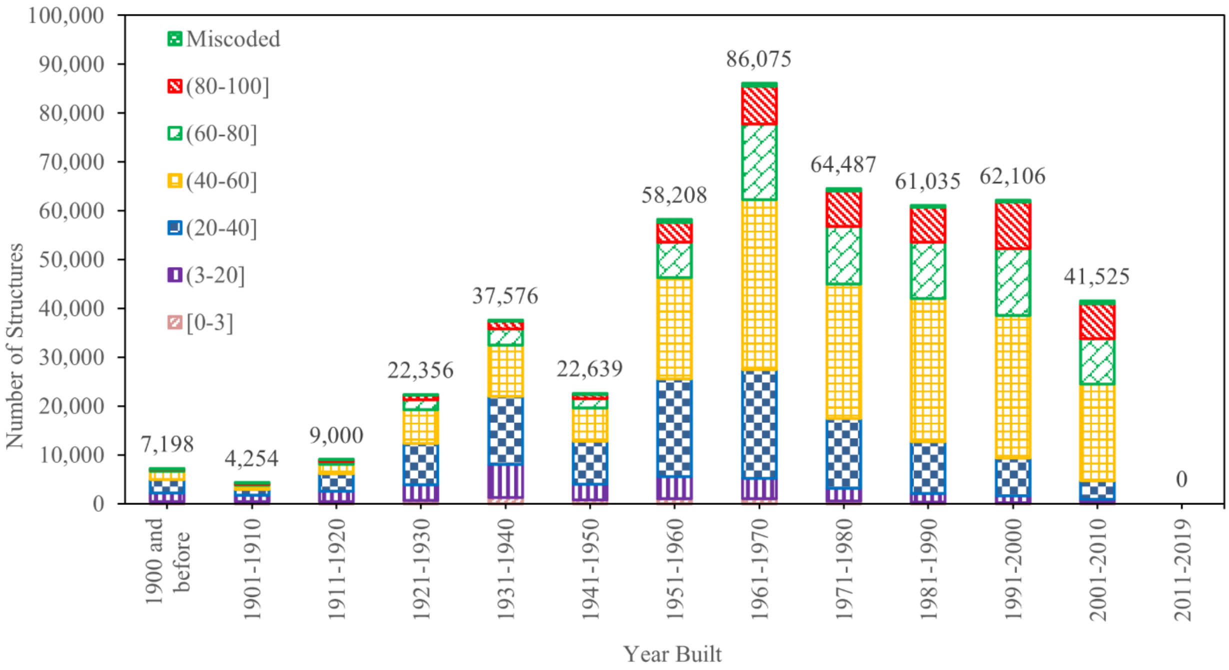


(a) 2009 data

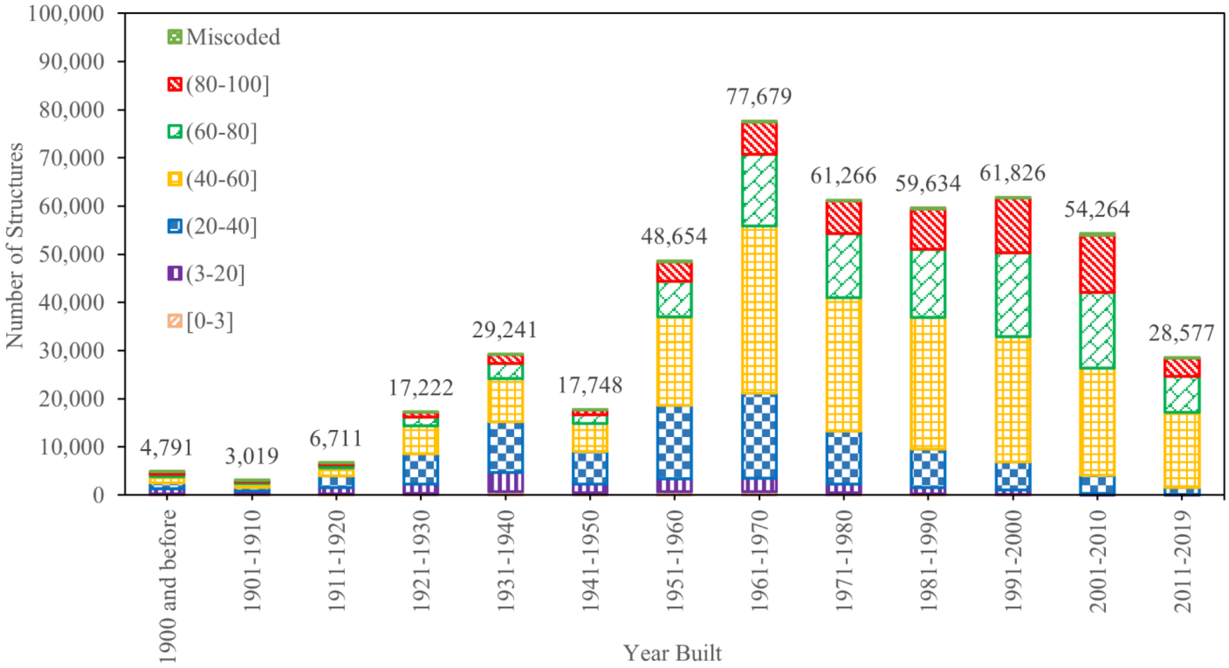


(b) 2019 data

Figure 28. Number of structures vs. Item 27: Year Built and Item 64: Operating Rating for culvert structure

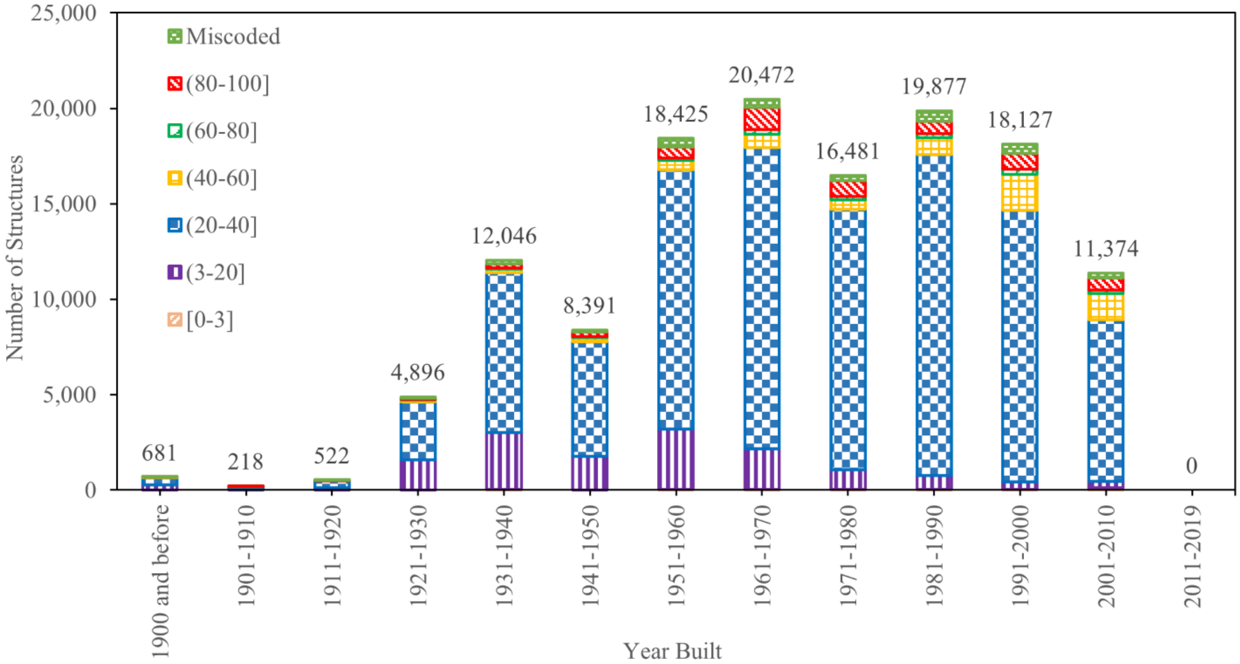


(a) 2009 data

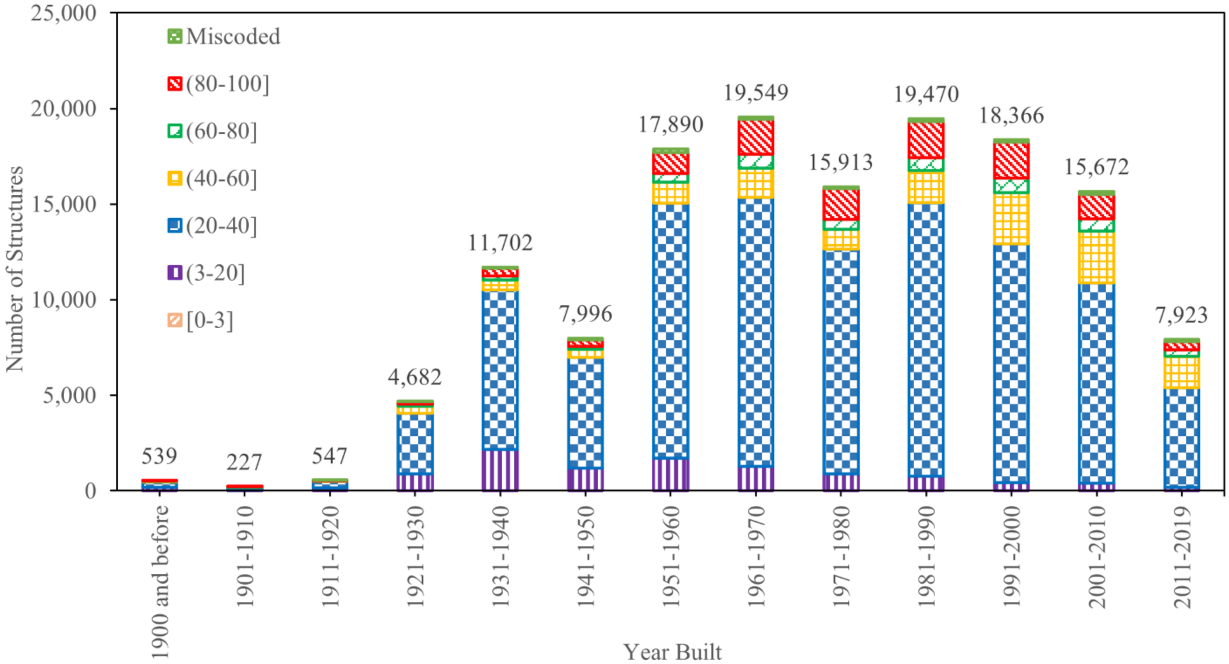


(b) 2019 data

Figure 29. Number of structures vs. Item 27: Year Built and Item 64: Operating Rating for non-culvert structure

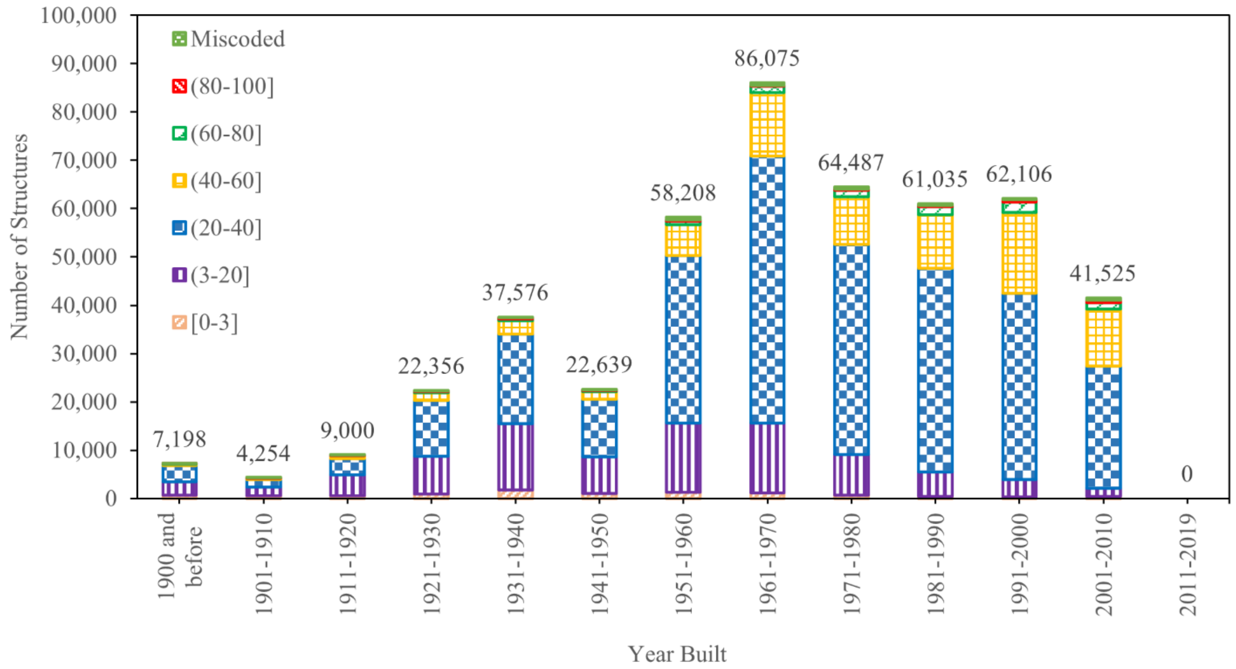


(a) 2009 data

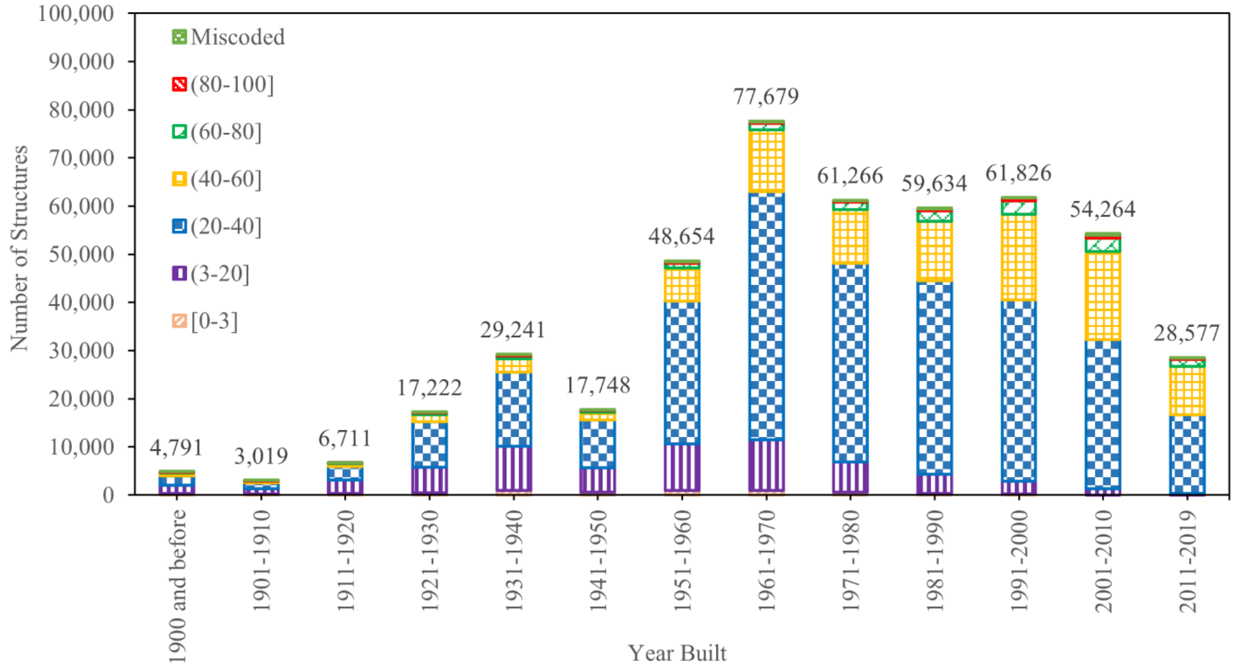


(b) 2019 data

Figure 30. Number of structures vs. Item 27: Year Built and Item 66: Inventory Rating for culvert structure



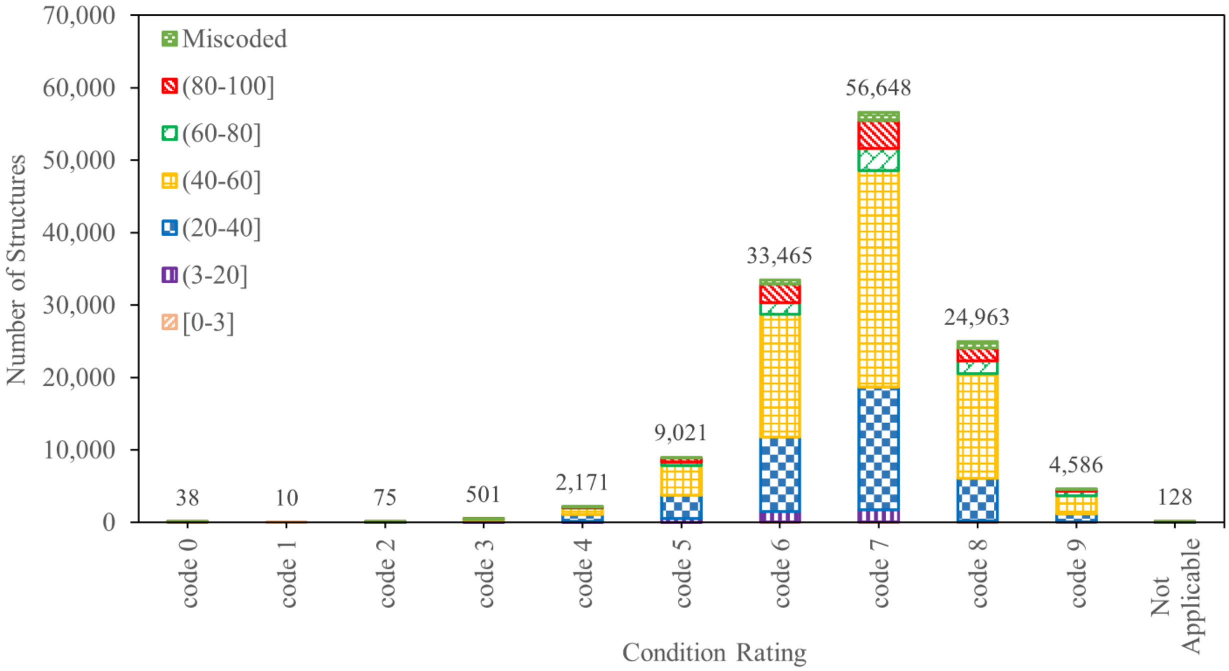
(a) 2009 data



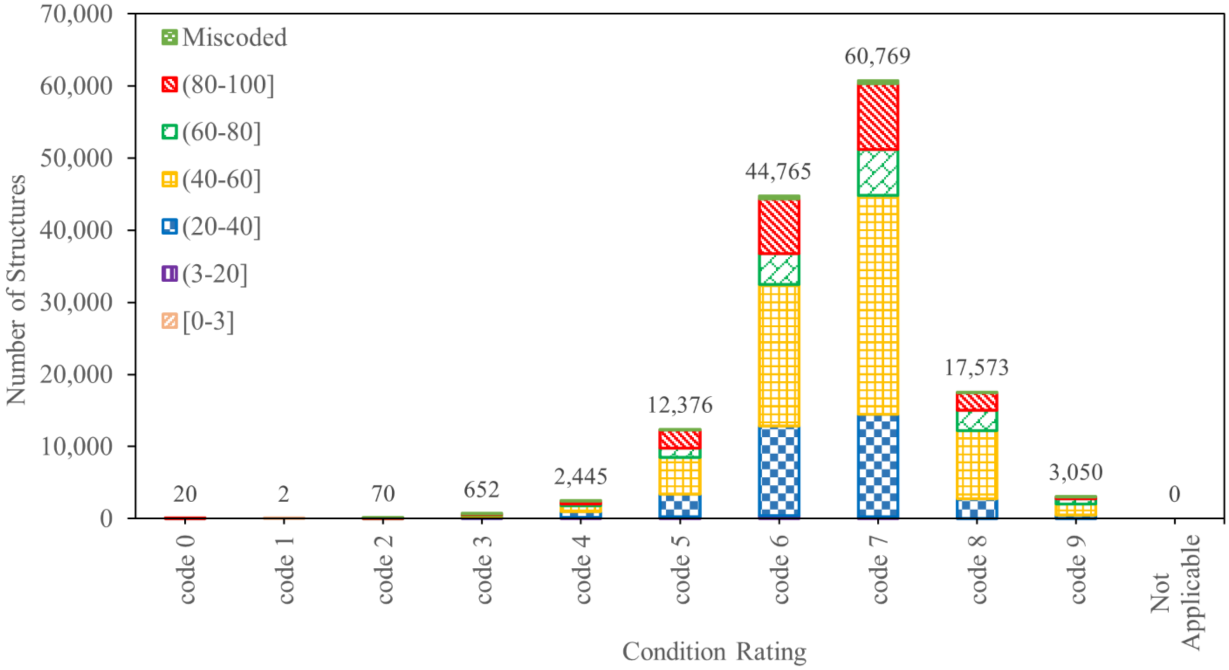
(b) 2019 data

Figure 31. Number of structures vs. Item 27: Year Built and Item 66: Inventory Rating for non-culvert structure

Figure 32 through Figure 35 show the relation between structure condition ratings and load ratings. The results indicated that the structures with better condition show higher capacities.



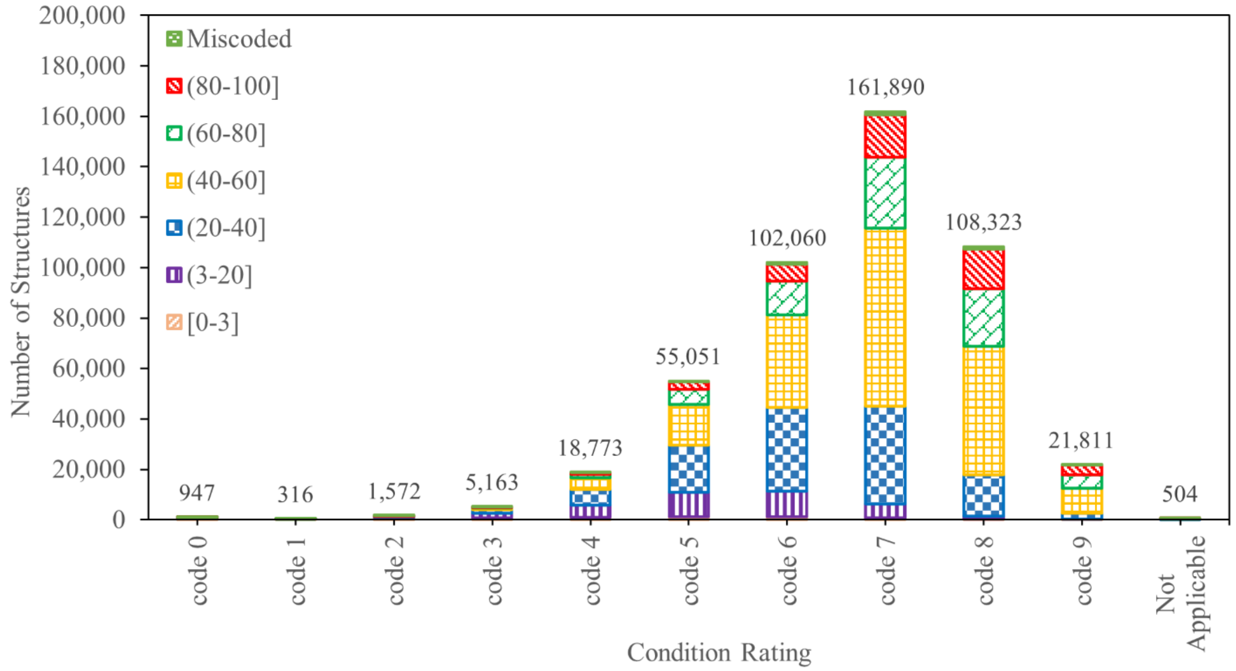
(a) 2009 data



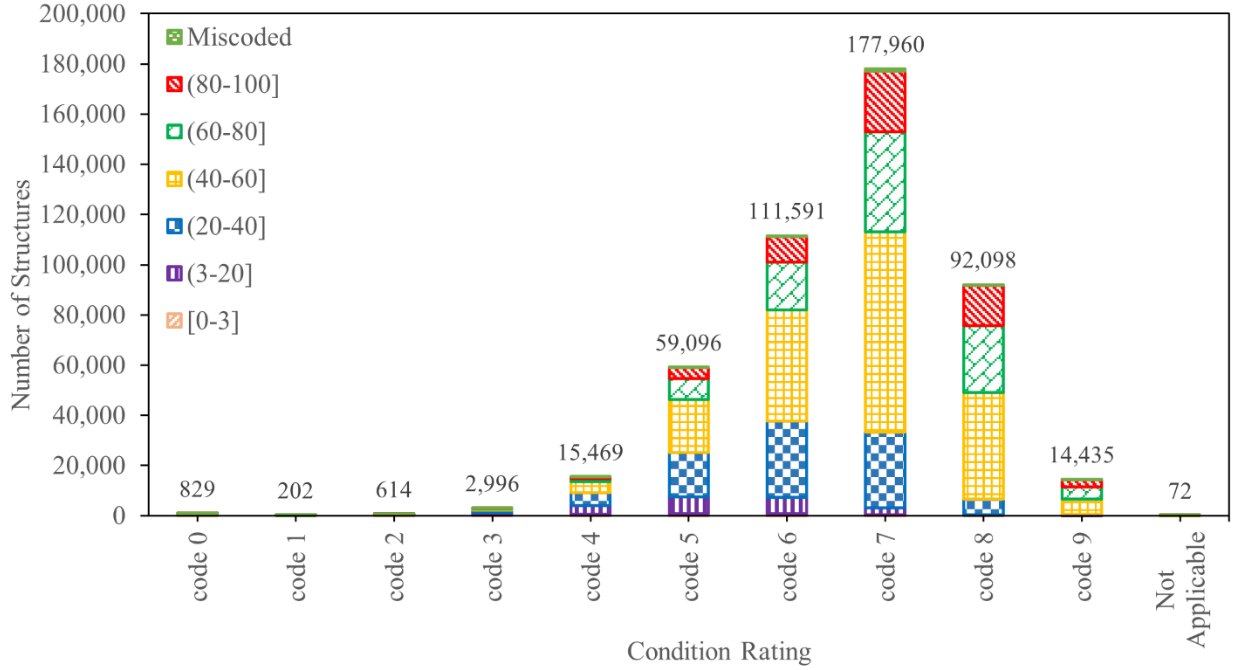
(b) 2019 data

NOT APPLICABLE: Miscoded data; Code 9: EXCELLENT CONDITION; Code 8: VERY GOOD CONDITION; Code 7: GOOD CONDITION; Code 6: SATISFACTORY CONDITION; Code 5: FAIR CONDITION; Code 4: POOR CONDITION; Code 3: SERIOUS CONDITION; Code 2: CRITICAL CONDITION; Code 1: "IMMINANT" FAILURE CONDITION; Code 0: FAILED CONDITION

Figure 32. Number of structures vs. Item 62: Culvert Condition and Item 64: Operating Rating for culvert structure



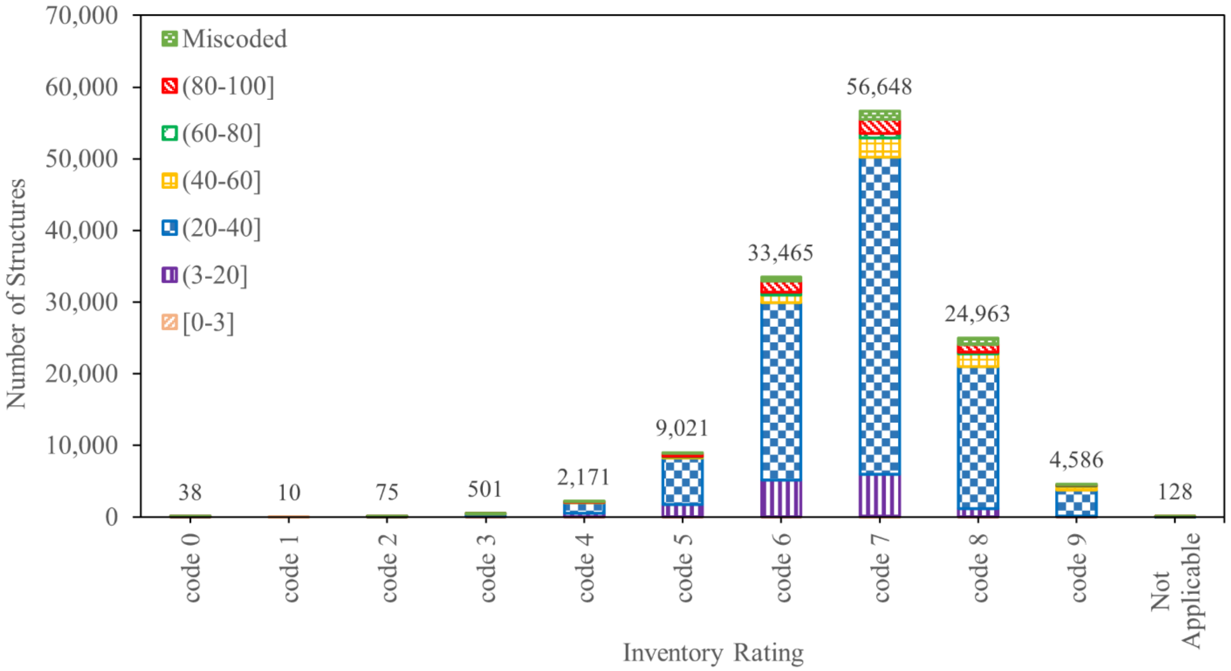
(a) 2009 data



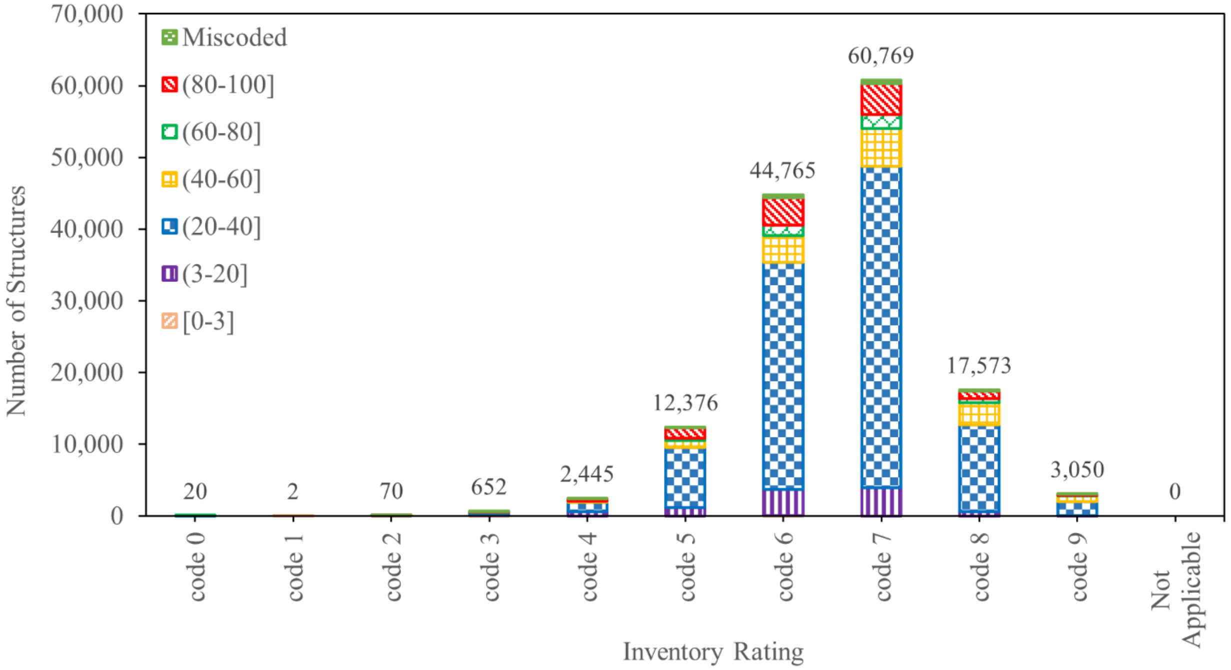
(b) 2019 data

NOT APPLICABLE: Miscoded data; Code 9: EXCELLENT CONDITION; Code 8: VERY GOOD CONDITION; Code 7: GOOD CONDITION; Code 6: SATISFACTORY CONDITION; Code 5: FAIR CONDITION; Code 4: POOR CONDITION; Code 3: SERIOUS CONDITION; Code 2: CRITICAL CONDITION; Code 1: "IMMINANT" FAILURE CONDITION; Code 0: FAILED CONDITION

Figure 33. Number of structures vs. Item 59: Superstructure Condition Rating and Item 64: Operating Rating for Non-culvert structure



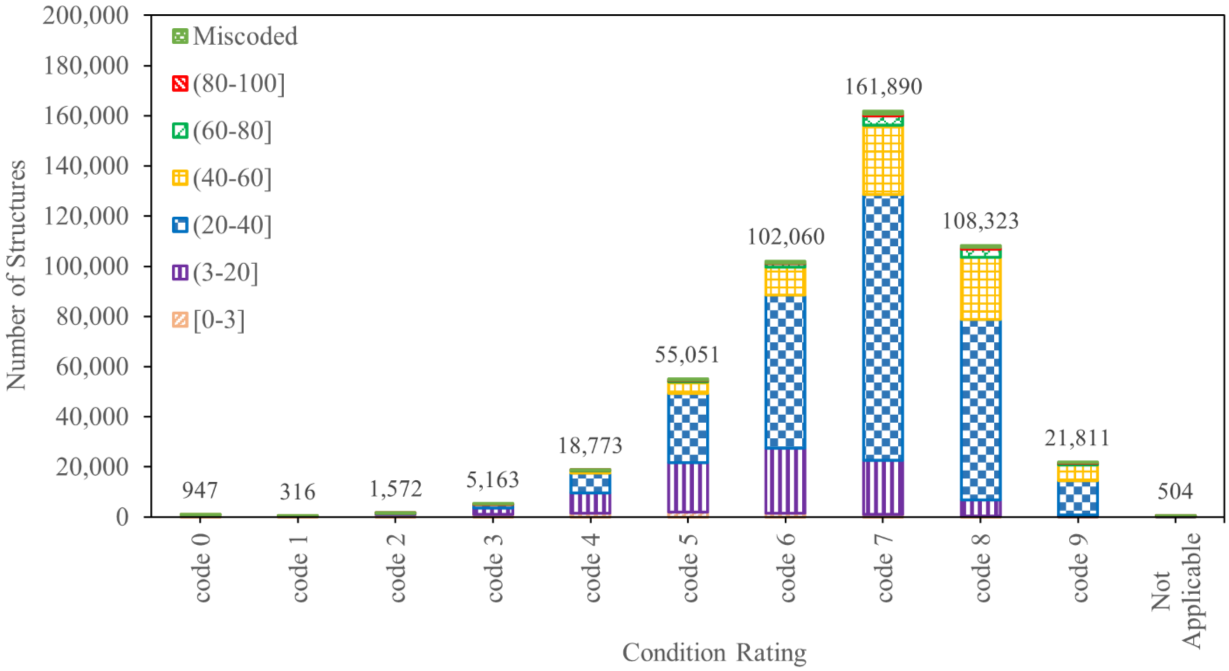
(a) 2009 data



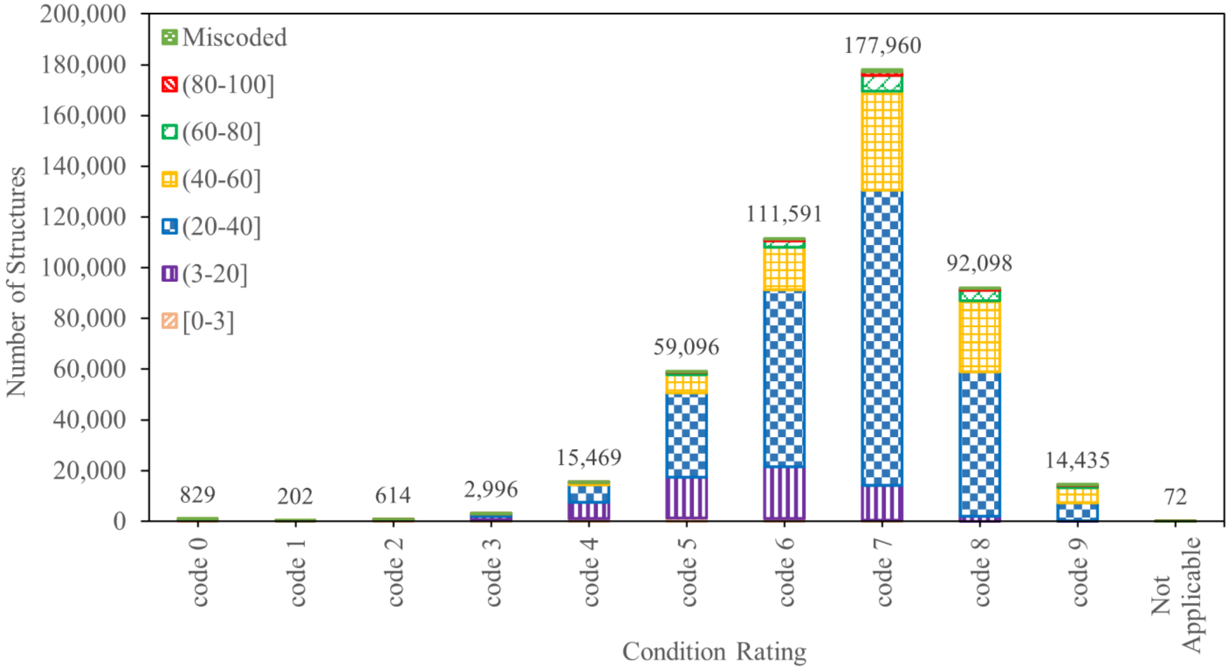
(b) 2019 data

NOT APPLICABLE: Miscoded data; Code 9: EXCELLENT CONDITION; Code 8: VERY GOOD CONDITION; Code 7: GOOD CONDITION; Code 6: SATISFACTORY CONDITION; Code 5: FAIR CONDITION; Code 4: POOR CONDITION; Code 3: SERIOUS CONDITION; Code 2: CRITICAL CONDITION; Code 1: "IMMINANT" FAILURE CONDITION; Code 0: FAILED CONDITION

Figure 34. Number of structures vs. Item 62: Culvert Condition and Item 66: Inventory Rating for culvert structure



(a) 2009 data



(b) 2019 data

NOT APPLICABLE: Miscoded data; Code 9: EXCELLENT CONDITION; Code 8: VERY GOOD CONDITION; Code 7: GOOD CONDITION; Code 6: SATISFACTORY CONDITION; Code 5: FAIR CONDITION; Code 4: POOR CONDITION; Code 3: SERIOUS CONDITION; Code 2: CRITICAL CONDITION; Code 1: "IMMINANT" FAILURE CONDITION; Code 0: FAILED CONDITION

Figure 35. Number of structures vs. Item 59: Superstructure Condition Rating and Item 66: Inventory Rating for Non-culvert structure

CHAPTER 4. STATE OF PRACTICES AND FUTURE FRAMEWORKS

4.1 State of Practices and Emerging Technologies

According to the findings from the desk scan, State survey, and follow-up interviews, many components for building an automated, next-generation, load rating and permitting system have been conceptualized, and development has been initiated in some cases; however, no complete integrated automated load rating, posting or permitting system has been put into practice nationwide.

4.2 Future Framework

The goal of the developed framework is to better aggregate and use information to improve both efficiency and reliability (and, by incorporation, safety) of bridge rating, posting, and permitting. At its very core, this future framework will improve productivity, efficiency, and consistency by closing process gaps and by the application of newer technologies, such as digital twin concepts; integrating various (new) data; creating, updating, or reusing models; integrating sensing (bridge, traffic, WIM), utilizing better analysis methods, and regular or continuous updating of the digital asset from on-site condition information.

Based on previous findings, it appears that many components of an automatic load rating system have been proposed and put into research; however, no completely integrated and automated load rating, posting, or permitting system has been put into practice.

Limited—although promising—automated practice has been seen in the process of permitting, load rating, or both that could provide significant support to an integrated system. Because of this, the proposed future framework would comprise a next-generation load rating, posting, and permitting system with which some of the components may not yet be off-the-shelf. Some additional research is needed before this framework could be fully put into practice.

The general logistics of the proposed framework are presented in Section 4.2.1, and the details of each component and the challenges encountered are discussed in Section 4.2.2 through Section 4.2.4.

4.2.1 Future Framework Development

To achieve an efficient and reliable bridge load rating, posting, and permitting system, the suggested framework includes three key components: digital twin concept, bridge load rating and digital asset maintenance or synchronization, and a user interface. Figure 36 provides a conceptual diagram of the suggested framework.

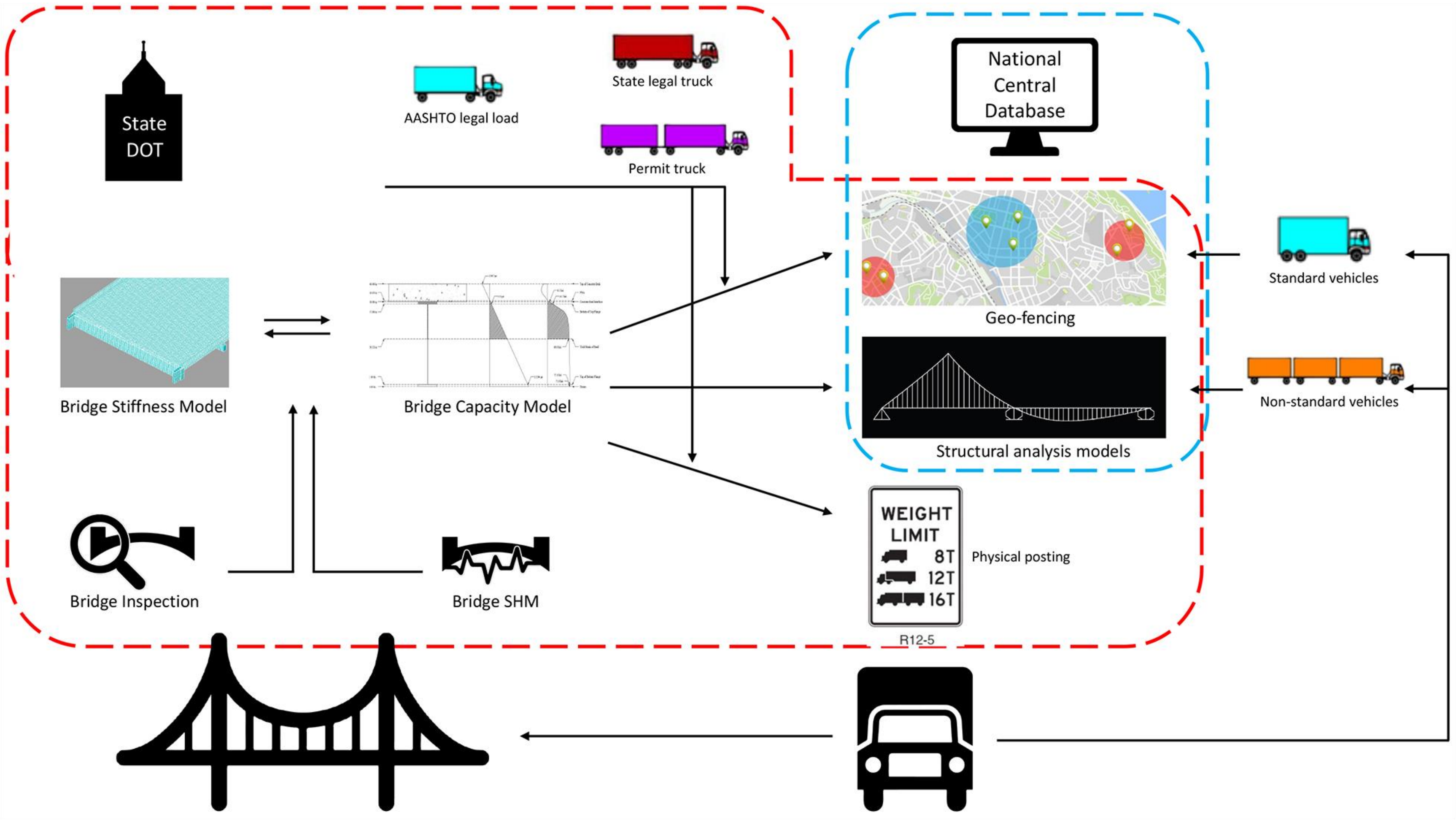


Figure 36. Future framework[1]

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[1] Graphic created by authors; colored truck and weight limit sign images: FHWA

Under the suggested framework, bridges would be analyzed using two types of analytical models, the Bridge Stiffness Model and the Bridge Capacity Model, commonly referred to as digital twins. These models would satisfy two conditions: (1) ability to closely reflect actual structural behavior and capacity at the time of analysis and (2) ability to be updated based on the most recent condition information from either visual inspection, structural monitoring, or both.

Once the virtual model of a bridge structure is created or updated, vehicle loads can be analyzed to calculate the operating (legal) and inventory ratings. In addition, an influence surface, which reflects the bridge response subject to unit loads from the full stiffness model, would be created based on the output of the virtual bridge models, but due to a unit load. This influence surface allows for quick calculation of the bridge response subject to non-standard vehicles (vehicles other than the standard trucks) without the need to re-analyze the bridge using the full FEM. However, in situations of need, the full FEM structural analysis will be performed. Both load rating results (based on standard vehicles) and influence surfaces (used for non-standard vehicles) together with structural analysis models would be stored in a central database and used by State, national, and other entities.

4.2.2 Digital Twin Concept

A digital twin serves as a virtual representation of the bridge that can be updated in near real-time as new data are collected, provide feedback into the physical twin, and perform what-if scenarios for assessing asset risks and predicting asset performance. A key component of the use of digital twins is that the virtual representation needs to be updated as new data and information are available or provided.

In the case of current bridge management, inspection, and assessment, these data would be in the form of condition information and, more specifically, deterioration. The proposed load rating system includes two levels of simulation: Level 1 rating, updated based on biannual inspection results, and Level 2 rating, updated based on real-time structural response data.

A Level 1 rating is somewhat similar to current load rating, posting, and permitting activities. However, one key component to the proposed framework is that consistent, appropriate, and codified means and methods need to be developed that result in updated stiffness and capacity models from the visual inspection results. Once the bridge models are updated, they can be used as previously described.

For a Level 2 rating, a fully 3D FEM is created for each bridge. To differentiate from the girder-line model in the Level 1 rating (although it would be preferred that the FEM be used for a Level 1 rating also), this 3D model is called the bridge stiffness model. Figure 37, which was created by the authors, lists the details and illustrates the relations of the capacity model and the stiffness model.

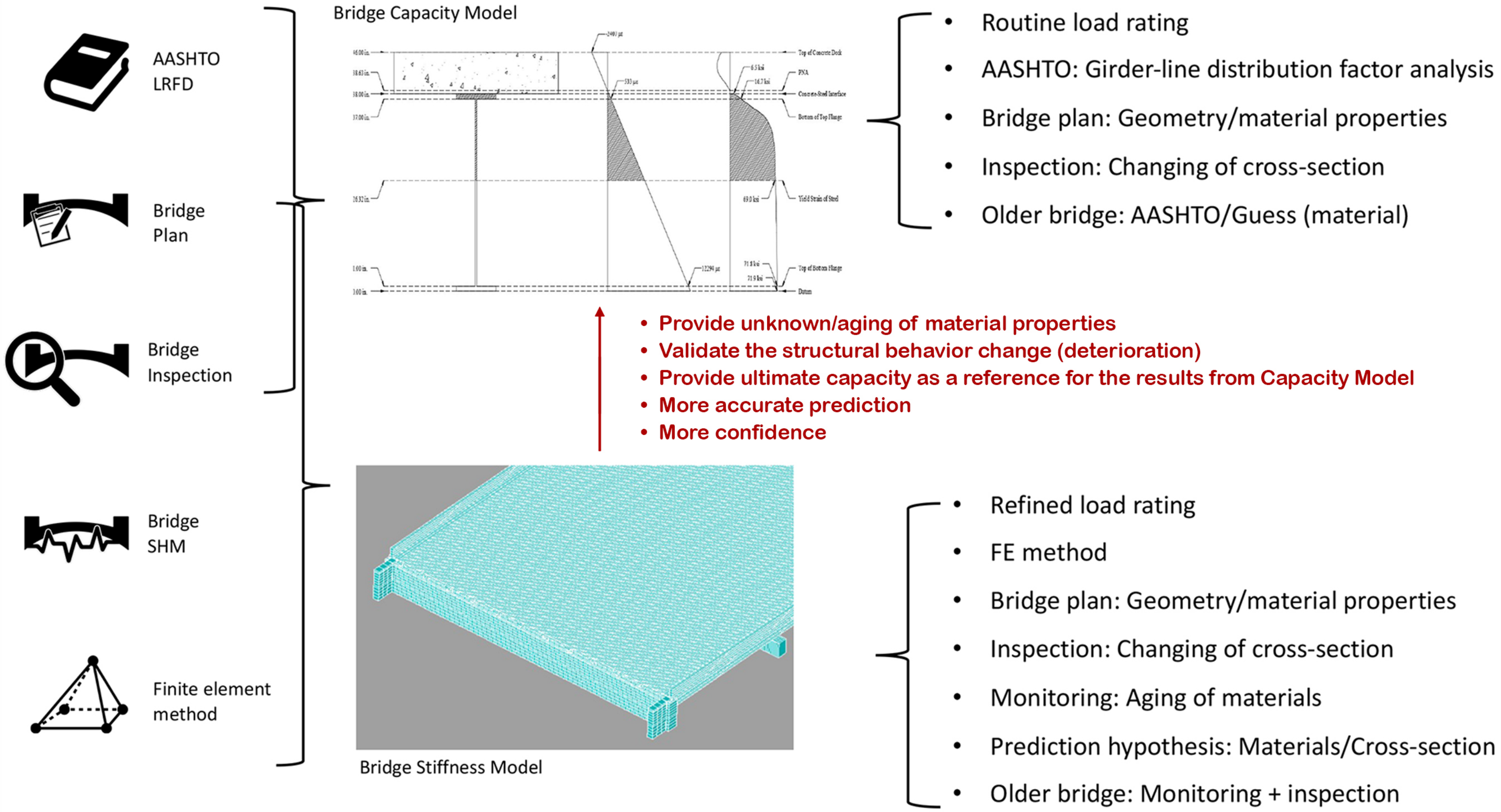

Figure 37. Digital twin concept implementation

The initial bridge stiffness model is created based on the bridge geometry and material properties on the bridge plans. In addition to being updated based on regular bridge inspection data, it can or will also be updated using the data collected from a monitoring system. This effort will result in a more accurate stiffness prediction—resulting in a better estimate of the actual bridge behavior (from a load distribution perspective).

Additionally, a prediction hypothesis, such as Monte Carlo simulation, will be used to estimate the actual bridge capacity (capacity model) based on the stiffness determined from the monitoring or visual inspection data. The stiffness model will benefit the capacity model by providing estimates of unknown or aging of material properties, quantifying structural behavior change (deterioration), and provide a better estimate of actual ultimate capacity from the capacity model. This eventually results in a more accurate virtual representation with higher confidence levels.

Additional discussion on the effectiveness of the capacity model, developed with a combination of WIM plus sensors or sensing technologies and other communication technologies in the load rating can be found in Jayathilaka (2018).

Once updated from either visual inspection or monitoring data, the virtual twin can then be used to represent the actual condition based on the most current data. When the bridge response information is overlaid with loading information from WIM systems, the updated digital twin can be used to perform a calibration of the digital twin model to ensure that the deterioration is being properly represented. With a properly designed framework, these updates and a subsequent re-rating can be done automatically and generally autonomously, which leads to a tremendous improvement in both organizational efficiency and reliability in the results.

4.2.3 Digital Asset Maintenance or Synchronization

The digital assets generated from the suggested load rating system include the following: bridge capacity model, bridge stiffness model, load rating report (including rating results), and influence surfaces. Each bridge owner would be responsible for generating and updating these digital assets for each bridge and synchronizing them into a nationwide database. In addition, State or local DOTs keep the physical weight posting on the bridge in their administrative jurisdiction.

Figure 38, which was created by the authors, shows the detailed work allocation for digital asset maintenance or synchronization.

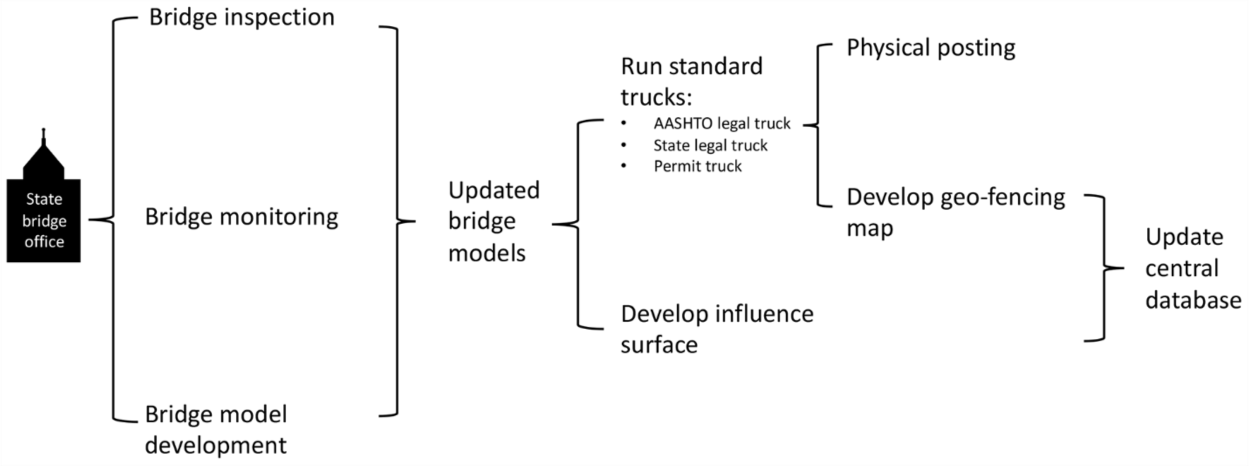

Figure 38. Digital asset maintenance or synchronization

The bridge models would be created from initial design and construction information and updated based on the results from bridge inspections, bridge monitoring results, or both. Once created or updated, various vehicles are run on the capacity model(s), stiffness model(s), or both to calculate the Inventory and Operating (Legal) rating capacities. In addition, influence surfaces are developed based on the virtual model. After that, the bridge is physically posted, if needed, and the digital assets, including the bridge capacity model, bridge stiffness model, load rating report (including rating results), and influence surface data, are synchronized into the central database. All of the above steps are accomplished by each State or agency.

The geofencing map with the vehicle's OBE or computer and GPS would provide alerts or notification to the driver about bridge weight postings or load restrictions on the route. ITS equipment, such as a roadside safety device (RSD) installed near a bridge, may broadcast bridge capacity and geometric restriction information and notify approaching vehicles using that information.

4.2.4 User Interface and Usage

Although the outcome from the proposed framework could be implemented in various ways, one conceptual interaction, which was created by the authors, is illustrated in Figure 39.

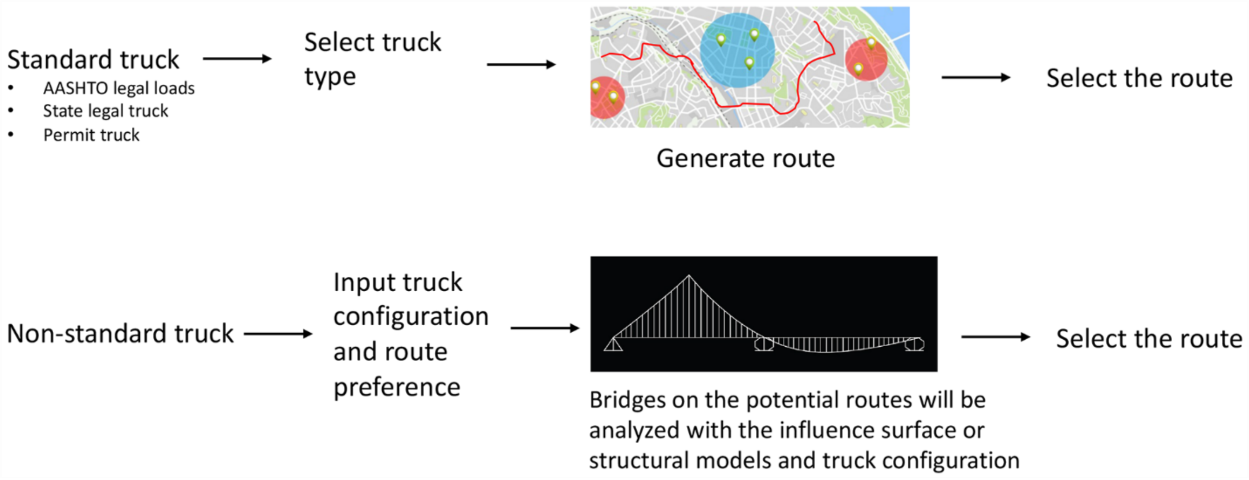

Figure 39. User interface

For standard vehicles, a nationwide geofencing map could be developed. This map would automatically generate routes based on the origins, destinations, truck size and weight, and user preference. When drivers of standard trucks enter the app, they will be asked to pin the origin and destination and input the truck information and route preference.

When generating routes, the map would identify all of the bridge structures on the possible routes, extract the bridge rating capacity from the central database, and perform a quick check of the bridge capacities based on the truck information input by the driver. Once the capacity check is accomplished and approved for all the bridges in one route, this route will be presented to the driver. Once the driver approves the suggested route, the app will automatically issue the needed permits if the truck is OS/OW.

For drivers operating a non-standard vehicle, in addition to the origins and destination, the driver would also input the truck configuration, including the axle spacings and weights, axle gauge width, etc. Once a route is generated, the bridges on the route will be identified and the structural analysis and capacity models of those bridges would be extracted from the database. With the user-specified truck information, an analysis would be performed for each bridge to see if the truck exceeds the capacity. Once the analyses are accomplished and approved for all bridges along a route, the app will automatically issue the permits needed.

4.2.5 Benefits of the Proposed System

More accurate, efficient, or comprehensive load rating results. The NBI data analysis results indicated an increasing percentage of bridges being evaluated with the latest AASHTO load rating method (i.e., LRFR), which is a sign that States are adopting the latest in bridge rating tools. The digital twin concept in the proposed load rating system would provide a more accurate prediction of the load rating capacity for all bridges and will allow for changes in condition to be captured as new condition data are available. The automatic data collection, model calibration, and load rating calculation will increase the efficiency of load rating, permitting, and routing operations.

24 hour – Quick permitting service. The traditional permitting system usually generates the route manually and needs a human effort with respect to the bridge capability, which significantly increases the cost of the labor and the time until a permit can be issued. In some States, drivers need to plan their routes and send the permitting request many days before anticipated travel. The proposed user interface enables a capacity check to be performed, generating acceptable routes and issuing permits automatically. In addition, the consistent load rating and permitting procedures across State lines would be user-friendly and reduce the time that drivers usually spend getting familiar with the different permitting systems for each State. Ideally, with the proposed framework, the whole process could take only a few seconds and the system could work 24 hours a day, 7 days a week (24/7).

Reduced long-term cost. Although the instrumentation of bridges, creation of the nationwide database, and development of the user interface may require considerable initial cost, most of these costs will be one-time investments, and the benefits of this work will last for the length of each bridge life. Compared to the traditional load rating and permitting systems, the proposed system will significantly reduce labor costs for permitting. In addition, the proposed system continuously monitors the bridges, which helps bridge engineers to make decisions regarding rehabilitation and replacement needs. The additional savings could also come from delays in bridge replacement after gaining sufficient confidence from the data collected using the bridge monitoring system.

Better bridge infrastructure management and potential. The proposed system enables the collection of extensive and comprehensive data on bridge usage by heavy and non-standard vehicles. These unusual loads may lead to bridge deterioration and play a role in bridge service life. With these “big data,” the Federal and State DOTs will be able to gain a more comprehensive understanding of bridge usage, which eventually assists future bridge management decisions. In addition, these data also guide the potential for future research investigation, including improved, efficient usage of bridge infrastructure and bridge remaining life prediction, etc.

4.3 Workshop

On July 28 and 29, 2021, a workshop was held to report the outcomes from the current research to engineers from various State DOTs. About 30 attendees participated in the workshop, which included representatives from the FHWA, State DOT agencies, and industry or technology organizations.

CHAPTER 5. SUMMARY AND CONCLUSIONS

5.1 Summary

The United States has more than 600,000 bridges, making the process of load rating, posting, and permitting an effort that can further benefit from improvements in efficiency. It has been used to (1) prioritize structures for repair or replacement, (2) restrict the weight of vehicles that are allowed on a particular bridge, and (3) determine routes for permit vehicles. As such, States are interested in modifying their procedures to implement technology and improved means and methods to reduce the time associated with load rating. However, disparities remain in how quick different Sates are to adopt new technologies and concepts. Being able to load rate bridges efficiently and accurately is a necessity, particularly in the use case of permit load routing and analysis.

5.2 Conclusions

Based on the information collected during the framework development, the following conclusions were drawn:

- In general, there is an overall push to incorporate automation into the load rating and permitting processes. As more and more bridges have refined models available, these data will inherently allow for more integration within the process.

- The analysis of the NBI data presented trends based on the survey results and information collection efforts. In general, significant changes in the way structures have been rated were not seen, pointing to slow adoption rates when it comes to modifications or updates to load rating practices.

- It appears that many components of an automatic load rating system have been suggested and put into research; however, no completely integrated and automated load rating, posting, or permitting system has been put into practice on a wide-scale basis.

- The suggested framework was developed to improve efficiency, reliability and safety of bridge rating, posting, and permitting. With the proposed load rating, posting, and permitting framework, benefits could be achieved, including more accurate, efficient, and comprehensive load rating results; 24 hour – quick permitting service; reduced long-term cost; and better bridge infrastructure management and potential.

- The suggested future framework comprises a next-generation load rating, posting, and permitting system. However, some of the components may not yet be available or ready for rollout. Some issues that would need to be addressed are the creation and adoption of processes and procedures. Some additional research is needed before this framework could be fully put into practice.

- Size and weight of trucks operating off the Interstate, bridge load posting processes and procedures, and overweight load permitting are all regulated by States. In these aspects, differences exist between States. In addition, any legal issues related to implementation of such an automated system need to be identified and resolved. This research only investigated the technical feasibility of such a system.

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