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DEVELOPMENT OF STATE LEGAL AND OVERWEIGHT
LIVE LOAD MODELS

BY
THOMAS DA LOMBA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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2015

MASTER OF SCIENCE THESIS

OF

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2015

ABSTRACT

Live load models are essential to assess the safety of highway bridges. To determine the maximum permissible load, Rhode Island currently uses legal live load models developed for a national level application based on federal weight restrictions. However, the state has allowable limits higher than those mandated federally, therefore, the models are not entirely representative of the truck traffic in the state. Furthermore, the state's transportation agencies may issue permits for the operation of trucks in excess of the weight restrictions. To assist in permitting decisions, permit live load models developed from previous applications are introduced in the evaluation of bridges. Changes in the characteristics of permit applications diminishes the effectiveness of the permit live load models.

A database of approved permit applications was utilized to analyze the models through their ability to exceed, or envelope, the structural responses due to the applicant trucks. As a result, state-specific 3- and 5-axle legal live load models were developed. A validation of the permit live load models was also performed and revealed that they did not perform adequately. New permit live load models were developed to further assist and expedite the state's transportation agencies permit reviewing process.

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CHAPTER 1. INTRODUCTION

Highway bridges are an essential component to the continuing efficiency of the national highway system. The ability of bridges to provide a reliable manner of travel for the public and transportation of products assists in stimulating the economy and improving society's quality of life. In the United States as of December 2014, there are 610,749 bridges in the National Bridge Inventory (NBI) providing a means of travel to enhance traffic operations or where terrain constrictions impose the construction of roads ("Bridges & Structures," 2014). Dependence on the highway system has grown with an increase of 50 billion miles traveled on U.S. roads each year from 1985 to 2008 (Bell et al., 2013). However, the aging and deteriorating infrastructure presents challenges to continue the high utilization of the highway system.

Bridges may be deemed structurally deficient given its state of deterioration or functionally obsolete as being incapable of fulfilling its intended purpose. Structurally deficient bridges have one of its three elements (i.e., deck, superstructure, and substructure) found to be in poor condition or if it has insufficient carrying capacity (Bell et al., 2013). Functionally obsolete bridges have a geometric design not in compliance with current specifications or presents constraints to normal traffic operations (Bell et al., 2013). Approximately 10% of bridges are structurally deficient, and 14% are functionally obsolete in the U.S. ("Bridges & Structures," 2014). Rhode Island faces a severe problem with structurally deficient bridges having the worst rate in the country with 174 out of 766 (23%) deemed as such and 255 (33%) as functionally obsolete ("Bridges & Structures," 2014).

A contributor to the deterioration of the structural integrity of highway bridges is the exposure to increasing traffic volume and load spectra. Stresses on bridge elements beyond those expected develop from repetitive overweight loading undermining a bridge's load carrying capacity. To protect bridges and prevent such occurrences, weight restrictions set at a national level are imposed on trucks. State-specific restrictions in excess of national standards is allowable under "grandfather clauses," such as the case in Rhode Island. Trucks meeting all limitations are classified as legal and may travel unrestrictedly in the jurisdiction it is in compliance. Different live load (LL) models, defined as moving loads, are used in the analysis of bridges to ensure it has sufficient capacity for the anticipated traffic. There are LL models used for design purposes that generates effects that exceeds, or envelopes, those of normal national truck traffic. Other LL models representative of the legal trucks are used to calculate the responses of an existing bridge to the maximum permissible load.

Trucking accounts for about 80% of the expenditure on freight transportation in the U.S. (Zhao & Tabatabai, 2012). To provide a more economical and efficient manner or due to inability to reduce a load, there are occasions in which a truck must operate with a total weight exceeding the restrictions. Under a state's transportation agency review, such trucks may apply for a permit to ensure the bridges on the intended route have sufficient resistance. Evaluating each bridge along the route with the permit truck can be a time consuming task. However, many states like Rhode Island incorporate another set of LL models developed from characteristics of previous permit applications during the evaluation of existing bridges. In this manner, the effects generated by the permit truck can

be compared to the effects of the corresponding model. If the model has an effect greater than the permit truck and a particular bridge performs well with the model, the permit truck is also safe to travel.

1.1 Problem Statement

Rhode Island currently uses legal LL models developed for a national level application based of federal weight restrictions. However, these models may not be representative of the truck traffic in the state as it has restrictions in excess of those federally mandated, particularly for 3- and 5-axle trucks. Also, the permit LL models used by the state may be outdated due to possible changes in the characteristics of trucks in recent applications.

1.2 Objectives of this Study

This study had the objective of using a database of approved permit applications by Rhode Island's transportation agencies for the development of state-specific 3- and 5-axle legal LL models and compare its performance with the currently used legal LL models for bridge load rating. Furthermore, this study analyzed the performance of the Rhode Island permit LL models and developed or made alterations to existing ones to assist transportation officials in the permit reviewing process by being sufficiently representative of expected applications.

CHAPTER 2. LITERATURE REVIEW

The expected truck traffic is of great concern in the design and evaluation of existing bridges. Due to the irregular and evolving truck traffic characteristics to sustain an ever-growing demand to efficiently transport products, numerous research have been dedicated to develop LL models in an effort to reduce the uncertainties.

Bridges are effected by load effects rather than a truck's gross vehicle weight (GVW). The calculation of load effects is dependent on several parameters including axle weight (AXW), axle configuration, the transverse and longitudinal position of the truck, multiple truck presence, span length, stiffness of structural members, and future growth (Nowak & Hong, 1991). However, the parameters associated with the static effects (i.e., AXW, axle configuration, and span length) are analyzed separately from the remaining due to the complexity of their interaction. Four types of load effects are considered in an analysis as they are required by specifications: end shear force and mid-span moment of a simply-supported beam; and the shear force and negative moment at the interior support of a two-equal span continuous beam.

To protect the structural integrity of our national bridge inventory, weight and size restrictions are enforced on trucks at a national and state level. As a result, those meeting restrictions are considered legal and allowed unrestricted operations. The load effects of such trucks are typically enveloped by LL models used in the analysis of bridges. Trucks exceeding restrictions are classified as oversize/overweight (OSOW), and may be granted

permission to travel a specific route with an approved permit application reviewed by a state's transportation agency. However, the load effects developed by an OSOW truck may not be properly represented by existing LL models. Therefore, an analysis must be performed using the information provided by the applicant truck to determine the bridge's capacity to support its passage.

2.1 Weight and Size Restrictions

Vehicles traveling on bridges must comply with weight and size restrictions developed to maintain the integrity of the national highway system. The first federal regulation on size and weight of vehicles operating on the Interstate System was enacted in the Federal-Aid Highway Act (1956) to protect the substantial federal investment in its construction (Sivakumar et al., 2007). The Act established a maximum GVW of 73.28 kips, tandem-axle weight of 32 kips, single-axle weight of 18 kips and a maximum width of 96 inches (Federal-Aid Highway Act, 1956). Prior to the adoption of the federal limits, states had their own restrictions. Provided in the act was a "grandfather right" provision allowing states to continue applying their own limits even if they exceeded those mandated federally to not disrupt the operation of heavier trucks accustomed to the region.

The Federal-Aid Highway Amendments (1975) increased the GVW and AXW limits in part to provide additional cargo carrying capacity to truckers faced with large fuel cost increases at the time, but Congress balanced this concession to productivity by enacting the Federal Bridge Formula B (FBF B) (Sivakumar et al., 2007). The purpose of the

formula is to reduce the risk of overstressing bridge elements by having heavy axles closely concentrated. Load effect calculations is dependent on AXW and axle spacing (AXS) rather than the GVW. As shown by Figure 2.1, a truck with a short configuration (B) in comparison to a longer one with the same GVW will generate higher stresses on a bridge element. To reduce the effect, the load must be spread over additional axles or have an increase in AXS.

Figure 2.1: Effect of truck configuration on a bridge (“Bridge Formula Weights,” 2015)

The FBF B determines the maximum allowable weight for a group of two or more axles along with compliance of the other weight restrictions on GVW, single-axle and tandem-axle (“Bridge Formula Weights,” 2015). The FBF B is as following (Federal-Aid Highway Amendments, 1975):

$$W = 500\left[\frac{LN}{N-1} + 12N + 36\right] \quad (2.1)$$

where: W is the overall gross weight on any group of two or more consecutive axles to the nearest 500 pounds; L is the distance in feet between the outer axles of any group of two or more consecutive axles; and N is the number of axles in the group under consideration. An exception to the Bridge Formula is that two consecutive sets of tandem axles may carry 34 kips each if the overall distance between the first and last axle of these tandems is 36 ft. or more (“Bridge Formula Weights,” 2015).

The “grandfather right” continued in the 1975 amendments. Table 2.1 summarizes the federal and Rhode Island General Laws restrictions, which exercises the provision. Vehicles meeting all restrictions imposed by the RI General Laws are classified as legal in the state and may operate on the Interstate Highways.

Table 2.1: Federal and Rhode Island restrictions on truck size and weight

Criteria		Limit			Comments
		Federal	RI General Laws		
Width		102"	102"	31-25-3	The total outside width of any vehicle or the load on it.
Height		N/A	162"	31-25-4	Vehicle including any load on it.
GVW		80 kips	80 kips	31-25-14	Weight of a vehicle and any load on it.
Single Axle		20 kips	22.4 kips	31-25-13	Total load transmitted to the road by all wheels whose centers are included between two parallel transverse vertical planes 40" apart.
Tandem Axle		34 kips	36 kips	31-25-14	Total weight on two or more consecutive axles more than 40" but not more than 96" apart.
FBF B		FBF B	FBF B	31-25-14	In any calculation in which the tandem axle is less than 36 kips, 36 kips shall be considered the legal limit.
Legal Loads	GVW	N/A	104.8 kips	31-25-21a	Five (5) axle vehicles
	GVW	N/A	76.65 kips	31-25-21a	Three (3) axle vehicles
Blanket Permit	GVW	N/A	130 kips	31-25-21e	Less than six (6) axles
	Any Axle	N/A	25 kips	31-25-21e	

There is also limitations on the length of single and coupled vehicles as well as front and rear extensions of loads for maneuverability and safety purposes. These restrictions can be found in RI General Laws 31-25-5, 31-25-6, and 31-2-7.

Vehicles exceeding the limits may apply for a permit to operate a designated route. As of April 2, 2008, applications for OSOW permits in RI are submitted through an online application (“RI DMV/ DOT,” n.d). In RI, OSOW permits are administered by the Rhode Island Division of Motor Vehicles (RIDMV) including processing applications, collecting fees, and issuing permits.

There are two types of permits issued to OSOW vehicles in RI. The first type of permit is a routine, or blanket permit (BP), approved for unlimited trips for a period no longer than a year over a specified route or within a restricted area (RIDOT, 2011). Limits for BP are found in Table 2.1. The other type of permit is for a single-trip, or overweight permit (OWP), issued for a one-way or round-trip movement of overweight (OW) vehicles valid only for a specific date, time, vehicle and route designated in the permit (RIDOT, 2011). Also, restrictions on mixing with traffic and speed may apply. An OWP is issued to vehicles exceeding both legal and BP restrictions. Permits may be issued for divisible or non-divisible loads. Divisible loads consists of those that can be reduced in weight and dimension to comply with all restrictions. Non-divisible, on the contrary, cannot be reduced in weight or size, or they might be impractical to do so.

2.2 Design Live Load Model

Advances in bridge design specifications has further minimized the potential of detrimental effects developed by OW loads through improvements in the calculation of resistance as well as the expected demand. Adopted in 1994, the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) of Highway Bridge Design Specifications introduced a limit state design philosophy, based on structural reliability methods, to achieve a more uniform level of safety in bridge design (Minervino et al., 2004). Uncertainties associated with the design process are reduced in the specification by the application of factors developed from statistical variations of resistance and loads.

Introduced during the calibration of the LRFD was the HL-93 design LL model as shown on Figure 2.2. The model is a key component in the specification to develop a uniform level of reliability by providing a method of estimating bridge responses to highly variable truck traffic characteristics. Lacking reliable truck data in the United States, the HL-93 was developed using a truck survey conducted in the mid-1970s by the Ontario Ministry of Transportation. For each of the 9,250 trucks in the survey the maximum load effects (i.e., shear force and bending moments) were determined for span lengths ranging from 30 ft. through 200 ft. (Kozikowski, 2009). It was assumed that the economic life time for newly designed bridges to be 75 years (Nowak, 1993). Therefore, the maximum load effects were calculated by extrapolations and simulations for the equivalent return period (Nowak & Hong, 1991). The HL-93 model is referred to as a notional model, meaning it

does not resemble an actual truck configuration but rather a combination of concentrated and distributed loads to produce maximum load effects that are greater than or equal to those produced by normal truck traffic.

Figure 2.2: AASHTO LRFD HL-93 design LL model (Kozikowski, 2009)

The HL-93 has three components: design truck; design tandem; and design lane. The design truck resembles a 3-axle 72 kips semitrailer truck, namely HS20, that has been used by AASHTO Standard Specifications since 1944 (Barker & Puckett, 2013). A variable rear AXS of 14 ft. to 30 ft. is provided to generate critical load effects. A longer spacing typically only controls where the front and rear portions of the truck may be positioned in adjacent structurally continuous spans such as for continuous short-span bridges (Barker & Puckett, 2013). The design tandem is a short 2-axle with 25 kips AXW each. Similarly to the HS20, the design tandem was previously used in the AASHTO Standard Specifications, however, in the LRFD the AXWs were increased from 24 to 25 kips. The last component of the HL-93 is the design lane load having a uniformly distributed load of

0.64 kips/ft. that was also previously used in the AASHTO Standard Specifications but with an alteration by removing a concentrated load. For design purposes, the HL-93 design load is taken as the larger effect produced by the design truck with the lane load or the design tandem with the lane load. For negative bending moment and reaction at the interior support of a continuous span, the design load is calculated by taking 90% of the lane load and two design trucks with a variable position of at least 50 ft. apart with a fixed 14 ft. rear AXS.

In the calculation of the strength limit state, referring to the bending and shear load effects, the calculated design demand values are multiplied by a factor of 1.75. This load factor was calibrated in the development of the LRFD to provide a reliability index, or β , of 3.5. The β value gives a measurement to the structural reliability or, conversely, the risk that a design component has insufficient capacity and that some limit state will be reached (Moses, 2001).

2.3 Bridge Rating Live Load Models

For the evaluation of existing bridges, the AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges was adopted in 2002 and extends the limit state design philosophy of the LRFD. However, the live load factors in LRFR are calibrated to provide a uniform and acceptable level of reliability for load rating, load posting and permit decisions (RIDOT, 2011).

Bridge load rating is required for all newly designed and existing bridges to determine the live load carrying capacity for safety and management decision purposes. The following is the general rating-equation (Eq. 2.2) presented in the State of Rhode Island Department of Transportation (RIDOT) Guidelines for Load and Resistance Factor Rating (LRFR) of Highway Bridges:

$$RF = \frac{\phi_c \phi_s \phi R_n - (\gamma_{DC})(DC) - (\gamma_{DW})(DW) \pm (\gamma_p)(P)}{(\gamma_L)(LL + IM)} \quad (2.2)$$

where: RF= Rating Factor; R_n = Nominal member resistance (as inspected); ϕ_c = Condition Factor; ϕ_s = System Factor; ϕ = LRFD Resistance Factor; DC= Dead load effect due to structural components and attachments; DW= Dead load effect due to wearing surface and utilities; P= Permanent loads other than dead loads; LL= Live load effect of rating vehicle; IM= Dynamic load allowance; γ_{DC} = LRFD load factor for structural components and attachments; γ_{DW} = LRFD load factor for wearing surfaces and utilities; γ_p = LRFD load factor for permanent loads other than dead loads; and γ_L = Evaluation live load factor for rating vehicle.

A RF is calculated for several LL models at different load rating levels. It is undesirable to have a RF less than 1 as it implies there is insufficient structural capacity to support the analyzed model.

There are two main load rating levels, namely design and legal load rating. The design load rating composes of two evaluation levels, namely inventory and operating. Inventory is the first evaluation level performed at a design level of reliability of a new bridge for an in-service one taking into consideration the current condition of the structure. Therefore, it

provides a direct comparison of an in-service bridge to a new design. The HL-93 shown on Figure 2.2 is used along with the appropriate LL factor shown in Table 2.2 to determine a bridge's capacity to carry normal truck traffic for an indefinite amount of time. Therefore, if a rating factor is acceptable, it can be assumed that the proceeding rating levels will also be satisfied. At the operating evaluation level the LL factor is calibrated for a lower β of 2.5 equivalent to the one used for the legal load rating.

Table 2.2: LL factors for design rating level (RIDOT, 2011)

Evaluation Level	Load Factor
Inventory	1.75
Operating	1.35

The legal load rating determines the maximum single safe load that can be placed on a bridge during the interval between routine inspections. Therefore, the LL factors are calibrated at a lower β of 2.5 due to the shorter exposure period compared to the 75-year assumed for design (Minervino et al., 2004). Table 2.3 displays the factors used at the legal load rating level based on a bridge's traffic volume. Linear interpolation is permitted for other ADTT between 1000 and 5000 (MBE, 2013). At this rating level AASHTO legal LL models are introduced for their capability of assisting in management decisions as they resemble real commercial trucks commonly found on highways.

Table 2.3: LL factors for legal load rating (MBE, 2013)

Traffic Volume (One Direction)	Load Factor
Unknown	1.45
$ADTT \geq 5000$	1.45
$ADTT \leq 1000$	1.30

AASHTO provides several legal LL models for rating and posting purposes. Although the models do not represent an actual truck configuration, they were developed to resemble and encompass the load effects of the various trucks each one describes. The first is the 2-axle, 40 kips, H20 model having an AXS of 14 ft. AASHTO also developed the Family 3 Series (i.e. Type3, Type 3S2, and Type 3-3) in the 1970s to be sufficiently representative of commercial truck configurations at the time (Sivakumar et al., 2007). Figure 2.3 displays the H20 and Family 3 Series models. For span lengths greater than 200 ft., the analysis must be performed with Lane-Type loading which uses 75% of Type 3-3 with a uniformly distributed lane load of 0.2 kips/ft. for all types of load effects, as shown on Figure 2.4. When evaluating negative bending moment and reaction at the interior support, a uniformly distributed lane load of 0.2 kips/ft. and 75% of two Type 3-3 trucks spaced at 30 ft. heading in the same direction must be applied as shown on Figure 2.4.

Type 3 Unit Weight = 50 kips (25 tons).

H20 Weight = 40 kips (20 tons).

Type 3S2 Unit Weight = 72 kips (36 tons).

Type 3-3 Unit Weight = 80 kips (40 tons).

Figure 2.3: AASHTO legal LL models (RIDOT, 2011)

Lane-Type Loading for Spans Greater than 200 ft.

Lane-Type Legal Load Model—Apply for negative moment and interior reaction for all span lengths.

Lane-Type Loading for Negative Moment and Interior Reaction.

Figure 2.4: AASHTO legal LL Lane-Type loading models (RIDOT, 2011)

Over the years the trucking industry has made adaptations to truck configurations by placing closely spaced axles in compliance with the FBF B to carry the maximum permissible GVW. To ensure the short haul vehicle's (SHVs) configurations were not overstressing bridges by exceeding the load effects of the existing legal models, in 2005 AASHTO adopted the SU Series. These models represent single-unit short-wheelbase multi-axle trucks and are referred to as SU4, SU5, SU6, and SU7 with four- to seven-axle, as shown by Figure 2.5.

Figure 2.5: SU Series (RIDOT, 2011)

The AASHTO legal LL models were developed to be sufficiently representative of vehicles commonly found in the nation's highway that comply with federal weight restrictions. However under the "grandfather rights," trucks exceeding federal restrictions are considered legal within the state's own limits. Therefore, the AASHTO legal LL models may not accurately envelope the load effects of the truck traffic of a particular state. The LRFR provides flexibility for states to implement their own legal LL models that satisfy their regulations. State-specific legal LL models are allowed by LRFR as long as they are load rated in the same manner as those provided by AASHTO (Hayworth et al., 2008). Although RI has weight limits that exceed those federally mandated, it currently does not have state-specific legal LL models.

2.4 Permit Live Load Models

OSOW vehicles may operate with the approval of a permit application reviewed by a state's transportation agency. Permit application analysis can be a time consuming task. Therefore, it is beneficial for a state to have OWP models, either notional or resembling real truck configurations, developed based on truck characteristics of previous applications to be evaluated during a bridge rating at a permit level. This procedure has the ability of expediting future permitting decisions of applicant trucks meeting load effect bounds set by models. The one reviewing the permit application can compare the applicant truck to a model having similar characteristics (i.e., NAX, GVW and AXW) and if the bridge performed well for the model it also has a satisfactory performance for the applicant truck. Shown in Figure 2.6 are the standard permit vehicles (SPVs) currently used in RI developed in 2009 by examining the load effects induced by various truck configuration obtained from past permit applications. If the applicant truck exceeds the load effect of the respective model, then an analysis of the bridge with the permit truck must be performed to ensure there is sufficient carrying capacity. The models satisfy two types of permits issued to OW vehicles: BP and single-trip permits (OWP). There are four BP models, namely RI-BP1 through RI-BP4, and three OWP, namely RI-OP1 through RI-OP3.

RI Blanket Permit Vehicle Configurations (Unlimited Crossings)

RI Overweight Permit Vehicle Configurations (Single Trips)

Figure 2.6: RI permit LL models (RIDOT, 2011)

Similarly with the design and legal LL models, the permit models must also utilize load factors in the analysis. Permit load factors depend on the type of permit, traffic volume, weight and configuration of permit vehicle as shown in Table 2.4. The factors for routine permits were calibrated using a β of 2.5. Due to risk of structural damage and associated benefit/ cost considerations lead to a higher β of 3.5 for single- and multiple-trip special permits.

Table 2.4: LL factors for permit rating (MBE, 2013)

Permit Type	Frequency	Loading Condition	DF ^a	ADTT (one direction)	Load Factor by Permit Weight Ratio ^b		
					GVW/A $L \leq 2.0$ (kip/ft)	$2.0 < \text{GVW/A}$ $L < 3.0$ (kip/ft)	GVW/A $L \geq 3.0$ (kip/ft)
Routine or Annual (BP)	Unlimited Crossing	Mix with traffic (other vehicles may be on the bridge)	Two or more lanes	> 5000	1.4	1.35	1.3
				= 1000	1.35	1.25	1.2
				< 100	1.3	1.2	1.15
Special or Limited Crossing (OWP)	Single-Trip	Escorted with no other vehicles on the bridge	One Lane	N/A	1.1		
	Single-Trip	Mix with traffic (other vehicles may be on the bridge)	One Lane	All ADTTs	1.2		
	Multiple-Trips (less than 100 crossings)	Mix with traffic (other vehicles may be on the bridge)	One Lane	All ADTTs	1.4		

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

^b Permit Weight Ratio = GVW/AL; AL = Front axle to rear axle length; use only axles on the bridge.

CHAPTER 3. METHODOLOGY

This chapter presents the approach adopted to achieve the study's objectives. A review of the research database is described and detailed information on the data analysis procedure is provided.

3.1 Characteristics of OSOW Truck Database

RIDMV maintains a log of approved single-trip permit applications reviewed by the agency as well as RIDOT. A database containing 44,507 records extending from April 2008 through June 2013 was obtained from RIDMV as an excel spreadsheet. Each row in the spreadsheet pertains to a specific application and the columns its details. Table 3.1 summarizes the information provided by each column of the database. Details on the truck's configuration and weights (i.e., NAX, AXS and AXW) are necessary for the calculation of load effects and the development of the LL models. Other data provided by the database such as the reviewing agency and number of submittals were used to analyze the characteristics of the applications.

Table 3.1: Approved OSOW permit database parameters

Column	Field/ Parameter	Units	Description
1	ID	-	6-digit permit application identification number
2	Company Name	-	Name of trucking company
3	Route	-	Specific trip route requested
4	Initials	-	e-mail address of the permit reviewer
5-10	Year, Month, Day, Hours, Minute, Second In	-	Date and time application is submitted by applicant
11-16	Year, Month, Day, Hours, Minute, Second Out	-	Date and time permit review is complete
17	Agency	CODE	RI agency reviewing permit (DMV=1, DOT=2)
18	Origin	CODE	Originating state of travel (RI=1, CT=2, MA=3)
19	Destination	CODE	Destination state of travel (RI=1, CT=2, MA=3)
20	Submittal	-	Number of times the same permit was submitted
21	Height	in	Height of the vehicle
22	GVW	lbs.	Gross vehicle weight
23	Width	in	Width of the vehicle
24	Length	in	Length of the vehicle
25	NAX	-	Number of axles
26	AXW1	lbs.	Weight of axle 1
27	AXS1	in	Spacing between axle 1 and 2
28	AXW2	lbs.	Weight of axle 2
29	AXS2	in	Spacing between axle 2 and 3
...	...	...	...
63	AXS19	in	Spacing between axle 19 and 20
64	AXW20	lbs.	Weight of axle 20

3.2 Database Quality Analysis

A data quality analysis was the first procedure performed with the purpose of removing erroneous records. The latter was achieved by the use of data quality filters based on possible sources of error as well as observed discrepancies in the input values. Records failing one or more data quality filters were separated from the database. It is important to eliminate such records as they could impair the findings of this study.

The records meeting all quality filters were used for the progression of the study and its characteristics were evaluated. By incorporating the RI General Laws, the records were then categorized into groups based NAX and weight restrictions as legal, BP, or OWP loads (e.g., legal 5-axle, BP 5-axle, and OWP 5-axle). In this study of concern was the classification of trucks based on weight restrictions, therefore, the size restrictions were not taken into consideration to categorize the trucks.

3.3 Model Performance

For each record within the different groups, the maximum load effects (i.e., mid-span moment and end shear force of a simply-supported beam, and negative moment and shear force at the interior support of a two-equal span continuous beam) were calculated for 37 span lengths ranging from 20 ft. through 300 ft. with fixed intervals (i.e., 20-30 ft. every 1 ft., 30-60 ft. every 10 ft., 100-200 ft. every 20 ft., 250 ft., and 300 ft.). Therefore, each record had a total of 148 calculated load effects. No LL factors were applied to the calculations. A detailed explanation of the method taken to calculate the load effect can be found in the appendix. The selected method was incorporated into a MATLAB code due to the highly computational effort involved in calculating the load effects.

The performance of a LL model was assessed by its ability to exceed, or envelope, the load effects of the trucks in the group it represents. Load effect ratios were used for evaluating the latter, as shown in Equation 3.1. The model and records were compared for all types of

load effects and span lengths. A target value of ≤ 1 is desirable meaning the model sufficiently envelopes or is equivalent to the load effect of the record.

$$\text{Load Effect Ratio} = \frac{\text{Load Effect of Record}}{\text{Load Effect of Model}} \quad (3.1)$$

A visual representation of the load effect ratios assists in determining the models performance. The number of times the model is exceeded for a specific span length divided by the number of records in the group is plotted as a percentage against the span lengths. Based on the percent exceeding graphs, an observation of the span lengths in which the model is exceeded can be made. A uniform percent exceedance is desirable for the application of a single LL factor for all span lengths and type of load effects.

There were many records in the database not eliminated by the quality analysis that displayed information raising concerns. These records have configurations that appear unlikely, or rare, while others could have a user input error. It is difficult to decipher the distinction between the two possibilities due to the database's nature of uncommon trucks. A specific concern is with the low value of the summation of AXS compared to the truck's total length. These trucks can generate extremely high load effects due to the proximity of the axles. Under RIDOT advisement, characteristics of such records were identified and deemed rare or with a potential user input error. Furthermore, applications are submitted in advance to the truck being loaded, which can cause applicants to input higher weights to avoid fines if the truck surpasses what is specified on the permit. Given the presented uncertainties and the inability to eliminate records through a coherent manner, an assumption was made that a maximum exceedance of 10% would be acceptable. Therefore,

at least 90% of the records are well represented by the model without being excessively conservative.

3.4 Live Load Model Development

Models that represent a group composed of trucks having the same NAX were developed using an actual truck configuration found within that group. A better understanding of the characteristics of trucks traveling on the state's bridges and the ones that can generate the maximum load effects are beneficial aspects of such models that assists in management decisions such as closure and posting.

A systematic procedure was adopted to create actual truck configuration LL models. Since one of the configurations within the group would be used to develop the model, only the AXWs had to be determined. "Trial models" were developed using a MATLAB code that used all the configurations of trucks within the group with replaced AXWs from several predetermined cases. The maximum percent exceedance of all "trial models" for each load effect were calculated by the code that then ranked them based on performance.

AXWs for the "trial models" were selected using the group's database characteristics. To be sufficiently representative of the database and develop suitable models, it was determined to use the 90th and 95th percentile of the GVW and AXWs. Also, the division of GVW among the axles was another parameter investigated. For all records in the group, the percent of the GVW each axle supports was calculated. Then, statistical parameters

(i.e., mean and mode) for each axle was determined. In situations where the division of GVW among the axles of the model exceeded the restrictions it represents, the maximum allowable AXW value was applied. Lastly, the restrictions themselves were used as the GVW and AXWs. The latter was not performed directly as it could potentially develop conservative or inadequate models, or the values may deviate from the characteristics of the database.

The possible cases of GVW and AXWs and the performance of the existing model for comparison purposes were analyzed as listed:

1. a. 90th percentile of GVW with the mean division among the axles.
b. 90th percentile of GVW with the mode division among the axles.
2. a. 95th percentile of the GVW with the mean division among the axles.
b. 95th percentile of the GVW with the mode division among the axles.
3. 90th percentile of each AXW.
4. 95th percentile of each AXW.
5. a. GVW restriction with the mean division among the axles. Where applicable, AXWs are limited by the restriction.
b. GVW restriction with the mode division among the axles. Where applicable, AXWs are limited by the restriction.
6. Existing model.

Notional models, in contrary to actual truck configuration models, are fabricated with the purpose of representing a group with multiple types of trucks based on NAX. However,

the development of a notional model in this study follows the same systematic procedure of the actual configuration model except with different GVW and AXW cases. Furthermore, the notional model has the same NAX as the trucks with the most NAX in the group's database. Therefore, the "trial models" and the GVW division among axles for the model development only uses such trucks. The best case is then used as the starting point for the alterations to fabricate the model in a trial and error approach to enhance its performance. The following are the cases evaluated:

1. a. Highest 90th percentile GVW of the trucks in the group, and the mean division among the axles.
b. Highest 90th percentile GVW of the trucks in the group, and the mode division among the axles.
2. a. Highest 95th percentile GVW of the trucks in the group, and the mean division among the axles.
b. Highest 95th percentile GVW of the trucks in the group, and the mode division among the axles.
3. 90th percentile of each AXW of the highest NAX trucks.
4. 95th percentile of each AXW of the highest NAX trucks.
5. Existing model.
6. a. Existing model with the highest 90th percentile GVW of the trucks in the group, and the mean division among the axles
b. Existing model with the highest 90th percentile GVW of the trucks in the group, and the mode division among the axles

7. a. Existing model with the highest 95th percentile GVW of the trucks in the group,
and the mean division among the axles

b. Existing model with the highest 95th percentile GVW of the trucks in the group,
and the mode division among the axles
8. Trial and error approach

In this study, actual configuration models were developed for all legal and BP groups as the restrictions are specific to a trucks NAX. A combination of notional and actual truck configuration models were developed for OWP groups depending on the number of records.

CHAPTER 4. DATABASE ANALYSIS

In this chapter the findings of the database analysis is presented. Initially a data quality analysis was performed to eliminate erroneous records found in the provided spreadsheet by RIDMV of approved single-trip OSOW permits. Figure 4.1 displays the distribution based on NAX of the database and Table 4.1 summarizes the findings. The classification of trucks into groups using the RI General Laws is also presented. Then, the characteristics of the applications within these groups were investigated.

Figure 4.1: OSOW database distribution based on NAX

Table 4.1: OSOW database number of records by NAX

NAX	Number of Vehicles	% of Database
1	2	0.00%
2	248	0.56%
3	659	1.48%
4	4,376	9.83%
5	22,524	50.61%
6	10,253	23.04%
7	3,371	7.57%
8	2,010	4.52%
9	432	0.97%
10	430	0.97%
11	78	0.18%
12	61	0.14%
13	62	0.14%
20	1	0.00%
Total	44,507	

4.1 Data Quality Analysis

The quality analysis was completed by using filters selected from expected sources of error and observed discrepancies in the input values. MATLAB was used to assign flags to records failing filters. Records meeting all filters were compiled into a database named “Good Data,” and those eliminated into a database named “Bad Data.”

There were six filters used to perform the quality analysis, as shown in the flowchart on Figure 4.2. Filter 5 had the purpose of eliminating a single truck that had the NAX equal to 20 which did not require the development of a model. The last filter was included from an assumption made that any $AXS \leq 24$ inches is extremely short and unlikely to occur given the characteristics of the remaining trucks in the database. As a result, filter 2 was responsible for flagging the most trucks (6.10%) followed by filter 3 (0.96%).

Figure 4.2: Data quality analysis

4.2 "Bad Data"

Figure 4.3 displays the distribution of the "Bad Data" based on NAX developed from the results summarized in Figure 4.2.

Figure 4.3: “Bad Data” distribution based on NAX

Quality filter 2 was responsible for the majority of the records being deemed erroneous. This can be due to missing a significant figure in the GVW input (e.g., actual GVW of 80,000 entered as 8,000 pounds).

Filter 3 and 6 evaluated the configuration of the trucks. A possible explanation to errors flagged by these filters could have originated from the manner in which the information is requested in the application process, as shown on Figure 4.4. The AXS necessary to fill in the application does not specify that the measurement must be taken from center-to-center of axles. Therefore, an applicant could have measured the gap between the tires instead.

Axle Information

Permit Type

Company Information

Truck / Trailer Information

Size / Weight

Axle Information

Load / Route Information

Permit Declarations

Submit Permit

Axle Number	Axle Load Rating	Axle Numbers	Distance Between	Number of Axles
1	<input type="text"/> lbs.	1-2	<input type="text"/> feet <input type="text"/> inches	5 CHANGE ▶
2	<input type="text"/> lbs.	2-3	<input type="text"/> feet <input type="text"/> inches	
3	<input type="text"/> lbs.	3-4	<input type="text"/> feet <input type="text"/> inches	
4	<input type="text"/> lbs.	4-5	<input type="text"/> feet <input type="text"/> inches	
5	<input type="text"/> lbs.			

BACK

CONTINUE

Figure 4.4: Single-trip permit application axle information input screen (“RI DMV/ DOT,” n.d.)

4.3 Truck Classification by RI General Laws

The progression of the study utilized the records found in the “Good Data.” To develop the LL models, these records had to be categorized and separated based on the weight restrictions specified in the RI General Laws. Table 4.2 summarizes the possible classification of each truck depending on the NAX.

Table 4.2: Possible truck classification under RI General Laws by NAX

NAX	Legal	BP	OWP
2	GVW $\leq$ 80 kips Single-Axle $\leq$ 22.4 kips Tandem-Axle $\leq$ 36 kips FBF B	GVW $\leq$ 130 kips Any Axle $\leq$ 25 kips	Exceed Legal and BP
3	GVW $\leq$ 76.65 kips	GVW $\leq$ 130 kips Any Axle $\leq$ 25 kips	Exceed Legal and BP
4	GVW $\leq$ 80 kips Single-Axle $\leq$ 22.4 kips Tandem-Axle $\leq$ 36 kips FBF B	GVW $\leq$ 130 kips Any Axle $\leq$ 25 kips	Exceed Legal and BP
5	GVW $\leq$ 104.8 kips	GVW $\leq$ 130 kips Any Axle $\leq$ 25 kips	Exceed Legal and BP
≥ 6	GVW $\leq$ 80 kips Single-Axle $\leq$ 22.4 kips Tandem-Axle $\leq$ 36 kips FBF B	—	Exceed Legal

Shown on Figure 4.5 is a flowchart with the results of applying the information found in Table 4.2 to classify the trucks. Trucks classified as legal under the weight restrictions applied for permits due to a size violation.

Figure 4.5: RI General Laws truck classification by weight restrictions

4.4 Application Characteristics

The yearly variation of approved permits by each agency is shown on Figures 4.6-4.8 and summarized in Tables 4.3-4.5 for legal, BP, and OWP applications. Combined, the agencies had the most number of approved applications in 2012 for legal trucks (4,915), 2011 for BP (607), and 2009 for OWP (3,868). Note, the data from 2008 and 2013 are incomplete since the collection period spans from April 2008 through June 2013.

Figure 4.6: Legal yearly variation of approved applications by agency

Table 4.3: Legal yearly variation of approved applications by agency

Year	RIDOT		RIDMV	
	No. of Records	% of Records	No. of Records	% of Records
2008	233	0.95%	3583	14.67%
2009	249	1.02%	4499	18.42%
2010	326	1.34%	3511	14.38%
2011	477	1.95%	4031	16.51%
2012	413	1.69%	4502	18.44%
2013	176	0.72%	2419	9.91%

Figure 4.7: BP yearly variation of approved applications by agency

Table 4.4: BP yearly variation of approved applications by agency

Year	RIDOT		RIDMV	
	No. of Records	% of Records	No. of Records	% of Records
2008	9	0.61%	159	10.81%
2009	34	2.31%	191	12.98%
2010	45	3.06%	152	10.33%
2011	34	2.31%	573	38.95%
2012	54	3.67%	131	8.91%
2013	31	2.11%	58	3.94%

Figure 4.8: OWP yearly variation of approved applications by agency

Table 4.5: OWP yearly variation of approved applications by agency

Year	RIDOT		RIDMV	
	No. of Records	% of Records	No. of Records	% of Records
2008	468	3.02%	2315	14.93%
2009	719	4.64%	3149	20.30%
2010	480	3.09%	2039	13.15%
2011	867	5.59%	2222	14.33%
2012	1329	8.57%	878	5.66%
2013	588	3.79%	455	2.93%

Figures 4.9-4.11 shows the average monthly variation of approved permits by agency for each truck classification and is also summarized in Tables 4.6-4.8. The calculations were done by compiling all records by month of approval and dividing by 5, the number of years the data was collected. June is the month with the highest average of legal (11.95%) and OWP (11.55%) applications reviewed by the agencies combined, and May for BP (24.57%). These calculations used the “Good Data” composed of approved permits, therefore, the total number of reviewed applications can be higher if the statistics on the rejected ones were known.

Figure 4.9: Legal average monthly variation of approved applications by agency

Table 4.6: Legal average monthly variation of approved applications by agency

Month	RIDOT		RIDMV	
	No. of Records	% of Records	No. of Records	% of Records
January	35	0.72%	312	6.39%
February	28	0.57%	302	6.18%
March	28	0.57%	333	6.82%
April	32	0.66%	444	9.09%
May	41	0.84%	527	10.79%
June	35	0.72%	549	11.24%
July	29	0.59%	351	7.19%
August	24	0.49%	367	7.51%
September	28	0.57%	336	6.88%
October	29	0.59%	341	6.98%
November	36	0.74%	346	7.08%
December	30	0.61%	302	6.18%

Figure 4.10: BP average monthly variation of approved applications by agency

Table 4.7: BP average monthly variation of approved applications by agency

Month	RIDOT		RIDMV	
	No. of Records	% of Records	No. of Records	% of Records
January	0	0.00%	11	3.75%
February	1	0.34%	13	4.44%
March	1	0.34%	8	2.73%
April	5	1.71%	26	8.87%
May	11	3.75%	61	20.82%
June	4	1.37%	49	16.72%
July	1	0.34%	11	3.75%
August	4	1.37%	9	3.07%
September	3	1.02%	15	5.12%
October	7	2.39%	19	6.48%
November	3	1.02%	16	5.46%
December	1	0.34%	14	4.78%

Figure 4.11: OWP average monthly variation of approved applications by agency

Table 4.8: OWP average monthly variation of approved applications by agency

Month	RIDOT		RIDMV	
	No. of Records	% of Records	No. of Records	% of Records
January	56	1.81%	127	4.10%
February	49	1.58%	110	3.55%
March	56	1.81%	136	4.39%
April	88	2.84%	172	5.55%
May	88	2.84%	221	7.13%
June	113	3.65%	245	7.90%
July	85	2.74%	207	6.68%
August	74	2.39%	222	7.16%
September	73	2.35%	266	8.58%
October	62	2.00%	180	5.81%
November	74	2.39%	167	5.39%
December	71	2.29%	158	5.10%

As previously stated, an application may be rejected if the truck cannot be accommodated in the requested route or necessary information is not provided. However, applications may be re-submitted with the necessary corrections. Tables 4.9-4.11 shows the number of application submittals required until approval. The OWP reviewing process had the lowest first time submittal approval rate of 88.97% in comparison to legal and BP. However, the legal applications required the most number of re-submittals, up to seven.

Table 4.9: Number of submittals required for approval of a legal truck by agency

Agency	Submittals							Total of Approved Submittals
	1	2	3	4	5	6	7	
RIDMV	21,385 87.58%	887 3.63%	219 0.90%	38 0.16%	9 0.04%	6 0.02%	1 0.00%	22,545
RIDOT	1,563 6.40%	219 0.90%	71 0.29%	18 0.07%	3 0.01%	0 0.00%	0 0.00%	1,874
Total	22,948 93.98%	1,106 4.53%	290 1.19%	56 0.23%	12 0.05%	6 0.02%	1 0.00%	24,419

Table 4.10: Number of submittals required for approval of a BP by Agency

Agency	Submittals							Total of Approved Submittals
	1	2	3	4	5	6	7	
RIDMV	1,215 82.60%	41 2.79%	5 0.34%	2 0.14%	1 0.07%	0 0.00%	0 0.00%	1,264
RIDOT	184 12.51%	17 1.16%	6 0.41%	0 0.00%	0 0.00%	0 0.00%	0 0.00%	207
Total	1,399 95.11%	58 3.94%	11 0.75%	2 0.14%	1 0.07%	0 0.00%	0 0.00%	1,471

Table 4.11: Number of submittals required for approval of an OWP by agency

Agency	Submittals							Total of Approved Submittals
	1	2	3	4	5	6	7	
RIDMV	10,438 67.30%	471 3.04%	123 0.79%	22 0.14%	4 0.03%	0 0.00%	0 0.00%	11,058
RIDOT	3,332 21.48%	815 5.26%	229 1.48%	57 0.37%	10 0.06%	8 0.05%	0 0.00%	4,451
Total	13,770 88.79%	1,286 8.29%	352 2.27%	79 0.51%	14 0.09%	8 0.05%	0 0.00%	15,509

The percent of applications reviewed by each agency separated into NAX is summarized in Tables 4.12-4.14. RIDMV reviews the most applications for all types of trucks based on NAX for both legal and BP. However for OWP, as the NAX increases RIDOT reviews more applications than RIDMV.

Table 4.12: Percent of approved legal applications by NAX and agency

NAX	RIDMV	RIDOT
2	0.79%	0.02%
3	1.61%	0.11%
4	9.97%	0.29%
5	67.71%	5.52%
6	8.17%	1.04%
7	1.83%	0.18%
8	1.11%	0.26%
9	0.72%	0.14%
10	0.38%	0.09%
11	0.02%	0.00%
12	0.01%	0.01%
13	0.00%	0.00%

Table 4.13: Percent of approved BP applications by NAX and agency

NAX	RIDMV	RIDOT
2	0.61%	0.00%
3	0.00%	0.00%
4	46.84%	11.01%
5	38.48%	3.06%

Table 4.14: Percent of approved OWP applications by NAX and agency

NAX	RIDMV	RIDOT
2	0.00%	0.00%
3	0.77%	0.05%
4	3.38%	0.47%
5	16.48%	0.26%
6	41.26%	6.43%
7	7.69%	9.34%
8	1.38%	8.34%
9	0.24%	1.07%
10	0.06%	1.73%
11	0.01%	0.39%
12	0.04%	0.28%
13	0.00%	0.34%

Another important characteristic of the database is the requested travel route. These routes can be termed as intrastate, interstate, or thru-state. An intrastate route refers to a truck that originates its travel in RI with a destination within the state. The interstate route originates from RI and has a final destination in another state, and vice versa. Thru-state route refers to a truck originating and ending its trip in another state other than RI, but traveling in the state to complete the journey. Massachusetts, Connecticut, and RI are the three states present in all permit applications. Therefore, there are a total of 9 possible combinations of routes as shown by Tables 4.15-4.17 with the percent of applications approved by each agency. For all types of truck classifications, the most requested route originates in CT, particularly with RI as the destination.

Table 4.15: Approved legal applications travel route by agency

Travel Route	RIDMV	RIDOT	Total		Origin State
RI-RI	1,450	181	1,631	3.94%	13.24%
RI-CT	2,076	164	2,240	5.41%	
RI-MA	1,565	47	1,612	3.89%	
CT-RI	5,697	489	6,186	14.94%	25.61%
CT-CT	1	2	3	0.01%	
CT-MA	3,790	622	4,412	10.66%	
MA-RI	4,945	153	5,098	12.31%	20.13%
MA-CT	1,937	213	2,150	5.19%	
MA-MA	1,084	3	1,087	2.63%	
Total	22,545	1,874	24,419		

Table 4.16: Approved BP applications travel route by agency

Travel Route	RIDMV	RIDOT	Total		Origin State
RI-RI	120	142	262	0.63%	1.21%
RI-CT	57	6	63	0.15%	
RI-MA	170	5	175	0.42%	
CT-RI	462	15	477	1.15%	1.36%
CT-CT	0	0	0	0.00%	
CT-MA	71	15	86	0.21%	
MA-RI	328	18	346	0.84%	0.99%
MA-CT	48	5	53	0.13%	
MA-MA	8	1	9	0.02%	
Total	1,264	207	1,471		

Table 4.17: Approved OWP applications travel route by agency

Travel Route	RIDMV	RIDOT	Total		Origin State
RI-RI	758	844	1,602	3.87%	11.79%
RI-CT	619	446	1,065	2.57%	
RI-MA	1,698	518	2,216	5.35%	
CT-RI	3,476	1,056	4,532	10.95%	15.84%
CT-CT	3	1	4	0.01%	
CT-MA	1,512	509	2,021	4.88%	
MA-RI	2,435	740	3,175	7.67%	9.83%
MA-CT	437	319	756	1.83%	
MA-MA	120	18	138	0.33%	
Total	11,058	4,451	15,509		

Lastly, there are several restrictions a truck can exceed to be classified OW. Figure 4.12 demonstrates the percent of approved OWP by each agency that failed to comply with a specific restriction. Approximately 78% of approved OWP applications did not meet FBF B requirements and 77% violated the GVW limit. For both types of restrictions RIDMV reviewed the most number of applications, similarly to single- and tandem-axle limits.

Figure 4.12: Weight violations of approved OWP by agency

CHAPTER 5. LEGAL LIVE LOAD MODELS

This chapter presents the development of the legal LL models: RI-3 and RI-5, for 3- and 5-axle trucks, respectively. Currently, there are no state-specific legal LL models. However, the 3-axle RI-BP1 and 5-axle RI-BP3 models used for BP purposes have characteristics that resemble the limitations of legal trucks imposed by the RI General Laws. Therefore, the two BP models were evaluated in this chapter as the existing legal LL models.

5.1 Proposed RI-3

A total of 419 records in the “Good Data” were classified as legal 3-axle trucks having a $GVW \leq 76.65$ kips. These records were further used to develop the RI-3 model and to evaluate its performance. Figure 5.1 demonstrates the distribution of GVW with a maximum of 69.32 kips, minimum of 11.4 kips, and mode of 60 kips. The database has a mean GVW of 54.1 kips and standard deviation of 10.6 kips.

Figure 5.1: Legal 3-axle records GVW distribution

The variation of the GVW statistics by year is shown on Figure 5.2. In 2009 the maximum GVW of 69.32 kips occurred and the minimum of 11.4 kips in 2008.

Figure 5.2: Legal 3-axle records yearly variation of GVW statistics

Shown on Figure 5.3 is the normal probability plot (NPP) of the AXWs. The plot was used in this study to identify similarities in the distribution of the AXWs as well as to determine the 90th and 95th percentile values. Axles 2 and 3, by inspection of Figure 5.3, have similar distributions of AXWs. For higher weight values, axle 1 approaches the distribution of the other axles. These observations were considered in the model development.

Figure 5.3: Legal 3-axle records AXW NPP

All statistical parameters discussed so far is summarized in Table 5.1 with the inclusion of other necessary information. This data was used to create the “trial model” cases accordingly to the adopted procedure for an actual truck configuration model development, explained in Chapter 3.

Table 5.1: Legal 3-axle records weight statistics

	Axle			GVW
	1	2	3	
Min (kips)	3.00	4.20	4.00	11.4
Max (kips)	24.00	26.00	26.00	69.32
Mean (kips)	16.41	18.78	18.91	54.085
SD (kips)	4.68	3.34	3.42	10.612
Mode (kips)	20.00	20.00	20.00	60
90 th percentile (kips)	21.00	22.49	22.49	65
95 th percentile (kips)	22.00	23.00	23.00	68

The distribution of GVW among the axles of the legal 3-axle records was also calculated as it is required to develop certain “trial model” cases. For each record, the percent of GVW

each axle supports was calculated and from those values statistical parameters were determined with results shown in Table 5.2.

Table 5.2: Legal 3-axle statistics on GVW division among axles

	Axle		
	1	2	3
Mean (%)	29.95	34.92	35.13
SD (%)	4.67	2.40	2.42
Mode (%)	33.33	33.33	33.33
Max (%)	45.46	42.67	42.67
Min (%)	14.65	27.27	25.00

Once all the necessary information was obtained, the “trial model” cases were selected, as presented in Table 5.3.

Table 5.3: Legal 3-axle AXWs of investigated cases

Case		AXW 1 (kips)	AXW 2 (kips)	AXW 3 (kips)
1	a	19.5	22.8	22.8
	b	21.7	21.7	21.7
2	a	20.4	23.8	23.8
	b	22.4	22.4	22.4
3		21.0	22.5	22.5
4		22.0	23.0	23.0
5	a	23.0	26.8	26.8
	b	25.2	25.2	25.2
6		18.0	29.0	29.0

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 5.4-5.5. Case 5a and case 6 both had the best and equivalent performances only having CSMomNeg exceeded by 0.7%.

Table 5.4: Legal 3-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	8.4	8.1	8.1	12.2
	b	11.5	8.4	11.2	14.1
2	a	3.3	3.8	3.6	8.4
	b	6.0	6.2	6.2	11.9
3		7.4	7.4	8.1	12.9
4		6.0	6.0	3.3	11.2
5	a	0.0	0.0	0.0	0.7
	b	0.2	2.1	2.1	2.6
6		0.0	0.0	0.0	0.7

Table 5.5: Legal 3-axle configuration case results

Case		AXS 1 (ft.)	AXS 2 (ft.)
1	a	17.3	4.2
	b	17.7	3.0
2	a	17.5	4.0
	b	17.7	3.0
3		17.7	3.0
4		16.1	4.2
5	a	13.8	4.5
	b	17.7	3.0
6		12.9	4.6

Although both cases 5a and 6 performed equally well, the latter is selected as the proposed RI-3 given its current functional application in bridge rating purposes as the RI-BP1. Figure 5.4 displays the proposed RI-3 configuration.

Figure 5.4: Proposed RI-3 model

Shown on Figure 5.5 is the percent exceeding plot of the proposed model. The maximum percent exceeding of 0.72% for CSMomNeg occurs in span lengths of 32-34 ft. All other load effects generated by the proposed model is not exceeded by the records.

Figure 5.5: Proposed RI-3 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 5.6-5.9. From the figures it can be seen that although the percent exceeding values are low, the ratio distribution is skewed to the left, thus the ratios are mostly concentrated at the higher values. The statistical parameters also demonstrates that for all load effects and span lengths the mean is above 0.6 and increases with an increase in span length.

(a)

(b)

Figure 5.6: Proposed RI-3 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 5.7: Proposed RI-3 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 5.8: Proposed RI-3 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 5.9: Proposed RI-3 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-3 and existing AASHTO design and legal LL models was performed to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing models. Note that the load effects used to calculate the ratios are un-factored. Figure 5.10 displays the ratios of the proposed RI-3 to the AASHTO Family 3 Series load effects. It can be seen that for shorter spans the proposed model exceeds the Family 3, however, after a span length of approximately 200 ft. both SSMomMid and SSShear are controlled by the AASHTO models. The proposed RI-3 also exceeds the Family 3 for CSMomNeg and CSShear up to approximately 52 ft. and 60 ft., respectively.

Figure 5.10: Proposed RI-3 vs. AASHTO Family 3 Series

The proposed model is then compared to the SU Series. For all span lengths SSShear of the proposed model exceeds the SU Series as shown in Figure 5.11. Also shown in the figure is the proposed model exceeding the SU Series up to approximately 48 ft. for CSShear, 80 ft. for CSMomNeg, and 200 ft. for SSMomMid.

Figure 5.11: Proposed RI-3 vs. SU Series

Lastly, the model was compared to the design LL model, HL-93. As shown on Figure 5.12, the proposed model exceeds the HL-93 up to a certain span length: CSMomNeg at 20 ft. and between 25-32 ft., CSShear up to 24 ft., and SSShear up to 32 ft. For SSMomMid the HL-93 exceeds the proposed model for all span lengths.

Figure 5.12: Proposed RI-3 vs. HL-93

Tables 5.6-5.7 summarizes the ratios calculated used to develop the plots displayed in Figures 5.10-5.12

Table 5.6: Continuous span load effects model comparison ratio

Span Length (ft)	CSMomNeg			CSShear		
	Family 3	SU Series	HL-93	Family 3	SU Series	HL-93
20	1.89	1.25	1.00	2.25	1.09	1.10
21	1.84	1.19	0.98	2.20	1.08	1.08
22	1.84	1.17	0.99	2.17	1.07	1.05
23	1.83	1.16	0.99	2.13	1.06	1.03
24	1.78	1.14	1.00	2.05	1.06	1.01
25	1.71	1.13	1.00	1.96	1.05	0.99
26	1.63	1.12	1.01	1.88	1.05	0.98
27	1.56	1.11	1.01	1.82	1.04	0.96
28	1.50	1.09	1.02	1.76	1.04	0.95
29	1.45	1.08	1.02	1.72	1.03	0.94
30	1.41	1.06	1.03	1.67	1.03	0.93
32	1.30	1.02	1.02	1.60	1.02	0.90
34	1.23	1.00	0.96	1.54	1.02	0.88
36	1.21	1.01	0.93	1.47	1.02	0.86
38	1.21	1.03	0.90	1.42	1.01	0.85
40	1.21	1.05	0.86	1.37	1.01	0.83
42	1.20	1.06	0.84	1.33	1.01	0.82
44	1.17	1.07	0.81	1.29	1.00	0.80
46	1.14	1.06	0.77	1.26	1.00	0.79
48	1.09	1.05	0.72	1.23	1.00	0.78
50	1.05	1.04	0.68	1.21	1.00	0.76
52	1.02	1.04	0.64	1.18	1.00	0.75
54	0.99	1.03	0.60	1.15	1.00	0.74
56	0.96	1.03	0.57	1.12	1.00	0.73
58	0.94	1.03	0.54	1.10	0.99	0.72
60	0.90	1.02	0.52	1.07	0.99	0.71
70	0.76	1.01	0.44	0.93	0.99	0.61
80	0.67	1.00	0.41	0.81	0.99	0.53
90	0.62	1.00	0.39	0.73	0.99	0.48
100	0.59	1.00	0.37	0.67	0.99	0.44
120	0.56	0.99	0.35	0.60	0.98	0.39
140	0.56	0.99	0.32	0.55	0.98	0.36
160	0.55	0.99	0.31	0.52	0.98	0.33
180	0.55	0.99	0.29	0.49	0.98	0.31
200	0.52	0.98	0.27	0.47	0.98	0.29
250	0.45	0.98	0.24	0.43	0.98	0.25
300	0.41	0.98	0.21	0.40	0.98	0.22

Table 5.7: Simple span load effects model comparison ratio

Span Length (ft)	SSMomMid			SSShear		
	Family 3	SU Series	HL-93	Family 3	SU Series	HL-93
20	1.64	1.27	0.96	1.71	1.39	1.04
21	1.65	1.25	0.96	1.69	1.40	1.05
22	1.65	1.23	0.96	1.68	1.40	1.06
23	1.65	1.22	0.95	1.67	1.39	1.07
24	1.66	1.20	0.95	1.66	1.38	1.07
25	1.66	1.18	0.95	1.65	1.37	1.07
26	1.66	1.17	0.95	1.65	1.36	1.07
27	1.69	1.17	0.96	1.64	1.36	1.06
28	1.71	1.16	0.96	1.63	1.35	1.05
29	1.73	1.16	0.97	1.63	1.34	1.04
30	1.75	1.16	0.98	1.62	1.34	1.03
32	1.73	1.16	0.98	1.62	1.33	1.01
34	1.71	1.16	0.99	1.61	1.31	1.00
36	1.69	1.16	1.00	1.60	1.28	0.98
38	1.68	1.15	1.00	1.60	1.26	0.97
40	1.67	1.13	1.00	1.59	1.24	0.95
42	1.66	1.12	1.00	1.59	1.22	0.94
44	1.65	1.11	0.98	1.58	1.20	0.93
46	1.64	1.10	0.96	1.55	1.19	0.92
48	1.64	1.10	0.95	1.51	1.18	0.91
50	1.63	1.09	0.94	1.48	1.17	0.90
52	1.62	1.09	0.92	1.46	1.16	0.89
54	1.62	1.08	0.91	1.43	1.15	0.88
56	1.61	1.08	0.90	1.41	1.14	0.87
58	1.61	1.07	0.89	1.40	1.13	0.86
60	1.59	1.07	0.88	1.38	1.13	0.86
70	1.47	1.05	0.84	1.32	1.10	0.82
80	1.39	1.04	0.80	1.25	1.08	0.79
90	1.34	1.03	0.77	1.21	1.07	0.76
100	1.28	1.03	0.74	1.17	1.06	0.74
120	1.21	1.02	0.69	1.13	1.05	0.69
140	1.16	1.01	0.65	1.10	1.04	0.65
160	1.12	1.01	0.61	1.08	1.03	0.62
180	1.10	1.00	0.58	1.06	1.02	0.58
200	1.03	1.00	0.55	1.01	1.02	0.56
250	0.95	1.00	0.50	0.94	1.01	0.50
300	0.88	0.99	0.45	0.87	1.00	0.45

5.2 Proposed RI-5

There were 17,881 records in the “Good Data” classified as legal 5-axle trucks having a $GVW \leq 104.8$ kips. These records were utilized to develop the RI-5 model and to evaluate its performance. Figure 5.13 demonstrates the distribution of GVW with a maximum of 104.75 kips, minimum of 8.5 kips, and mode of 80 kips. The database has a mean GVW of 78.5 kips and standard deviation of 14.8 kips.

Figure 5.13: Legal 5-axle records GVW distribution

The variation of the GVW statistics by year is shown on Figure 5.14. In 2009 the maximum GVW of 104.75 kips occurred while all other years had a value of 104 kips. The minimum GVW of 8.5 kips occurred in 2008.

Figure 5.14: Legal 5-axle records yearly variation of GVW statistics

Shown on Figure 5.15 is the NPP of the AXWs. It was observed that for lighter weights, the distribution of the AXWs are relatively similar for all axles. However, as the weights increase the AXW1 distribution deviates from the others. This observation was considered in the model development.

Figure 5.15: Legal 5-axle records AXW NPP

All statistical parameters discussed so far is summarized in Table 5.8 with the inclusion of other necessary information. This data was used to create the “trial model” cases accordingly to the adopted procedure for an actual truck configuration model development, explained in Chapter 3.

Table 5.8: Legal 5-axle records weight statistics

	Axle					GVW
	1	2	3	4	5	
Min (kips)	1.70	1.70	1.50	1.50	1.50	8.50
Max (kips)	25.00	25.00	25.00	26.50	26.50	104.75
Mean (kips)	11.65	16.87	16.63	16.64	16.71	78.50
SD (kips)	1.45	3.22	3.61	3.64	3.77	14.80
Mode (kips)	12.00	17.00	17.00	17.00	17.00	80.00
90 th percentile (kips)	12.00	21.00	21.00	21.00	21.75	99.00
95 th percentile (kips)	12.00	23.00	23.00	23.00	23.00	104.00

The statistics on the distribution of GVW among the axles of the legal 5-axle records was also analyzed as it is required to develop certain “trial model” cases. Table 5.9 displays the calculation results.

Table 5.9: Legal 5-axle statistics on GVW division among axles

	Axle				
	1	2	3	4	5
Mean (%)	15.26	21.58	21.03	21.03	21.10
SD (%)	2.83	2.44	1.46	1.54	1.63
Mode (%)	15.00	21.25	21.25	21.25	21.25
Max (%)	56.67	52.50	34.48	35.15	31.25
Min (%)	5.26	7.69	6.73	5.00	5.00

Once all the necessary information was obtained, the “trial model” cases were selected as presented in Table 5.10.

Table 5.10: Legal 5-axle AXWs of investigated cases

Case		AXW 1 (kips)	AXW 2 (kips)	AXW 3 (kips)	AXW 4 (kips)	AXW 5 (kips)
1	a	14.85	21.78	20.79	20.79	20.79
	b	14.85	21.04	21.04	21.04	21.04
2	a	15.60	22.88	21.84	21.84	21.84
	b	15.60	22.10	22.10	22.10	22.10
3		12.00	21.00	21.00	21.00	21.75
4		12.00	23.00	23.00	23.00	23.00
5	a	15.72	23.06	22.01	22.01	22.01
	b	15.72	22.27	22.27	22.27	22.27
6		12.00	23.20	23.20	23.20	23.20

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 5.11-5.12. Cases 1, 3 and 6 (existing model) did not perform well for CSMomNeg with a maximum exceeding as high as 14.43%. The target maximum percent exceeding for cases 2, 4 and 5 is satisfactory for all load effects, therefore, any could be selected as the proposed model.

Table 5.11: Legal 5-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	0.02	0.01	6.06	10.84
	b	0.02	0.01	6.06	10.84
2	a	0.00	0.00	0.01	5.98
	b	0.00	0.00	0.01	5.98
3		0.24	0.02	10.98	11.12
4		0.00	0.00	0.01	5.56
5	a	0.00	0.00	0.00	5.78
	b	0.00	0.00	0.00	5.78
6		0.10	0.29	0.06	14.43

Table 5.12: Legal 5-axle configuration of case results

Case		AXS 1 (ft)	AXS 2 (ft)	AXS 3 (ft)	AXS 4 (ft)
1	a	11.33	4.33	4.00	4.00
	b	11.33	4.33	4.00	4.00
2	a	11.33	4.33	4.00	4.00
	b	11.33	4.33	4.00	4.00
3		11.33	4.33	4.00	4.00
4		11.33	4.33	4.00	4.00
5	a	11.33	4.33	4.00	4.00
	b	11.33	4.33	4.00	4.00
6		8.00	4.50	14.00	4.50

Although cases 2, 4, and 5 performed well, case 4 was selected as the proposed RI-5. The proposed model was selected as it has the lowest CSMomNeg maximum percent exceeding and the AXWs are a better representation of the database than the other cases as it uses the 95th percentile. Also, the proposed model has a distribution of GVW among the axles similarly to the observation made from the NPP on Figure 5.15. Furthermore, the proposed model's AXWs are similar to the existing model except for the rear axles being lighter by 0.2 kips. A modification to the rear AXWs of the proposed model was performed by increasing it to become the same as the existing model since the difference was very low and it also generates a GVW that matches the maximum permissible value by the restriction. The increase in the AXWs also slightly enhanced the performance of the proposed model as will be demonstrated in the percent exceeding plot. Figure 5.16 displays the proposed RI-5 configuration.

Figure 5.16: Proposed RI-5 model

Shown on Figure 5.17 is the proposed model's percent exceeding plot. The proposed model's CSMomNeg is exceeded by the database for span lengths of 23-80 ft. with the maximum reaching 5.31% at 48 ft. With the increase in the rear AXWs, no trucks in the database exceed the model's CSShear, similarly to SSMomMid and SSShear.

Figure 5.17: Proposed RI-5 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 5.18-5.21. From the figures it can be seen that for shorter span lengths the proposed model generates low mean ratio values for simple span load effects and CSShear, but high for CSMomNeg due to the short AXS. As the span lengths increases so do the mean values of the ratios for all load effects.

(a)

(b)

Figure 5.18: Proposed RI-5 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 5.19: Proposed RI-5 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 5.20: Proposed RI-5 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 5.21: Proposed RI-5 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-5 and existing AASHTO design and legal LL models was performed to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing models. Note that the load effects used to calculate the ratios are un-factored. Figure 5.22 displays the ratios of the proposed RI-5 to the AASHTO Family 3 Series load effects. For all span lengths the proposed RI-5 exceeds the Family 3 for simple span load effects, however, as the span length increases the ratios decrease. The proposed model exceeds the Family 3 up to approximately 70 ft. and 90 ft. for CSMomNeg and CSShear, respectively. Similarly to the simple span load effects, the continuous span load effect ratios decrease with an increase in span length.

Figure 5.22: Proposed RI-5 vs. AASHTO Family 3 Series

The proposed model is then compared to the SU Series. For all span lengths the proposed model exceeds the load effects of the SU Series but the ratios decrease with an increase in span length as shown on Figure 5.23. The characteristics of the proposed RI-5 is very similar to the SU Series as they possess a longer first AXS while all others are short in

comparison. The SU Series complies with federal weight restrictions primarily the FBF B. However, in RI such trucks with 5-axles to be considered legal must only comply with the maximum GVW of 104.8 kips regardless of the other weight restrictions. Therefore, an increase in the AXWs generates higher load effects of trucks with similar configurations.

Figure 5.23: Proposed RI-5 vs. SU Series

Lastly, the model was compared to the design LL model, HL-93. As shown on Figure 5.24, with an increase in span length the ratios decrease. The proposed RI-5 exceeds the HL-93 up to a certain span length for SSMomMid (100 ft.), SSShear (90 ft.), CSMomNeg (46 ft.), and CSShear (56 ft.).

Figure 5.24: Proposed RI-5 vs. HL-93

Tables 5.13-5.14 summarizes the ratios calculated used to develop the plots displayed in Figures 5.22-5.24

Table 5.13: Continuous span load effects model comparison ratio

Span Length (ft)	CSMomNeg			CSShear		
	Family 3	SU Series	HL-93	Family 3	SU Series	HL-93
20	2.25	1.49	1.19	3.07	1.49	1.51
21	2.25	1.46	1.20	3.02	1.48	1.47
22	2.25	1.44	1.21	2.97	1.47	1.44
23	2.26	1.43	1.23	2.92	1.46	1.41
24	2.22	1.43	1.24	2.81	1.45	1.39
25	2.15	1.42	1.26	2.69	1.44	1.36
26	2.07	1.43	1.28	2.58	1.44	1.34
27	2.00	1.42	1.30	2.50	1.43	1.32
28	1.96	1.43	1.33	2.42	1.42	1.30
29	1.93	1.43	1.36	2.36	1.42	1.29
30	1.90	1.43	1.39	2.30	1.42	1.27
32	1.82	1.42	1.42	2.20	1.41	1.24
34	1.73	1.41	1.35	2.12	1.40	1.21
36	1.67	1.40	1.28	2.03	1.40	1.19
38	1.63	1.40	1.22	1.95	1.39	1.17
40	1.64	1.42	1.17	1.88	1.39	1.14
42	1.64	1.45	1.14	1.83	1.39	1.12
44	1.60	1.45	1.11	1.78	1.38	1.10
46	1.55	1.44	1.05	1.73	1.38	1.09
48	1.49	1.44	0.98	1.70	1.38	1.07
50	1.44	1.43	0.93	1.66	1.38	1.05
52	1.39	1.42	0.87	1.62	1.37	1.03
54	1.35	1.42	0.82	1.58	1.37	1.02
56	1.32	1.41	0.78	1.55	1.37	1.00
58	1.29	1.41	0.75	1.51	1.37	0.99
60	1.24	1.40	0.72	1.47	1.37	0.97
70	1.04	1.39	0.61	1.28	1.36	0.84
80	0.92	1.38	0.56	1.11	1.36	0.74
90	0.85	1.38	0.54	1.00	1.36	0.66
100	0.82	1.37	0.52	0.93	1.36	0.61
120	0.78	1.37	0.48	0.82	1.36	0.54
140	0.76	1.36	0.45	0.76	1.36	0.49
160	0.76	1.36	0.42	0.72	1.35	0.45
180	0.76	1.36	0.40	0.68	1.35	0.42
200	0.72	1.36	0.38	0.65	1.35	0.40
250	0.63	1.36	0.33	0.59	1.35	0.34
300	0.56	1.35	0.30	0.55	1.35	0.31

Table 5.14: Simple span load effects model comparison ratio

Span Length (ft)	SSMomMid			SSShear		
	Family 3	SU Series	HL-93	Family 3	SU Series	HL-93
20	2.02	1.56	1.18	2.06	1.67	1.26
21	2.06	1.56	1.20	2.04	1.68	1.27
22	2.10	1.57	1.22	2.03	1.69	1.28
23	2.13	1.57	1.23	2.02	1.68	1.29
24	2.16	1.57	1.24	2.01	1.67	1.30
25	2.19	1.56	1.25	2.02	1.67	1.31
26	2.21	1.55	1.26	2.02	1.68	1.31
27	2.23	1.54	1.26	2.03	1.68	1.31
28	2.26	1.53	1.27	2.03	1.68	1.31
29	2.27	1.53	1.27	2.03	1.68	1.30
30	2.29	1.52	1.28	2.04	1.68	1.29
32	2.26	1.52	1.28	2.04	1.67	1.28
34	2.24	1.52	1.30	2.04	1.66	1.27
36	2.23	1.53	1.31	2.05	1.64	1.25
38	2.22	1.51	1.32	2.05	1.62	1.24
40	2.21	1.50	1.32	2.05	1.60	1.23
42	2.20	1.49	1.32	2.06	1.58	1.22
44	2.20	1.48	1.30	2.06	1.56	1.21
46	2.19	1.47	1.29	2.01	1.55	1.20
48	2.18	1.47	1.27	1.98	1.54	1.19
50	2.18	1.46	1.25	1.94	1.53	1.18
52	2.18	1.45	1.24	1.91	1.52	1.17
54	2.17	1.45	1.22	1.89	1.51	1.16
56	2.17	1.44	1.21	1.86	1.51	1.15
58	2.16	1.44	1.20	1.84	1.50	1.14
60	2.14	1.44	1.18	1.83	1.49	1.13
70	1.98	1.42	1.13	1.75	1.47	1.09
80	1.88	1.41	1.08	1.68	1.45	1.06
90	1.82	1.40	1.04	1.62	1.44	1.02
100	1.74	1.40	1.01	1.58	1.43	0.99
120	1.64	1.39	0.94	1.53	1.41	0.93
140	1.58	1.38	0.89	1.49	1.40	0.88
160	1.54	1.38	0.84	1.46	1.40	0.84
180	1.51	1.38	0.80	1.44	1.39	0.80
200	1.41	1.37	0.76	1.38	1.39	0.76
250	1.30	1.37	0.68	1.28	1.38	0.68
300	1.21	1.37	0.61	1.20	1.38	0.62

CHAPTER 6. BLANKET PERMIT LIVE LOAD MODELS

In this chapter the development of BP LL models is presented: RI-BP4 and RI-BP5, for 4- and 5-axle trucks, respectively. Any truck with NAX less than six above legal restrictions and with a GVW ≤ 130 kips and any axle ≤ 25 kips classifies as a BP in the RI General Laws. Therefore, 2- and 3-axle trucks may also fall within this category. However, models for these trucks were not developed as there was insufficient or no records available. The existing 4-axle RI-BP2 was evaluated for the development of the proposed RI-BP4, while the existing 5-axle RI-BP3 was not analyzed in this chapter as it was used in the development of the proposed RI-5 for having legal restrictions characteristics.

6.1 Proposed RI-BP4

There were 851 records in the “Good Data” classified as BP 4-axle trucks. These records were further used to develop the RI-BP4 model and to evaluate its performance. Shown on Figure 6.1 is the distribution of GVW with a maximum of 100 kips, minimum of 40 kips, and mode of 72 kips. The database has a mean GVW of 75.46 kips and standard deviation of 12.24 kips.

Figure 6.1: BP 4-axle records GVW distribution

The variation of the GVW statistics by year is shown on Figure 6.2. Throughout all years permit applications reached the maximum GVW of 100 kips. The minimum GVW of 40 kips occurred in 2010. All other years had an application with a minimum GVW between 49.5 kips and 50.1 kips.

Figure 6.2: BP 4-axle records yearly variation of GVW statistics

Shown on Figure 6.3 is the NPP of the AXWs. For lighter weights, each axle has a different distribution. As the weights increase the distributions off all axles become similar particularly at the 90th and 95th percentiles.

Figure 6.3: BP 4-axle records AXW NPP

All statistical parameters discussed so far is summarized in Table 6.1 with the inclusion of other necessary information. This data was used to create the “trial model” cases accordingly to the adopted procedure for an actual truck configuration model development, explained in Chapter 3.

Table 6.1: BP 4-axle records weight statistics

	Axle				GVW
	1	2	3	4	
Min (kips)	7.00	7.00	3.50	3.50	40.00
Max (kips)	25.00	25.00	25.00	25.00	100.00
Mean (kips)	15.37	20.75	19.79	19.55	75.46
SD (kips)	5.29	3.86	3.44	3.84	12.24
Mode (kips)	11.52	24.48	18.00	18.00	72.00
90 th percentile (kips)	24.20	24.48	24.50	24.50	98.00
95 th percentile (kips)	24.50	24.50	25.00	25.00	98.00

The statistics on the distribution of GVW among the axles of the BP 4-axle records was also analyzed as it is required to formulate certain “trial model” cases. Table 6.2 displays the calculation results.

Table 6.2: BP 4-axle statistics on GVW division among axles

	Axle			
	1	2	3	4
Mean (%)	20.12	27.80	26.22	25.86
SD (%)	5.30	5.30	2.65	3.33
Mode (%)	16.00	34.00	25.00	25.00
Max (%)	50.51	56.82	36.00	36.00
Min (%)	14.00	14.00	7.95	7.95

Once all the necessary information was obtained, the “trial model” cases were selected as presented in Table 6.3. In cases where the division of GVW among the axles resulted in AXWs exceeding the limit imposed by the RI General Laws, the AXW was set at the maximum allowable value of 25 kips. This was done to develop a model that is both representative of the BP 4-axle database and of the restrictions imposed on such trucks.

Table 6.3: BP 4-axle AXWs of investigated cases

Case		AXW 1 (kips)	AXW 2 (kips)	AXW 3 (kips)	AXW 4 (kips)
1	a	19.60	25.00	25.00	25.00
	b	15.68	25.00	24.50	24.50
2	a	19.60	25.00	25.00	25.00
	b	15.68	25.00	24.50	24.50
3		24.20	24.48	24.50	24.50
4		24.50	24.50	25.00	25.00
5	a	20.00	25.00	25.00	25.00
	b	16.00	25.00	25.00	25.00
6		18.10	17.30	19.80	19.80

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 6.4-6.5. For all cases trucks having equally spaced axles of 33” had maximum percent exceeding values of zero or within the allowable range. However, such configuration was considered rare or might have a user input error. Therefore, it was not considered among the cases as a suitable configuration for the model. The next best configurations and their results are presented in the tables. Case 4 had the best performance with acceptable maximum percent exceeding values. Case 6, the existing model, had high maximum percent exceeding values and was no considered as one of the potential configurations for the proposed model.

Table 6.4: BP 4-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	13.40	8.11	18.10	17.74
	b	18.33	18.21	19.15	19.27
2	a	13.40	8.11	18.10	17.74
	b	18.33	18.21	19.15	19.27
3		2.35	1.65	10.11	14.34
4		1.18	1.65	2.00	5.76
5	a	13.40	8.34	13.40	13.40
	b	18.33	18.10	18.45	18.92
6		33.02	30.79	33.49	87.66

Table 6.5: BP 4-axle configuration of case results

Case		AXS 1 (ft)	AXS 2 (ft)	AXS 3 (ft)
1	a	10.00	3.67	3.67
	b	10.00	3.67	3.67
2	a	10.00	3.67	3.67
	b	10.00	3.67	3.67
3		10.00	3.67	3.67
4		15.00	4.00	4.58
5	a	13.50	4.50	4.17
	b	10.00	3.67	3.67
6		8.67	4.42	4.42

By evaluating the results, case 4 was selected as the proposed RI-BP4. All other cases did not generate a suitable configuration to envelope the load effects of the database. The existing model had the worst performance among all the cases. AXW1 and AXW2 of the proposed model was changed from 24.5 kips used in the case analysis to 25 kips. This alteration was made to enhance the performance of the model and also due to the proximity of the value to the maximum allowable BP AXW. Shown on Figure 6.4 is the proposed RI-BP4 model.

Figure 6.4: Proposed RI-BP4 model

Figure 6.5 displays the proposed model's percent exceeding plot. The proposed RI-BP4 model is exceeded by the database for all types of load effects, but within the tolerable percentage. For CSMomNeg, a maximum percent exceedance (5.76%) occurs at 49 ft. and then decreases (1.53%) and becomes uniform at 70 ft. The CSShear of the model envelopes the database up to 21 ft., then increases with a maximum exceedance of 1.99%. Then, the

percent exceedance decreases (1.53%) at 34 ft. and becomes uniform. The SSMomMid of the model envelopes the database up to 30 ft. and then increases reaching the maximum exceedance of 1.6% between 38-42 ft. Afterwards, the percent exceeding decreases to 1.53% at 44 ft. and becomes uniform. For SSShear the model also exceeds the database up to 22 ft. and then the percent exceedance increases (1.18%) and stays uniform.

Figure 6.5: Proposed RI-BP4 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 6.6-6.9. In shorter spans the proposed model generates ratios with low mean and mode values for simple span load effects and CSShear. However, as the span length increases so does the mean and mode values. For CSMomNeg, the statistical parameters of the ratios peak at short spans and then lowers before following the same pattern as the other load effects.

(a)

(b)

Figure 6.6: Proposed RI-BP4 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 6.7: Proposed RI-BP4 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 6.8: Proposed RI-BP4 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 6.9: Proposed RI-BP4 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-BP4 and the design LL model, HL-93, was conducted to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing model. Note that the load effects used to calculate the ratios are un-factored. Figure 6.10 displays the results of the ratio calculations summarized in Table 6.6. The proposed model exceeds the HL-93 in shorter spans for all load effects. For CCMomNeg and CSShear the proposed model exceeds the HL-93 up to approximately 42 ft. and 48 ft., respectively. Both SSMomMid and SSShear effects of the proposed model exceed the HL-93 up to approximately 70 ft. All load effect ratios decreases with an increase in span length.

Figure 6.10: Proposed RI-BP4 vs. HL-93

Table 6.6: Load effects model comparison ratio

Span Length (ft)	CSMomNeg	CSShear	SSMomMid	SSShear
20	1.27	1.30	1.15	1.15
21	1.28	1.29	1.16	1.16
22	1.30	1.27	1.16	1.16
23	1.31	1.25	1.16	1.16
24	1.33	1.24	1.16	1.16
25	1.34	1.22	1.16	1.17
26	1.35	1.21	1.16	1.17
27	1.36	1.20	1.15	1.18
28	1.37	1.18	1.15	1.18
29	1.39	1.17	1.15	1.18
30	1.40	1.16	1.15	1.17
32	1.38	1.14	1.14	1.16
34	1.30	1.12	1.13	1.16
36	1.22	1.10	1.13	1.15
38	1.15	1.08	1.12	1.14
40	1.08	1.06	1.13	1.13
42	1.02	1.05	1.14	1.13
44	0.99	1.03	1.13	1.12
46	0.94	1.02	1.12	1.11
48	0.89	1.00	1.11	1.10
50	0.84	0.99	1.10	1.09
52	0.80	0.97	1.10	1.09
54	0.75	0.96	1.09	1.08
56	0.72	0.95	1.08	1.07
58	0.69	0.93	1.07	1.07
60	0.66	0.92	1.06	1.06
70	0.57	0.79	1.02	1.02
80	0.53	0.70	0.99	0.99
90	0.50	0.63	0.96	0.96
100	0.49	0.58	0.93	0.93
120	0.45	0.51	0.88	0.88
140	0.42	0.47	0.83	0.83
160	0.40	0.43	0.79	0.79
180	0.38	0.40	0.75	0.75
200	0.36	0.38	0.71	0.72
250	0.31	0.33	0.64	0.65
300	0.28	0.29	0.58	0.58

6.2 Proposed RI-BP5

In the “Good Data” there were 611 records classified as BP 5-axle trucks. These records were further used to develop the RI-BP4 model and to evaluate its performance. Shown on Figure 6.11 is the distribution of GVW with a maximum of 125 kips, minimum of 105 kips, and mode of 110 kips. The database has a mean GVW of 111.64 kips and standard deviation of 4.93 kips.

Figure 6.11: BP 5-axle records GVW distribution

The yearly variation of GVW statistics of the BP 5-axle records is shown on Figure 6.12. From 2008 through 2011 the minimum GVW was 105 kips. The maximum GVW of 125 kips occurred in 2010 and 2011. Also, in 2010 the most common approved permit application GVW was also 125 kips.

Figure 6.12: BP 5-axis records yearly variation of GVW statistics

Shown on Figure 6.13 is the NPP of the AXWs. The rear axles, 2 through 5, have similar distributions, thus similar percentile values. At the higher AXWs the distribution of the first axle approaches those of the other axles.

Figure 6.13: BP 5-axis records AXW NPP

All statistical parameters discussed so far is summarized in Table 6.7 with the inclusion of other necessary information. This data was used to create the “trial model” cases accordingly to the adopted procedure for an actual truck configuration model development, explained in Chapter 3.

Table 6.7: BP 5-axle records weight statistics

	Axle					GVW
	1	2	3	4	5	
Min (kips)	8.00	20.23	18.77	20.00	20.00	105.00
Max (kips)	25.00	25.00	25.00	25.00	25.00	125.00
Mean (kips)	14.92	24.25	24.24	24.11	24.13	111.64
SD (kips)	4.89	0.81	0.92	0.96	0.94	4.93
Mode (kips)	12.00	24.50	24.50	24.50	24.50	110.00
90 th percentile (kips)	24.00	25.00	25.00	25.00	25.00	120.00
95 th percentile (kips)	25.00	25.00	25.00	25.00	25.00	125.00

The statistics on the distribution of GVW among the axles of the BP 5-axle records was also analyzed as it is required to formulate certain “trial model” cases. Table 6.8 displays the calculation results.

Table 6.8: BP 5-axle statistics on GVW division among axles

	Axle				
	1	2	3	4	5
Mean (%)	13.24	21.75	21.74	21.63	21.65
SD (%)	3.75	0.98	1.03	1.13	1.10
Mode (%)	10.91	22.27	22.27	22.27	22.27
Max (%)	20.58	23.15	23.15	23.81	23.81
Min (%)	7.52	19.21	17.82	18.52	18.52

Once all the necessary information was obtained, the “trial model” cases were selected as presented in Table 6.9. In cases where the division of GVW among the axles resulted in AXWs exceeding the limit imposed by the RI General Laws, the AXW was set at the maximum allowable value of 25 kips. This was done to develop a model that is both representative of the BP 5-axle database and of the restrictions imposed on such trucks.

Table 6.9: BP 5-axle AXWs of investigated cases

Case		AXW 1 (kips)	AXW 2 (kips)	AXW 3 (kips)	AXW 4 (kips)	AXW 5 (kips)
1	a	15.84	25.00	25.00	25.00	25.00
	b	13.08	25.00	25.00	25.00	25.00
2	a	16.50	25.00	25.00	25.00	25.00
	b	13.63	25.00	25.00	25.00	25.00
3		24.00	25.00	25.00	25.00	25.00
4		25.00	25.00	25.00	25.00	25.00
5	a	16.50	25.00	25.00	25.00	25.00
	b	13.63	25.00	25.00	25.00	25.00
6		-	-	-	-	-

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 6.10-6.11. For all cases a truck with an AXS3 of 30” outperformed the other configurations. However, the sum of AXS compared to the total length of the truck is very short making it one of the trucks considered rare or that might have a user input error. Therefore, it was not considered among the cases as a suitable configuration for the model. The next best configurations and their results are presented in the tables. Cases 3 and 4 resulted in the best performances with maximum percent exceeding values within the allowable range. All other cases have high maximum percent exceeding values particularly for CSMomNeg.

Table 6.10: BP 5-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	15.88	15.88	15.88	83.63
	b	18.82	18.82	18.82	86.42
2	a	14.24	14.24	15.88	81.51
	b	18.17	18.17	18.82	85.60
3		7.20	7.20	7.20	7.20
4		0.16	0.65	0.00	5.89
5	a	14.24	14.24	15.88	81.51
	b	18.17	18.17	18.82	85.60
6		-	-	-	-

Table 6.11: BP 5-axle configuration of case results

Case		AXS 1 (ft)	AXS 2 (ft)	AXS 3 (ft)	AXS 4 (ft)
1	a	4.50	5.42	8.50	5.00
	b	7.67	5.33	6.58	5.33
2	a	7.67	5.33	6.58	5.42
	b	7.67	5.33	6.58	5.42
3		4.50	5.42	8.50	5.00
4		4.50	5.42	8.50	5.00
5	a	7.67	5.33	6.58	5.42
	b	7.67	5.33	6.58	5.42
6		-	-	-	-

Case 4 resulted in the best performance and was selected as the proposed RI-BP5 model.

The AXWs all match the maximum permissible value of 25 kips, therefore, it also matches the maximum GVW of 125 kips. Figure 6.14 displays the proposed RI-BP5 configuration.

Figure 6.14: Proposed RI-BP5 model

Figure 6.15 displays the proposed model's percent exceeding plot. The proposed model's CSMomNeg is exceeded by the database for span lengths between 28-44 ft. with the maximum (5.89%) occurring at 36 ft. For CSShear the proposed model envelopes the database in all span lengths. The SSMomMid of the proposed model is exceeded by the database for all span lengths with the maximum (0.65%) occurring at 27 ft. before decreasing (0.16%) at 54 ft. and becoming uniform. For SSShear the proposed model is exceeded by the database for span lengths of 20-36 ft., reaching a maximum value of 0.16%.

Figure 6.15: Proposed RI-BP5 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 6.16-6.19. The simple span load effects and CSShear ratios mean and mode values start off high for short spans, then decreases before increasing with longer span lengths. For CSMomNeg, the statistical parameters of the ratios peak at short spans and then lowers before following the same pattern as the other load effects.

(a)

(b)

Figure 6.16: Proposed RI-BP5 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 6.17: Proposed RI-BP5 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 6.18: Proposed RI-BP5 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 6.19: Proposed RI-BP5 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-BP5 and the design LL model, HL-93, was conducted to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing model. Note that the load effects used to calculate the ratios are un-factored. Figure 6.20 displays the results of the ratio calculations summarized in Table 6.12. The proposed model exceeds the HL-93 in shorter span lengths for all load effects. For CCMomNeg and CSShear the proposed model exceeds the HL-93 up to approximately 50 ft. and 60 ft., respectively. Both SSMomMid and SSShear effects of the proposed model exceeds the HL-93 up to approximately 140 ft. All load effect ratios decrease with an increase in span length.

Figure 6.20: Proposed RI-BP5 vs. HL-93

Table 6.12: Load effects model comparison ratio

Span Length (ft)	CSMomNeg	CSShear	SSMomMid	SSShear
20	2.39	2.65	1.97	1.89
21	2.40	2.63	1.98	1.86
22	2.42	2.61	1.99	1.83
23	2.42	2.58	2.01	1.81
24	2.36	2.50	2.02	1.79
25	2.29	2.41	2.03	1.80
26	2.18	2.33	2.03	1.81
27	2.09	2.26	2.04	1.82
28	2.02	2.20	2.05	1.83
29	1.96	2.15	2.05	1.84
30	1.90	2.10	2.06	1.85
32	1.77	2.02	2.00	1.86
34	1.66	1.96	1.96	1.87
36	1.60	1.88	1.92	1.88
38	1.55	1.81	1.89	1.89
40	1.51	1.75	1.89	1.89
42	1.46	1.70	1.90	1.90
44	1.43	1.66	1.91	1.90
46	1.39	1.62	1.91	1.87
48	1.34	1.59	1.92	1.83
50	1.31	1.56	1.92	1.81
52	1.27	1.52	1.93	1.78
54	1.24	1.49	1.93	1.76
56	1.21	1.46	1.93	1.74
58	1.18	1.43	1.94	1.72
60	1.14	1.39	1.92	1.71
70	0.97	1.21	1.80	1.64
80	0.86	1.06	1.72	1.58
90	0.80	0.95	1.67	1.53
100	0.77	0.88	1.61	1.49
120	0.74	0.78	1.53	1.44
140	0.73	0.72	1.47	1.41
160	0.72	0.68	1.44	1.39
180	0.72	0.65	1.41	1.37
200	0.69	0.62	1.33	1.31
250	0.60	0.57	1.23	1.22
300	0.54	0.52	1.14	1.14

CHAPTER 7. OVERWEIGHT PERMIT LIVE LOAD MODELS

This chapter presents the development of OWP LL models. Currently, RI has three notional OWP models, namely 5-axle RI-OP1, 8-axle RI-OP2, and 13-axle RI-OP3. Each model was developed to envelope the load effects of OWP trucks having the same NAX or less: RI-OP1 for 2-5-axle, RI-OP2 for 6-8-axle, and RI-OP3 for 9-13-axle. By grouping the trucks based on the NAX limits the necessary amount of models to be sufficiently representative of the expected OWP trucks to travel across RI's bridges.

The records in the OWP database were grouped in the same manner as the existing model's intended purpose. However, due to the high number of 6-axle OWP records, a model for such truck type was developed based on an actual truck configuration. Therefore, a total of four models were developed: three notional (i.e. RI-OP5 for 2-5-axle, RI-OP8 for 7/8-axle, and RI-OP13 for 9-13-axle) and one actual truck configuration model (i.e. RI-OP6 for 6-axle).

7.1 Proposed RI-OP5

There were 3,319 records in the "Good Data" classified as OWP 2-5-axle. Of the 3,319 records there were no trucks with 2-axle, 126 3-axle, 597 4-axle, and 2,596 5-axle. These records were further used to develop the RI-OP5 and to evaluate its performance. Figure 7.1 demonstrates the distribution of GVW with a maximum of 150 kips, minimum of 54

kips, and mode of 120 kips. The database has a mean GVW of 116.98 kips and standard deviation of 8.98 kips. Table 7.1 summarizes the GVW statistics.

Figure 7.1: OWP 2-5-axle records GVW distribution

Table 7.1: OWP 2-5-axle records GVW statistics

	GVW
Min (kips)	54.00
Max (kips)	150.00
Mean (kips)	116.98
SD (kips)	8.98
Mode (kips)	120.00
90 th percentile (kips)	120.00
95 th percentile (kips)	128.89

The variation of the GVW statistics by year is shown on Figure 7.2. In 2013 the maximum GVW of 150 kips occurred and minimum of 54 kips in 2009.

Figure 7.2: OWP 2-5-axle records yearly variation of GVW statistics

Shown in Tables 7.2-7.3 is the summarized statistical parameters of the records weight. The data was compiled by separating the database by NAX. The latter was necessary to create the “trial model” cases accordingly to the adopted procedure for notional models, explained in Chapter 3.

Table 7.2: OWP 2-5-axle records weight statistics by NAX (Part 1 of 2)

Parameter		Max (kips)			Mean (kips)			SD (kips)		
NAX		3	4	5	3	4	5	3	4	5
Axle	1	32.00	37.50	29.00	28.96	24.41	13.10	1.66	3.75	3.73
	2	32.50	37.50	30.00	29.04	24.87	26.90	1.63	3.20	0.52
	3	32.50	42.00	30.00	29.04	29.22	26.89	1.67	3.09	0.59
	4	-	40.00	33.00	-	29.18	26.85	-	3.06	0.88
	5	-	-	33.00	-	-	26.84	-	-	0.95
GVW		96.00	150.00	135.00	87.05	107.68	120.57	4.80	9.07	2.59

Table 7.3: OWP 2-5-axle records weight statistics by NAX (Part 2 of 2)

Parameter		90 th percentile (kips)			95 th percentile (kips)		
NAX		3	4	5	3	4	5
Axle	1	31.00	29.30	12.00	31.20	29.45	25.57
	2	31.00	29.45	27.00	32.00	29.45	27.00
	3	31.00	32.50	27.00	32.00	33.00	27.00
	4	-	32.50	27.00	-	33.00	27.00
	5	-	-	27.00	-	-	27.00
GVW		93.00	120.00	120.00	93.60	124.90	130.00

The statistics on the distribution of GVW among the axles of the 5-axle records was also analyzed as it is required to formulate the “trial model” cases. Table 7.4 displays the calculation results.

Table 7.4: OWP 5-axle statistics on GVW division among axles

	Axle				
	1	2	3	4	5
Mean (%)	10.82	22.32	22.31	22.28	22.27
SD (%)	2.78	0.71	0.73	0.89	0.93
Mode (%)	10.00	22.50	22.50	22.50	22.50
Max (%)	23.81	28.57	28.57	25.47	25.47
Min (%)	9.84	15.79	16.92	9.52	9.52

Once all the necessary information was obtained, the “trial model” cases were selected as presented in Table 7.5. Case 4 AXW1 was modified to 22 kips from 25.57 kips to have the summation of AXWs be the same as the 95th percentile of the 5-axle records GVW.

Table 7.5: OWP 2-5-axle AXWs of investigated cases

Case		AXW 1 (kips)	AXW 2 (kips)	AXW 3 (kips)	AXW 4 (kips)	AXW 5 (kips)
1	a	12.99	26.78	26.77	26.73	26.72
	b	12.00	27.00	27.00	27.00	27.00
2	a	14.07	29.02	29.01	28.96	28.95
	b	13.00	29.25	29.25	29.25	29.25
3		12.00	27.00	27.00	27.00	27.00
4		22.00	27.00	27.00	27.00	27.00
5		13.00	25.00	25.00	25.00	25.00
6	a	12.99	26.78	26.77	26.73	26.72
	b	12.00	27.00	27.00	27.00	27.00
7	a	14.07	29.02	29.01	28.96	28.95
	b	13.00	29.25	29.25	29.25	29.25
8		22.00	27.00	27.00	27.00	27.00

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 7.6-7.7. A majority of the cases generated high maximum percent exceedance for CSMomNeg, while acceptable for CSShear and simple span load effects. Case 5, the existing RI-OP1, had the worst performance for all types of load effects. Changes to the existing model's AXWs to meet the characteristics of the database were insufficient to significantly improve its CSMomNeg performance, although the other load effects maximum percent exceeding values decreased within tolerable limits. Case 4 generated the best results, however, CSMomNeg was still above the acceptable range. Case 8 used the AXWs of case 4 and configuration as the starting point for the trial and error approach. An alteration to AXS2 was made by increasing its length making it the same as of the existing model. The increase in length was done to capture higher CSMomNeg influence ordinates in shorter span lengths. On the contrary, the other load effects would capture lower influence ordinates. However, a balance was obtained to have the allowable maximum percent exceedance for all load effects.

Table 7.6: OWP 2-5-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	8.62	8.29	8.41	77.43
	b	8.62	8.29	8.38	77.43
2	a	1.27	1.33	0.18	15.85
	b	1.24	1.27	0.18	17.14
3		8.62	8.29	8.38	77.43
4		3.68	3.53	0.18	13.59
5		15.61	14.31	82.13	81.80
6	a	10.27	8.56	8.50	77.95
	b	9.88	8.56	8.50	77.89
7	a	5.18	3.53	1.05	19.71
	b	4.49	3.50	1.05	20.10
8		4.04	3.89	1.11	6.27

Table 7.7: OWP 2-5-axle configuration of case results

Case		AXS 1 (ft)	AXS 2 (ft)	AXS 3 (ft)	AXS 4 (ft)
1	a	7.92	5.25	5.33	5.33
	b	7.92	5.25	5.33	5.33
2	a	7.92	5.25	5.33	5.33
	b	7.92	5.25	5.33	5.33
3		7.92	5.25	5.33	5.33
4		7.92	5.25	5.33	5.33
5		5.33	6.50	5.33	8.25
6	a	5.33	6.50	5.33	8.25
	b	5.33	6.50	5.33	8.25
7	a	5.33	6.50	5.33	8.25
	b	5.33	6.50	5.33	8.25
8		7.92	6.50	5.33	5.33

Case 8 had the best performance, therefore, it was selected as the proposed RI-OP5 model.

Figure 7.3 displays the model's configuration.

Figure 7.3: Proposed RI-OP5 model

Shown on Figure 7.4 is the proposed model's percent exceeding plot. The proposed RI-OP5 is exceeded in all types of load effects by the database, but within the tolerable range. For CSMomNeg, a maximum percent exceedance of 6.27% occurs at 36 ft., and at 80 ft. the exceedance becomes uniform with a value of 0.27%. The CSShear has the maximum exceedance at 24 ft. of 1.11%. As the span length increases, the CSShear exceedance becomes relatively uniform varying between 0.30% and 0.27%. The SSMomMid has a maximum exceedance of 3.89% at 24 ft., and becomes uniform at 120 ft. with a value of 0.27%. For SSShear the maximum exceedance of 4.04% occurs at 25 ft., and at 80 ft. the percent exceedance becomes relatively uniform varying between 0.42% and 0.27%.

Figure 7.4: Proposed RI-OP5 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 7.5-7.8. From the box plots, the distribution of ratios is observed to be mostly concentrated at higher values.

(a)

(b)

Figure 7.5: Proposed RI-OP5 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.6: Proposed RI-OP5 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.7: Proposed RI-OP5 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.8: Proposed RI-OP5 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-OP5 and the design LL model, HL-93, was conducted to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing model. Note that the load effects used to calculate the ratios are un-factored. Figure 7.9 displays the results of the ratio calculations summarized in Table 7.8. The proposed model exceeds the HL-93 up to approximately 52 ft. and 70 ft. for CSMomNeg and CSShear, respectively. For both SSMomMid and SSshear the proposed model exceeds HL-93 up to approximately 160 ft.

Figure 7.9: Proposed RI-OP5 vs. HL-93

Table 7.8: Load effects model comparison ratio

Span Length (ft)	CSMomNeg	CSShear	SSMomMid	SSShear
20	1.46	1.72	1.13	1.23
21	1.45	1.69	1.14	1.26
22	1.45	1.66	1.14	1.28
23	1.44	1.64	1.15	1.30
24	1.46	1.62	1.16	1.32
25	1.48	1.60	1.19	1.33
26	1.50	1.58	1.21	1.35
27	1.50	1.57	1.23	1.36
28	1.50	1.55	1.25	1.37
29	1.50	1.53	1.26	1.38
30	1.50	1.52	1.29	1.38
32	1.53	1.49	1.34	1.38
34	1.48	1.46	1.37	1.39
36	1.40	1.44	1.41	1.38
38	1.38	1.41	1.43	1.38
40	1.34	1.39	1.45	1.38
42	1.31	1.37	1.46	1.38
44	1.29	1.35	1.45	1.37
46	1.23	1.33	1.44	1.37
48	1.16	1.31	1.43	1.36
50	1.09	1.29	1.42	1.36
52	1.04	1.27	1.41	1.35
54	0.98	1.25	1.40	1.34
56	0.93	1.23	1.39	1.34
58	0.89	1.22	1.38	1.33
60	0.86	1.20	1.37	1.32
70	0.74	1.03	1.32	1.29
80	0.69	0.91	1.28	1.25
90	0.66	0.82	1.24	1.22
100	0.63	0.76	1.20	1.19
120	0.59	0.67	1.13	1.13
140	0.55	0.61	1.07	1.07
160	0.52	0.56	1.02	1.02
180	0.49	0.52	0.97	0.97
200	0.46	0.49	0.93	0.93
250	0.41	0.43	0.83	0.83
300	0.37	0.38	0.75	0.76

7.2 Proposed RI-OP6

In the “Good Data” there were 7,397 records classified as OWP 6-axle trucks. These records were further used to develop the RI-OP6 model and evaluate its performance. Shown on Figure 7.10 is the distribution of GVW with a maximum of 159 kips, minimum of 52.1 kips, and mode of 120 kips. The database has a mean GVW of 111.8 kips and standard deviation of 14.58 kips.

Figure 7.10: OWP 6-axle records GVW distribution

The yearly variation of GVW statistics of the OWP 6-axle records is shown on Figure 7.11. In 2008 and 2009 the maximum GVW of 159 kips occurred, and in 2013 the minimum of 52.1 kips.

Figure 7.11: OWP 6-axis records yearly variation of GVW statistics

Shown on Figure 7.12 is the NPP of the AXWs. Axle 2 and 3 have a nearly identical distribution. Also, axle 4 through 6 have a similar distribution, with axle 4 being slightly heavier.

Figure 7.12: OWP 6-axis records AXW NPP

All statistical parameters discussed so far is summarized in Table 7.9 with the inclusion of other necessary information. This data was used to create the “trial model” cases accordingly to the adopted procedure for an actual truck configuration model development, explained in Chapter 3.

Table 7.9: OWP 6-axle records weight statistics

	Axle						GVW
	1	2	3	4	5	6	
Min (kips)	5.00	6.67	3.50	0.10	3.00	3.00	52.10
Max (kips)	26.50	29.50	29.50	30.06	30.06	30.06	159.00
Mean (kips)	12.48	20.73	20.79	19.26	19.28	19.26	111.80
SD (kips)	1.61	3.33	3.29	3.12	3.15	3.19	14.58
Mode (kips)	12.00	23.00	23.00	18.00	18.00	18.00	120.00
90 th percentile (kips)	14.00	24.00	24.00	23.20	23.20	23.20	130.00
95 th percentile (kips)	15.00	27.00	27.00	23.60	23.60	23.60	130.00

The statistics on the distribution of GVW among the axles of the OWP 6-axle records was also analyzed as it is required to formulate certain “trial model” cases. Table 7.10 displays the calculation results. It can be seen that the sum of the mode distribution is above 100%. These percentages were still used although they increase the model’s GVW in comparison to the GVW used to calculate the AXW.

Table 7.10: OWP 6-axle statistics on GVW division among axles

	Axle					
	1	2	3	4	5	6
Mean (%)	11.31	18.55	18.58	17.18	17.20	17.18
SD (%)	1.78	1.93	1.71	1.25	1.24	1.32
Mode (%)	10.00	22.50	22.50	17.50	15.00	15.00
Max (%)	27.27	47.27	34.55	22.78	22.78	22.78
Min (%)	6.46	9.26	6.36	0.19	4.92	4.92

Once all the necessary information was obtained, the “trial model” cases were selected as presented in Table 7.11. Cases 1 and 2 are the same as the 90th and 95th GVW percentile are equal. The last two cases, 5 and 6, are not evaluated as there is no maximum limit for an OWP truck nor an existing model.

Table 7.11: OWP 6-axle AXWs of investigated cases

Case		AXW 1 (kips)	AXW 2 (kips)	AXW 3 (kips)	AXW 4 (kips)	AXS 5 (kips)	AXS 6 (kips)
1	a	14.70	24.12	24.15	22.33	22.36	22.33
	b	13.00	29.25	29.25	22.75	19.50	19.50
2	a	14.70	24.12	24.15	22.33	22.36	22.33
	b	13.00	29.25	29.25	22.75	19.50	19.50
3		14.00	24.00	24.00	23.20	23.20	23.20
4		15.00	27.00	27.00	23.60	23.60	23.60
5	a	-	-	-	-	-	-
	b	-	-	-	-	-	-
6		-	-	-	-	-	-

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 7.12-7.13. For all cases trucks with equally spaced axles at 33” and others with AXS ranging from 29” to 36” outperformed the other configurations. However, such trucks are considered rare or might have a user input error due to the low sum of AXS compared to the total truck length. Therefore, they were not considered among the cases as a suitable configuration for the model. The next best configurations and their results are presented in the tables. Cases 1b, 2b and 4 had the best performance with maximum percent exceeding values within the allowable range. The other cases have high maximum percent exceeding values for CSMomNeg.

Table 7.12: OWP 6-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	1.28	3.72	1.57	16.95
	b	2.12	0.54	1.00	8.10
2	a	1.28	3.72	1.57	16.95
	b	2.12	0.54	1.00	8.10
3		1.15	2.74	1.23	10.22
4		0.97	0.38	0.47	2.80
5	a	-	-	-	-
	b	-	-	-	-
6		-	-	-	-

Table 7.13: OWP 6-axle configuration of case results

Case		AXS 1 (ft)	AXS 2 (ft)	AXS 3 (ft)	AXS 4 (ft)	AXS 5 (ft)
1	a	18.67	31.17	4.50	4.50	4.50
	b	10.00	4.08	4.50	35.00	4.50
2	a	18.67	31.17	4.50	4.50	4.50
	b	10.00	4.08	4.50	35.00	4.50
3		12.00	36.00	4.58	4.58	4.58
4		10.00	4.08	4.50	32.00	4.50
5	a	-	-	-	-	-
	b	-	-	-	-	-
6		-	-	-	-	-

Cases 1b and 2b had satisfactory results with a GVW of 133.25 kips, not significantly deviating from the 130 kips of the 90th and 95th percentile. In contrary, case 4 performed better but had an excessive GVW of 139.8 kips. Therefore, cases 1b and 2b were selected as the proposed RI-OP6 due to the lower GVW similar to the characteristics of the database. Figure 7.13 displays the proposed model's configuration.

Figure 7.13: Proposed RI-OP6 model

Figure 7.14 displays the proposed model's percent exceeding plot. The maximum CSMomNeg exceedance of 8.10% occurs at 29 ft., and CSShear of 1.00% at 300 ft. For SSMomMid the maximum exceedance of 0.54% occurs at 300 ft., and SSShear of 2.12% at 100 ft.

Figure 7.14: Proposed RI-OP6 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 7.15-7.18. The ratio distributions for all span lengths are mostly concentrated at higher values, therefore, the model sufficiently but not excessively exceeds the load effects of the database.

(a)

(b)

Figure 7.15: Proposed RI-OP6 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.16: Proposed RI-OP6 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.17: Proposed RI-OP6 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.18: Proposed RI-OP6 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-OP6 and the design LL model, HL-93, was conducted to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing model. Note that the load effects used to calculate the ratios are un-factored. Figure 7.19 displays the results of the ratio calculations summarized in Table 7.14. The proposed model exceeds the HL-93 CSMomNeg up to approximately 56 ft., and CSShear up to 60 ft. For simple span load effects, the proposed model exceeds the HL-93 up to approximately 120 ft.

Figure 7.19: Proposed RI-OP6 vs. HL-93

Table 7.14: Load effects model comparison ratio

Span Length (ft)	CSMomNeg	CSShear	SSMomMid	SSShear
20	1.18	1.42	1.27	1.27
21	1.17	1.38	1.27	1.28
22	1.17	1.34	1.27	1.28
23	1.18	1.31	1.27	1.27
24	1.18	1.29	1.27	1.28
25	1.19	1.26	1.27	1.28
26	1.19	1.24	1.27	1.28
27	1.22	1.22	1.27	1.27
28	1.31	1.20	1.26	1.26
29	1.40	1.18	1.27	1.25
30	1.48	1.17	1.27	1.24
32	1.60	1.14	1.28	1.22
34	1.63	1.11	1.28	1.20
36	1.62	1.08	1.28	1.19
38	1.60	1.09	1.28	1.17
40	1.56	1.10	1.28	1.16
42	1.52	1.11	1.28	1.14
44	1.48	1.11	1.25	1.13
46	1.40	1.12	1.23	1.12
48	1.30	1.12	1.21	1.11
50	1.23	1.12	1.19	1.10
52	1.15	1.11	1.17	1.09
54	1.08	1.11	1.16	1.09
56	1.01	1.10	1.14	1.09
58	0.96	1.10	1.13	1.09
60	0.91	1.09	1.11	1.09
70	0.72	0.97	1.05	1.08
80	0.63	0.87	1.03	1.07
90	0.58	0.80	1.03	1.05
100	0.57	0.74	1.02	1.04
120	0.55	0.66	1.00	1.02
140	0.53	0.61	0.97	0.99
160	0.51	0.56	0.94	0.95
180	0.48	0.53	0.91	0.92
200	0.46	0.50	0.87	0.88
250	0.41	0.43	0.80	0.81
300	0.37	0.39	0.73	0.74

7.3 Proposed RI-OP8

Of the 4,148 records in the “Good Data” classified as OWP 7/8-axle, 2,640 have 7-axle and 1,508 have 8-axle. These records were further used to develop the RI-OP8 and to evaluate its performance. Figure 7.20 demonstrates the distribution of GVW with a maximum of 193 kips, minimum of 54.9 kips, and mode of 130 kips. The database has a mean GVW of 135.25 kips and standard deviation of 19.12 kips. Table 7.15 summarizes the GVW statistics.

Figure 7.20: OWP 7/8-axle records GVW distribution

Table 7.15: OWP 7/8-axle records GVW statistics

	GVW
Min (kips)	54.90
Max (kips)	193.00
Mean (kips)	135.25
SD (kips)	19.12
Mode (kips)	130.00
90 th percentile (kips)	160.00
95 th percentile (kips)	160.00

The variation of GVW statistics by year is shown on Figure 7.21. In 2009 the maximum GVW of 193 kips occurred and the minimum of 54.9 kips in 2011.

Figure 7.21: OWP 7/8-axle records yearly variation of GVW statistics

Shown in Tables 7.16-7.17 is the summarized statistical parameters of the records weight. The data was compiled by separating the database by NAX. The latter was necessary to create the “trial model” cases accordingly to the adopted procedure for notional models, explained in Chapter 3.

Table 7.16: OWP 7/8-axle records weight statistics by NAX (Part 1 of 2)

Parameter		Max (kips)		Mean (kips)		SD (kips)	
NAX		7	8	7	8	7	8
Axle	1	22.75	20.00	12.95	13.96	2.02	2.17
	2	27.00	25.00	18.41	18.95	2.89	2.80
	3	28.00	25.00	19.57	20.65	2.79	2.53
	4	28.00	25.00	19.33	19.72	2.95	2.98
	5	26.00	26.50	19.25	18.77	2.84	2.90
	6	26.00	26.50	19.23	18.76	2.87	2.88
	7	25.92	26.40	19.15	18.71	2.90	2.95
	8	-	26.00	-	18.63	-	2.93
GVW		168.00	193.00	127.88	148.16	15.33	18.24

Table 7.17: OWP 7/8-axle records weight statistics by NAX (Part 2 of 2)

Parameter		90 th percentile (kips)		95 th percentile (kips)	
NAX		7	8	7	8
Axle	1	15.00	16.00	17.00	20.00
	2	22.00	22.00	22.00	23.50
	3	22.33	23.00	23.00	24.00
	4	22.60	23.00	23.00	24.00
	5	22.00	22.00	24.00	22.03
	6	22.00	21.75	24.00	22.00
	7	22.00	21.75	24.00	22.00
	8	-	21.33	-	22.00
GVW		140.00	160.00	150.00	170.00

The statistics on the distribution of GVW among the axles of the 8-axle records was also analyzed as it is required to formulate the “trial model” cases. Table 7.18 displays the calculation results.

Table 7.18: OWP 8-axle statistics on GVW division among axles

	Axle							
	1	2	3	4	5	6	7	8
Mean (%)	9.50	12.87	14.01	13.28	12.62	12.61	12.58	12.52
SD (%)	1.49	1.81	1.53	1.14	0.83	0.80	0.91	0.90
Mode (%)	9.30	12.99	14.29	12.69	12.69	12.69	12.69	12.69
Max (%)	21.86	41.89	27.50	19.17	16.24	15.39	15.39	15.39
Min (%)	6.25	5.52	6.04	5.92	5.92	5.92	5.48	5.48

Once all the necessary information was obtained, the “trial model” cases were selected as presented in Table 7.19.

Table 7.19: OWP 7/8-axle AXWs of investigated cases

Case		AXW 1 (kips)	AXW 2 (kips)	AXW 3 (kips)	AXW 4 (kips)	AXW 5 (kips)	AXW 6 (kips)	AXW 7 (kips)	AXW 8 (kips)
1	a	15.20	20.64	22.40	21.28	20.16	20.16	20.16	20.00
	b	14.90	20.80	22.90	20.30	20.30	20.30	20.30	20.30
2	a	16.15	21.93	23.80	22.61	21.42	21.42	21.42	21.25
	b	15.80	22.10	24.30	21.60	21.60	21.60	21.60	21.60
3		16.00	22.00	23.00	23.00	22.00	21.75	21.75	21.33
4		20.00	23.50	24.00	24.00	22.03	22.00	22.00	22.00
5		13.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
6	a	15.20	20.64	22.40	21.28	20.16	20.16	20.16	20.00
	b	14.90	20.80	22.90	20.30	20.30	20.30	20.30	20.30
7	a	16.15	21.93	23.80	22.61	21.42	21.42	21.42	21.25
	b	15.80	22.10	24.30	21.60	21.60	21.60	21.60	21.60
8		15.80	22.60	22.60	22.60	21.60	21.60	21.60	21.60

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 7.20-7.21. For all cases trucks having equally spaced axles of 33” and others with a short AXS of 29” outperformed the remaining configurations. However, the sum of AXS compared to the total length of these trucks is very short having characteristics of a rare truck or with a possible user input error. Therefore, these trucks were not considered among the cases as a suitable configuration for the model. The next best configurations and their results are presented in the tables. The best case was 4 having the lowest maximum percent exceedance for all load effects, followed by cases 3 and 2a. Case 5, the existing RI-OP2, does not perform well with SSMomMid and CSMomNeg exceeding the allowable maximum percentage. As shown in case 7b, the existing model with the updated AXWs based on the characteristics of the database improved its performance. Case 8 utilizes case 7b but with altered AXW2 through AXW4 by making them equivalent. The average of the three AXWs was taken as the new value for each. This modification improved slightly the CSMomNeg maximum percent exceeding.

Table 7.20: OWP 7/8-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	3.33	4.34	4.15	17.67
	b	2.97	4.34	4.17	17.67
2	a	1.78	4.39	1.90	5.18
	b	1.74	2.15	2.29	7.30
3		1.74	1.88	1.90	5.98
4		1.49	1.47	1.62	4.65
5		8.03	11.91	9.40	32.02
6	a	14.22	20.18	14.88	16.54
	b	13.43	18.32	14.54	16.64
7	a	6.58	7.14	7.67	8.22
	b	5.98	6.75	7.26	7.74
8		5.98	6.75	7.26	7.64

Table 7.21: OWP 7/8-axle configuration of case results

Case		AXS 1 (ft)	AXS 2 (ft)	AXS 3 (ft)	AXS 4 (ft)	AXS 5 (ft)	AXS 6 (ft)	AXS 7 (ft)
1	a	11.17	4.50	38.00	4.25	4.08	4.08	4.08
	b	11.17	4.50	38.00	4.25	4.08	4.08	4.08
2	a	11.17	4.50	38.00	4.25	4.08	4.08	4.08
	b	11.17	4.50	38.00	4.25	4.08	4.08	4.08
3		11.17	4.50	38.00	4.25	4.08	4.08	4.08
4		11.17	4.50	38.00	4.25	4.08	4.08	4.08
5		15.67	4.33	4.42	35.00	4.25	4.25	4.25
6	a	15.67	4.33	4.42	35.00	4.25	4.25	4.25
	b	15.67	4.33	4.42	35.00	4.25	4.25	4.25
7	a	15.67	4.33	4.42	35.00	4.25	4.25	4.25
	b	15.67	4.33	4.42	35.00	4.25	4.25	4.25
8		15.67	4.33	4.42	35.00	4.25	4.25	4.25

Although cases 3 and 4 had the overall best performance they were disregarded due to the high GVW of 171.25 kips and 179.53 kips, respectively, well above the 90th and 95th percentile of the database GVW. Case 8 was selected over these cases given the current use of the configuration in permit application evaluation and the updated AXWs resulted in a satisfactory performance. Figure 7.22 displays the model's configuration.

Figure 7.22: Proposed RI-OP8 model

Shown on Figure 7.23 is the proposed model's percent exceeding plot. The proposed RI-OP8 is exceeded in all types of load effects by the database, but within the tolerable percentage. For CSMomNeg the maximum exceedance of 7.64% occurs at 29 ft. and CSShear of 7.26% at 38 ft. The maximum exceedance of 6.75% for SSMomMid occurs at 80 ft. and SSShear of 5.98% at 48 ft.

Figure 7.23: Proposed RI-OP8 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 7.24-7.27. The ratio distributions for all load effects and span lengths are mostly concentrated at high values.

(a)

(b)

Figure 7.24: Proposed RI-OP8 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.25: Proposed RI-OP8 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.26: Proposed RI-OP8 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.27: Proposed RI-OP8 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-OP8 and the design LL model, HL-93, was conducted to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing model. Note that the load effects used to calculate the ratios are un-factored. Figure 7.28 displays the results of the ratio calculations summarized in Table 7.22. The proposed model exceeds the HL-93 up to approximately 60 ft. for CSMomNeg. At two different interval of up to approximately 36 ft., and between 42 ft. to 70 ft. the proposed model exceeds the HL-93 for CSShear. Similarly, the proposed model exceeds the HL-93 for SSMomMid at two different intervals of up to 60 ft., and between 140 ft. to 180 ft. The HL-93 only exceeds the model for SSShear at span lengths greater than 200 ft.

Figure 7.28: Proposed RI-OP8 vs. HL-93

Table 7.22: Load effects model comparison ratio

Span Length (ft)	CSMomNeg	CSShear	SSMomMid	SSShear
20	1.03	1.34	1.07	1.15
21	1.05	1.30	1.09	1.16
22	1.07	1.26	1.11	1.17
23	1.09	1.23	1.12	1.18
24	1.10	1.20	1.13	1.19
25	1.12	1.18	1.14	1.19
26	1.13	1.16	1.15	1.18
27	1.15	1.14	1.16	1.18
28	1.16	1.12	1.16	1.17
29	1.21	1.10	1.17	1.16
30	1.32	1.08	1.17	1.15
32	1.55	1.05	1.18	1.13
34	1.66	1.03	1.18	1.11
36	1.71	1.00	1.18	1.10
38	1.73	0.98	1.18	1.08
40	1.72	0.99	1.18	1.07
42	1.70	1.00	1.17	1.06
44	1.70	1.02	1.15	1.04
46	1.64	1.04	1.13	1.03
48	1.56	1.06	1.11	1.02
50	1.49	1.08	1.09	1.02
52	1.42	1.09	1.08	1.03
54	1.34	1.10	1.06	1.04
56	1.27	1.11	1.05	1.05
58	1.22	1.11	1.03	1.06
60	1.16	1.12	1.02	1.08
70	0.96	1.06	0.97	1.13
80	0.84	0.99	0.93	1.17
90	0.77	0.92	0.94	1.20
100	0.70	0.88	0.97	1.21
120	0.60	0.80	1.00	1.21
140	0.60	0.75	1.02	1.18
160	0.59	0.70	1.02	1.15
180	0.57	0.66	1.00	1.12
200	0.55	0.62	0.98	1.08
250	0.50	0.55	0.93	1.00
300	0.46	0.49	0.87	0.92

7.4 Proposed RI-OP13

There were 645 records in the “Good Data” classified as OWP 9-13-axle. The OWP 9-13-axle database is composed of 203 9-axle, 278 10-axle, 62 11-axle, 50 12-axle, and 52 13-axle records. These records were further used to develop the RI-OP13 and to evaluate its performance. Figure 7.29 demonstrates the distribution of GVW with a maximum of 360.3 kips, minimum of 68 kips, and mode of 199 kips. The database has a mean GVW of 167.56 kips and standard deviation of 35.98 kips. Table 7.23 summarizes the GVW statistics.

Figure 7.29: OWP 9-13-axle records GVW distribution

Table 7.23: OWP 9-13-axle records GVW statistics

	GVW
Min (kips)	68
Max (kips)	360.3
Mean (kips)	167.6
SD (kips)	35.98
Mode (kips)	199
90 th percentile (kips)	199
95 th percentile (kips)	199.9

The variation of the GVW statistics by year is shown on Figure 7.30. In 2013 the maximum GVW of 360.3 kips occurred and the minimum of 68 kips in 2009.

Figure 7.30: OWP 9-13-axle records yearly variation of GVW statistics

Shown in Tables 7.24-7.26 is the summarized statistical parameters of the records weight. The data was compiled by separating the database by NAX. The latter was necessary to create the “trial model” cases accordingly to the adopted procedure for notional models, explained in Chapter 3.

Table 7.24: OWP 9-13-axle records weight statistics by NAX (Part 1 of 3)

Parameter		Max (kips)					Mean (kips)				
NAX		9	10	11	12	13	9	10	11	12	13
Axle	1	18.0	18.0	18.0	30.0	14.0	13.2	12.8	12.9	13.1	11.9
	2	25.5	25.0	21.0	30.0	18.6	18.2	18.5	16.1	14.8	14.9
	3	25.5	25.0	21.0	30.0	22.0	18.9	19.0	16.3	14.8	16.3
	4	25.0	25.0	37.1	30.0	22.0	17.7	18.4	16.6	14.7	16.0
	5	23.3	23.0	37.1	30.0	20.0	15.6	16.6	17.6	15.0	15.7
	6	23.8	23.0	37.1	30.0	20.0	15.5	16.4	17.5	15.0	15.7
	7	23.8	23.0	37.1	30.0	20.5	15.3	17.3	17.1	14.9	16.5
	8	23.3	23.0	37.1	30.0	20.5	15.6	17.3	18.4	15.5	15.3
	9	23.3	23.0	37.1	30.0	20.6	15.6	17.4	18.3	15.5	15.5
	10	-	23.0	37.1	30.0	18.5	-	17.3	18.5	15.5	15.1
	11	-	-	37.1	30.0	19.0	-	-	18.5	16.0	15.2
	12	-	-	-	30.0	19.8	-	-	-	16.0	15.3
	13	-	-	-	-	19.5	-	-	-	-	15.0
GVW		199.9	199.8	353.3	360.3	235.0	145.7	170.9	187.6	180.9	198.5

Table 7.25: OWP 9-13-axle records weight statistics by NAX (Part 2 of 3)

Parameter		SD (kips)				
NAX		9	10	11	12	13
Axle	1	1.8	1.5	2.3	2.9	1.1
	2	4.3	3.1	2.4	4.6	3.0
	3	4.6	3.0	2.3	4.6	2.2
	4	5.3	4.4	4.3	3.6	2.6
	5	3.8	4.0	4.7	3.7	2.3
	6	4.5	4.0	4.8	3.7	2.4
	7	5.0	4.5	4.6	3.7	2.2
	8	4.6	4.5	4.9	3.9	1.9
	9	4.6	4.5	5.0	3.9	2.2
	10	-	4.5	5.0	3.9	1.6
	11	-	-	5.0	4.1	1.8
	12	-	-	-	4.1	2.1
	13	-	-	-	-	1.8
GVW		31.8	30.3	39.5	41.9	14.2

Table 7.26: OWP 9-13-axle records weight statistics by NAX (Part 3 of 3)

Parameter		90 th percentile (kips)					95 th percentile (kips)				
NAX		9	10	11	12	13	9	10	11	12	13
Axle	1	16.0	14.0	16.0	14.9	13.3	16.0	16.0	16.0	15.0	14.0
	2	23.1	22.0	18.6	22.0	18.0	24.4	23.0	20.1	22.5	18.5
	3	24.5	23.5	19.5	22.0	18.6	25.0	24.0	20.1	22.5	22.0
	4	24.5	23.5	18.4	18.0	18.6	24.7	24.0	20.0	20.0	22.0
	5	20.0	20.0	20.3	19.2	18.7	20.7	21.0	21.4	20.0	20.0
	6	20.6	20.0	20.3	19.2	18.7	22.5	20.7	21.4	20.0	20.0
	7	20.6	22.3	20.0	19.2	20.0	22.5	22.5	20.0	20.0	20.0
	8	20.1	22.5	25.0	20.0	18.2	22.5	22.5	25.0	20.0	18.5
	9	20.0	22.5	25.0	20.0	19.0	22.5	22.5	25.0	20.0	19.0
	10	-	22.5	25.0	19.3	17.3	-	22.5	25.0	20.0	18.3
	11	-	-	25.0	20.0	18.3	-	-	25.0	20.0	18.5
	12	-	-	-	20.0	18.9	-	-	-	20.0	18.9
	13	-	-	-	-	18.3	-	-	-	-	18.5
GVW		177.0	197.5	202.4	200.0	219.8	182.2	198.3	218.0	217.0	224.8

The statistics on the distribution of GVW among the axles of the 13-axle records was also analyzed as it is required to formulate the “trial model” cases. Table 7.27 displays the calculation results.

Table 7.27: OWP 13-axle statistics on GVW division among axles

Parameter		Mean (%)	SD (%)	Mode (%)	Max (%)	Min (%)
Axle	1	6.0	0.6	6.1	7.5	4.8
	2	7.5	1.4	8.7	9.2	4.1
	3	8.2	1.0	8.7	11.1	6.9
	4	8.1	1.2	8.7	11.1	5.9
	5	7.9	1.1	8.4	10.1	5.7
	6	7.9	1.1	8.4	10.1	5.5
	7	8.3	0.9	8.4	10.1	6.3
	8	7.7	0.8	7.1	9.4	6.3
	9	7.8	0.9	7.1	9.5	6.0
	10	7.6	0.6	7.1	8.8	6.3
	11	7.7	0.6	7.1	9.0	6.5
	12	7.7	0.8	7.1	9.5	6.0
	13	7.6	0.6	7.1	8.9	6.0

Once all the necessary information was obtained, the “trial model” cases were selected as presented in Table 7.28.

Table 7.28: OWP 9-13-axle AXWs of investigated cases

Case		AXW (kips)												
		1	2	3	4	5	6	7	8	9	10	11	12	13
1	a	13.2	16.5	18.1	17.8	17.4	17.3	18.3	17.0	17.2	1.7	16.8	16.9	16.6
	b	13.4	19.0	19.0	19.0	18.5	18.5	18.5	15.7	15.7	15.7	15.7	15.7	15.7
2	a	13.5	16.8	18.5	18.2	17.8	17.7	18.7	17.3	17.6	17.1	17.2	17.3	17.0
	b	13.7	19.4	19.4	19.4	18.9	18.9	18.9	16.0	1.0	16.0	16.0	16.0	16.0
3		13.3	18.0	18.6	18.6	18.7	18.7	20	18.2	19.0	17.3	18.3	18.9	18.3
4		14.0	18.5	22.0	22.0	20.0	20.0	20.0	18.5	19.0	18.3	18.5	18.9	18.5
5		9.0	15.0	17.0	17.0	17.0	17.0	14.0	20.0	20.0	20.0	20.0	20.0	20.0
6	a	13.2	16.5	18.1	17.8	17.4	17.3	18.3	17.0	17.2	1.7	16.8	16.9	16.6
	b	13.4	19.0	19.0	19.0	18.5	18.5	18.5	15.7	15.7	15.7	15.7	15.7	15.7
7	a	13.5	16.8	18.5	18.2	17.8	17.7	18.7	17.3	17.6	17.1	17.2	17.3	17.0
	b	13.7	19.4	19.4	19.4	18.9	18.9	18.9	16.0	1.0	16.0	16.0	16.0	16.0
8		9.0	15.0	17.0	17.0	17.0	17.0	14.0	22.5	22.5	22.5	18.3	18.9	18.3

The maximum percent exceeding for each load effect and the corresponding configuration for all analyzed cases are shown in Tables 7.29-7.30. In all analyzed cases, the maximum percent exceeding for all types of load effects were above the acceptable value. The best performance was by case 5, the existing RI-OP3 model. Therefore, the model was used in case 8 as the starting point for the necessary modifications to enhance its performance. To capture higher influence ordinates with higher AXWs, the last two groups of rear axles were altered by exchanging AXS11 with AXS12. As a result, axle 8 through 11 are evenly spaced at 4’-4” and AXS10 becomes 10’-6”. Lastly, AXWs 8 through 10 were changed to the 90th percentile of the OWP 10-axle records, and AXWs 11 through 13 to correspond to the 90th percentile of the OWP 13-axle records. These adjustments improved all types of load effects maximum percent exceeding.

Table 7.29: OWP 9-13-axle model development case results

Case		Max SSShear % Exceeding	Max SSMomMid % Exceeding	Max CSShear % Exceeding	Max CSMomNeg % Exceeding
1	a	52.56	56.43	43.57	44.50
	b	50.70	48.06	48.68	35.81
2	a	33.33	51.32	42.95	57.05
	b	42.02	44.03	43.88	28.22
3		34.26	43.10	30.70	38.76
4		32.093	33.18	32.87	6.20
5		32.25	34.88	15.97	15.35
6	a	64.50	64.81	37.52	12.56
	b	49.46	50.85	52.09	13.18
7	a	59.07	60.78	32.25	11.32
	b	44.34	45.74	46.05	11.78
8		5.58	4.96	2.17	6.05

Table 7.30: OWP 9-13-axle configuration of case results

Case		AXS (ft)											
		1	2	3	4	5	6	7	8	9	10	11	12
1	a	18.75	4.00	31.00	4.00	4.00	51.50	5.00	5.00	5.00	14.00	5.00	5.00
	b	10.00	4.08	4.50	15.75	5.00	5.00	39.67	5.00	5.00	14.08	5.00	5.00
2	a	13.33	4.50	4.50	16.50	4.08	4.08	68.00	4.08	4.08	6.33	4.08	4.08
	b	10.00	4.08	4.50	15.75	5.00	5.00	39.67	5.00	5.00	14.08	5.00	5.00
3		18.75	4.00	31.00	4.00	4.00	51.50	5.00	5.00	5.00	14.00	5.00	5.00
4		20.00	4.42	4.42	14.42	5.00	5.00	26.33	5.00	5.00	15.00	5.00	5.00
5		11.75	4.25	4.50	15.00	4.00	5.58	36.00	4.33	4.33	10.50	4.33	4.33
6	a	11.75	4.25	4.50	15.00	4.00	5.58	36.00	4.33	4.33	10.50	4.33	4.33
	b	11.75	4.25	4.50	15.00	4.00	5.58	36.00	4.33	4.33	10.50	4.33	4.33
7	a	11.75	4.25	4.50	15.00	4.00	5.58	36.00	4.33	4.33	10.50	4.33	4.33
	b	11.75	4.25	4.50	15.00	4.00	5.58	36.00	4.33	4.33	10.50	4.33	4.33
8		11.75	4.25	4.50	15.00	4.00	5.58	36.00	4.33	4.33	4.33	10.50	4.33

Based on the performance of case 8, it was selected as the proposed RI-OP13 model.

Figure 7.31 displays the model's configuration.

Figure 7.31: Proposed RI-OP13 model

Figure 7.32 shows the model's percent exceeding plot. The proposed RI-OP13 is exceeded in all types of load effects by the database, but within the tolerable percentage. For CSMomNeg the maximum exceedance of 6.05% occurs in the interval of 140-160 ft., and CSShear of 2.17% at 20 ft. The maximum exceedance of 5.58% for SSMomMid occurs at 23 ft. and SSShear of 4.96% in the interval of 22-24 ft.

Figure 7.32: Proposed RI-OP13 percent exceeding plot

The distribution of ratios displayed as box plots and the statistical parameters for all span lengths are shown on Figures 7.33-7.36. From the box plots, the distribution of ratios is observed to be mostly concentrated at higher values.

(a)

(b)

Figure 7.33: Proposed RI-OP13 SSMomMid: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.34: Proposed RI-OP13 SSShear: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.35: Proposed RI-OP13 CSMomNeg: (a) Distribution and (b) statistics of ratios

(a)

(b)

Figure 7.36: Proposed RI-OP13 CSShear: (a) Distribution and (b) statistics of ratios

A comparison of the proposed RI-OP13 and the design LL model, HL-93, was conducted to evaluate which span lengths each model controls. Ratios were calculated by dividing the proposed model's load effects by those of the existing model. Note that the load effects used to calculate the ratios are un-factored. Figure 7.37 displays the results of the ratio calculations summarized in Table 7.31. The simple span load effects of the proposed model exceeds the HL-93 for all span lengths. For CSMomNeg the proposed model exceeds the HL-93 up to approximately 100 ft. The CSShear effect of the proposed model envelopes the HL-93 up to approximately 120 ft.

Figure 7.37: Proposed RI-OP13 vs. HL-93

Table 7.31: Load effects model comparison ratio

Span Length (ft)	CSMomNeg	CSShear	SSMomMid	SSShear
20	1.40	1.48	1.09	1.15
21	1.42	1.47	1.10	1.17
22	1.43	1.46	1.12	1.18
23	1.46	1.45	1.13	1.18
24	1.51	1.44	1.14	1.20
25	1.54	1.43	1.15	1.22
26	1.57	1.42	1.16	1.22
27	1.59	1.41	1.16	1.22
28	1.60	1.40	1.17	1.23
29	1.63	1.39	1.17	1.24
30	1.65	1.38	1.18	1.24
32	1.66	1.36	1.18	1.25
34	1.55	1.34	1.21	1.26
36	1.44	1.32	1.22	1.26
38	1.46	1.30	1.24	1.26
40	1.49	1.29	1.26	1.26
42	1.51	1.27	1.28	1.26
44	1.53	1.25	1.28	1.26
46	1.50	1.23	1.27	1.26
48	1.46	1.23	1.27	1.26
50	1.44	1.24	1.26	1.25
52	1.41	1.25	1.26	1.25
54	1.39	1.26	1.25	1.24
56	1.36	1.26	1.25	1.24
58	1.34	1.27	1.24	1.23
60	1.31	1.27	1.23	1.23
70	1.21	1.20	1.20	1.20
80	1.15	1.15	1.17	1.18
90	1.09	1.12	1.14	1.21
100	1.03	1.08	1.13	1.25
120	0.90	1.02	1.14	1.33
140	0.79	0.96	1.15	1.36
160	0.71	0.91	1.18	1.36
180	0.71	0.86	1.19	1.34
200	0.70	0.82	1.19	1.32
250	0.65	0.73	1.15	1.24
300	0.60	0.65	1.09	1.16

CHAPTER 8. CONCLUSIONS

This study had the purpose of validating the OWP LL models currently used by RI's transportation agencies to assist in reviewing permit applications. Furthermore, this study also sought out to develop state-specific legal LL models representative of such defined in the RI General Laws. The study was accomplished by utilizing a database of approved single-trip permit applications by RIDMV and RIDOT expanding from April 2008 through June 2013. Incorporating the state's truck traffic characteristics in the LL models promotes more reliable bridges by protecting their structural integrity and reduces the potential of expenditures in repairs or replacements.

The proposed RI-3 and RI-5 legal LL models are shown on Figure 8.1. These models are based on an actual truck configuration beneficial in the legal rating of bridges to identify the maximum permissible load. The existing BP models resembling the characteristics of legal trucks were analyzed as potential legal models. As a result, the proposed RI-3 is the same RI-BP1 as it sufficiently envelopes the load effects of the legal 3-axle database. However, the RI-BP3 did not perform well for the legal 5-axle database. Therefore, the proposed RI-5 was developed using the characteristics of the database. Further research of state-specific legal LL models is encouraged with the application of weight-in-motion (WIM) sensors, an automated data collection system embedded in the road surface. Data collected by WIM includes AXWs and configuration at normal highway traffic speeds. In this manner, a broader understanding of the truck traffic is possible compared to the utilized database of permit applications. The protocols developed by Sivakumar et al. (2011) along

with the WIM data can be used to develop statistical models for a return period of 2-years, the interval between routine bridge inspections.

Figure 8.1: Proposed RI legal models

Figures 8.2-8.3 shows the proposed BP and OWP LL models. All models currently used for permitting decisions were unsatisfactory to envelope the load effects of the database of truck types each model represented. Therefore, new models are proposed with changes to configuration and AXWs. There were insufficient records for the development of 2- and 3-axle BP models. A new OWP 6-axle model was also developed given the high number of permit applications for such trucks. Continuing research on the validation of BP and OWP LL models is recommended due to possible changes in the characteristics of the permit applications.

Figure 8.2: Proposed RI BP models

Figure 8.3: Proposed RI OWP models

CHAPTER 9. REFERENCES

- Barker, R., & Puckett, J. (2013). Loads. In *Design of highway bridges: An LRFD approach* (Third ed., pp. 81-106). Hoboken, New Jersey: Wiley.
- Moses, F. (2001). Calibration of Load Factors for LRFR Bridge Evaluation. *NCHRP, Report 454*.
- Bell, E., Lefebvre, P., Sanayei, M., Brenner, B., Sipple, J., & Peddle, J. (2013). Objective Load Rating of a Steel-Girder Bridge Using Structural Modeling and Health Monitoring. *Journal of Structural Engineering*, 139(10), 1771-1779.
- Bhattacharya, B., Li, D., Chajes, M., & Hastings, J. (2005). Reliability-Based Load and Resistance Factor Rating Using In-Service Data. *Journal of Bridge Engineering*, 10(5), 530-543.
- Bridge Formula Weights. (2015, May 28). Retrieved September 21, 2015, from http://ops.fhwa.dot.gov/Freight/publications/brdg_frm_wgths/index.htm
- Bridges & Structures. (2014, December). Retrieved November 24, 2015, from <https://www.fhwa.dot.gov/bridge/nbi/no10/defbr14.cfm>
- Federal-Aid Highway Act of 1956, Pub. L. No. 627, § 108, 70 Stat. (1956)

Federal-Aid Highway Amendments of 1974, Pub. L. No. 93-643, §106, 88 Stat. (1975)

Ghosn, M., Sivakumar, B., & Miao, F. (2013). Development of State-Specific Load and Resistance Factor Rating Method. *Journal of Bridge Engineering*, 18(5), 351-361.

Hayworth, R., Huo, X., & Zheng, L. (2008). Effects of State Legal Loads on Bridge Rating Results Using the LRFR Procedure. *Journal of Bridge Engineering*, 13(6), 565-572.

Jian, Z., & Tabatabai, H. (2012). Evaluation of a Permit Vehicle Model Using Weigh-in-Motion Truck Records. *Journal of Bridge Engineering*, 17(2), 389-392.

Kozikowski, Marek (2009) WIM Based Live Load Model for Bridge Reliability (Doctoral dissertation). University of Nebraska- Lincoln.

Leet, K., & Uang, C. (2011). *Fundamentals of Structural Analysis* (4th ed.). New York, NY: McGraw-Hill

McIlrath, D., Frank, K., Wood, S., & Yura, J. (2000). Improving Bridge Rating and Truck Permitting Procedures through Finite Element Analysis. *Texas Department of Transportation, Research Report 1746-2*.

Megson, T. (2005). *Structural and Stress Analysis* (2nd ed.). Amsterdam: Elsevier Butterworth-Heineman.

Minervino, C., Sivakumar, B., Moses, F., Mertz, D., & Edberg, W. (2004). New AASHTO Guide Manual for Load and Resistance Factor Rating of Highway Bridges. *J. Bridge Eng. Journal of Bridge Engineering*, 9(1), 43-54.

Moses, F. (2001). Calibration of Load Factors for LRFR Bridge Evaluation. *NCHRP, Report 454*.

Nowak, A. (1993). Live load model for highway bridges. *Structural Safety*, (13), 53-66.

Nowak, A., & Hong, Y. (1991). Bridge Live-Load Models. *Journal of Structural Engineering J. Struct. Eng.*, 117, 2757-2767.

Nowak, A., Nassif, H., & Defrain, L. (1993). Effect of Truck Loads on Bridges. *Journal of Transportation Engineering J. Transp. Eng.*, 119(6), 853-867.

Pelphrey, J., Higgins, C., Sivakumar, B., Groff, R., Hartman, B., Charbonneau, J., Rooper, J., Johnson, B. (2008). State-Specific LRFR Live Load Factors Using Weigh-in-Motion Data. *Journal of Bridge Engineering*, 13(4), 339-350.

Rakoczy, Przemyslaw (2011). WIM Based Load Models for Bridge Serviceability Limit States (Doctoral dissertation). University of Nebraska- Lincoln

RIDOT (2011). Guidelines for Load and Resistance Factor Rating (LRFR) of Highway Bridges.

RI DMV/DOT Oversize Overweight Online Permitting System User Guide. (n.d.).

Retrieved July 12, 2015, from

https://www.ri.gov/subscriber/docs/osow/RI_OSOW_User_Guide_v12.pdf

Sivakumar, B., Ghosn, M., Moses, F. (2011). Protocols for Collecting and Using Traffic Data in Bridge Design. *NCHRP, Report 683*.

Sivakumar, B., Moses, F., Fu, G., & Ghosn, M. (2007). Legal Truck Loads and AASHTO Legal Loads for Posting. *NCHRP, Report 575*.

The Manual for Bridge Evaluation (MBE): 2013 Interim Revisions. (2nd. ed.). (2013).

Washington, DC: American Association of State Highway and Transportation Officials.

Zhao, J., & Tabatabai, H. (2012). Evaluation of a Permit Vehicle Model Using Weigh-in-Motion Truck Records. *Journal of Bridge Engineering*, 17(2), 389-392.

APPENDIX.

Load Effects Calculations

The maximum structural responses to an applied load, or load effects, are necessary in bridge analysis to determine its carrying capacity. There are four load effects generally considered: end shear force and mid-span moment of a simply-supported beam; and the shear force and negative moment at the interior support of a two-equal span continuous beam.

To establish the maximum load effects, loads must be positioned in the most critical manner. However, for a truck such placement is frequently not evident as the structural responses vary as it moves along a beam. A systematic procedure called influence lines is commonly used to determine the maximum load effects. An influence line is a diagram whose ordinates, which are plotted as a function of the distance along a beam, give the value of an internal force, a reaction, or a displacement at a particular point in a structure as a unit load of 1 moves across the structure (Leet & Uang, 2011). As the truck moves along the beam, the influence ordinate at the location of each axle is multiplied by the corresponding AXW. The load effect is the summation of the influence ordinate multiplied by the AXW. This computation is only valid for linear behavior, as the forces created in an elastic structure are directly proportional to the magnitude of the applied load (Leet & Uang, 2011). Load effects due to a distributed load can also be obtained by multiplying the magnitude of the force by the area under the influence line.

Construction of the influence lines for the four load effects of interest is further explained. The functions are then utilized to develop codes in the computer software MATLAB to simulate the trucks in the database crossing over bridges of various span lengths.

1. Simple Span End Shear Force

The maximum shear force in a simply-supported beam typically occurs adjacent to a support. Therefore, the maximum shear force is equal to the highest support reaction. Placement of a concentrated load directly over a support produces the highest reaction, therefore, the maximum shear force. To capture each axle over a support, the MATLAB code for simple span shear force (SSShear) positions the first axle over a support and moves the truck along the beam accordingly to the truck's AXS.

Figure 1 displays a simply-supported beam with a unit load varying in position, x , along the beam's length.

Figure 1: Simply-supported beam with a moving unit load

As the unit load moves further from the left support, the reaction A_y decreases while B_y increases. By taking the moment about support B, the function of A_y is determined:

$$\curvearrowleft + \sum M_B = 0;$$

$$0 = -IL_{A_y}(L) + 1(L - x)$$

$$IL_{A_y} = \frac{L-x}{L} \quad 0 \leq x \leq L \quad (1)$$

Summing the forces about the y-axis, the function for B_y is solved:

$$\uparrow + \sum F_y = 0;$$

$$0 = IL_{A_y} - 1 + IL_{B_y}$$

$$IL_{B_y} = \frac{x}{L} \quad 0 \leq x \leq L \quad (2)$$

Equations 1 and 2 are the influence functions of the support reactions A_y and B_y , respectively, as the unit load varies in position along the span. Figure 2 displays the influence lines for the calculated functions.

Figure 2: Left and right support reactions (SSShear) influence lines

2. Simple Span Mid-Span Moment

Bending moment increases as a concentrated load approaches mid-span of a simply-supported beam. The MATLAB code for simply-support mid-span moment (SSMomMid) positions the first axle over the center of the beam and moves the truck accordingly to the AXS to capture all axles at that location and maximize the load effect. Figure 3 shows the cut section of a beam used to calculate the SSMomMid influence function as the unit load moves closer to mid-span.

Figure 3: Unit load moving towards mid-span

Reaction A_y is shown in equation 1 and is used to take the moment about mid-span to determine the influence function as following:

$$\curvearrowleft + \sum M_{\frac{L}{2}} = 0;$$

$$0 = -IL_{A_y} \left(\frac{L}{2} \right) + 1 \left(\frac{L}{2} - x \right) + IL_{M_{\frac{L}{2}}}$$

$$IL_{M_{\frac{L}{2}}} = \frac{x}{2} \quad 0 \leq x \leq L/2 \quad (3)$$

As the unit load moves past mid-span, the bending moment decreases. Figure 4 displays the section used to calculate the mid-span moment influence function as the unit load moves always from mid-span.

Figure 4: Unit load moving away from mid-span

The influence function is determined for the above condition by taking the moment about mid-span:

$$\curvearrowleft + \sum M_{\frac{L}{2}} = 0;$$

$$0 = -IL_{Ay} \left(\frac{L}{2} \right) + IL_{M_{\frac{L}{2}}}$$

$$IL_{M_{\frac{L}{2}}} = \frac{L}{2} - \frac{x}{2} \quad L/2 < x \leq L \quad (4)$$

Shown on Figure 5 is the SSMomMid influence line developed by using equations 3 and 4.

Figure 5: Mid-span moment (SSMomMid) influence line

3. Continuous Span Interior Support Shear Force

In a continuous beam the shear force of interest is equivalent to the interior support reaction. Similarly to SSShear, the MATLAB code for the shear force at the interior support of two-equal span continuous beam (CSShear) positions the first axle over the interior support and moves the truck along the beam accordingly to the AXS. A continuous beam is an indeterminate structure and cannot be solved directly using the equations of equilibrium. Therefore, other methods must be applied to solve for the reactions. The flexibility method, or the method of superposition, was chosen for this analysis. Figure 6 displays the procedure to superimpose the indeterminate structure with determinate release structures in order to formulate the compatibility equation. The first structure is analyzed with a moving unit load. The second has a unit load applied to the released support and is multiplied by the actual magnitude of the redundant reaction.

Figure 6: Formulation of the compatibility equation

The deflections of the released structures are summed at the location of the interior support and set equal to the deflection of the indeterminate structure, which is zero as it is fixed against translation in the y-direction. Equation 5 formulates the latter statement:

$$\Delta B + \delta_{BB}(1)R_B = 0 \quad (5)$$

Calculating ΔB is accomplished through the same manner as δ_{BB} by the application of the Maxwell-Betti law of reciprocal deflections. The law states that a linear deflection ΔB due to a unit load at “x” of the first release structure is equal to the displacement at “x” (i.e., δ_{xB}) of the second release structure due to a unit load at the location of ΔB (Megson, 2005). Since the deflections of the release structures are assumed in opposite direction, $-\Delta B = \delta_{xB}$.

By making the appropriate substitutions and rearranging equation 5 results in:

$$\frac{\delta_{xB}}{\delta_{BB}} = R_B \quad (6)$$

The deflection equations for a simply supported beam with a concentrated unit load at mid-span is expressed as:

$$v = \frac{1}{48EI} (4x^3 - 3L^2x) \quad 0 \leq x \leq L/2 \quad (7)$$

$$v = \frac{1}{48EI} (4(L-x)^3 - 3L^2(L-x)) \quad L/2 < x \leq L \quad (8)$$

To solve for δ_{BB} , the distance to mid-span ($L/2$) is plugged into equation 7 and results in:

$$\delta_{BB} = -\frac{L^3}{48EI} \quad (9)$$

Because the interior reaction will increase as the unit load approaches its location and decreases as it moves away, the influence function is solved for two intervals. The deflection δ_{xB} is equal to equation 7 and 8 as it varies with the location of the applied unit load.

By substituting equations 7 and 9 into 6, the influence function for the interior support is calculated and results in:

$$IL_{By} = -\frac{4}{L^3}x^3 + \frac{3}{L}x \quad 0 \leq x \leq L/2 \quad (10)$$

By substituting equations 8 and 9 into 6, the influence function for the interior support is calculated and results in:

$$IL_{By} = -\frac{4}{L^3}(L-x)^3 + \frac{3}{L}(L-x) \quad L/2 < x \leq L \quad (11)$$

The influence functions represented as equations 10 and 11 are used to construct the CSShear influence line as shown on Figure 7.

Figure 7: Interior support reaction (CSShear) influence line

4. Continuous Span Negative Moment

Continuous beams are subjected to both positive and negative bending moments. Maximum negative bending moment at the interior support of a two-equal span beam is generally considered for evaluation purposes. A concentrated load maximizes the negative bending moment when placed at a location of about $0.577L$. Therefore, the MATLAB code for continuous span negative moment at the interior support of a two-equal span beam (CSMomNeg) positions the first axle at $0.577L$ and moves the truck along the length of the beam accordingly to the truck's AXS.

The influence function for the interior support reaction, B_y , was calculated in section 3. By applying the equations of equilibrium, the influence functions for the outer supports, A_y and C_y , are as shown:

$$IL_{B_y} = -\frac{4}{L^3}x^3 + \frac{3}{L}x \quad 0 \leq x \leq L/2 \quad (10)$$

$$IL_{A_y} = \frac{L-x}{L} - B_y\left(\frac{L}{2}\right) \quad 0 \leq x \leq L/2 \quad (12)$$

$$IL_{C_y} = \frac{x}{L} - B_y\left(\frac{L}{2}\right) \quad 0 \leq x \leq L/2 \quad (14)$$

Solving for the moment at the interior support, the negative moment influence function is:

$$IL_{M_B} = C_y\left(\frac{L}{2}\right) \quad 0 \leq x \leq L/2 \quad (15)$$

Once the unit load moves past the center support, the influence functions become:

$$IL_{B_y} = -\frac{4}{L^3}(L-x)^3 + \frac{3}{L}(L-x) \quad L/2 < x \leq L \quad (11)$$

$$IL_{A_y} = \frac{L-x}{L} - B_y\left(\frac{L}{2}\right) \quad L/2 < x \leq L \quad (12)$$

$$IL_{C_y} = \frac{x}{L} - B_y\left(\frac{L}{2}\right) \quad L/2 < x \leq L \quad (14)$$

The negative bending moment influence function for this interval is:

$$IL_{M_B} = A_y\left(\frac{L}{2}\right) \quad L/2 < x \leq L \quad (16)$$

Figure 8 displays the CSMomNeg influence line constructed using equations 15 and 16.

Figure 8: Negative moment at the interior support (CSMomNeg) influence line

BIBLIOGRAPHY

Barker, R., & Puckett, J. (2013). Loads. In *Design of highway bridges: An LRFD approach* (Third ed., pp. 81-106). Hoboken, New Jersey: Wiley.

Moses, F. (2001). Calibration of Load Factors for LRFR Bridge Evaluation. *NCHRP, Report 454*.

Bell, E., Lefebvre, P., Sanayei, M., Brenner, B., Sipple, J., & Peddle, J. (2013). Objective Load Rating of a Steel-Girder Bridge Using Structural Modeling and Health Monitoring. *Journal of Structural Engineering*, 139(10), 1771-1779.

Bhattacharya, B., Li, D., Chajes, M., & Hastings, J. (2005). Reliability-Based Load and Resistance Factor Rating Using In-Service Data. *Journal of Bridge Engineering*, 10(5), 530-543.

Bridge Formula Weights. (2015, May 28). Retrieved September 21, 2015, from http://ops.fhwa.dot.gov/Freight/publications/brdg_frm_wgths/index.htm

Bridges & Structures. (2014, December). Retrieved November 24, 2015, from <https://www.fhwa.dot.gov/bridge/nbi/no10/defbr14.cfm>

Federal-Aid Highway Act of 1956, Pub. L. No. 627, § 108, 70 Stat. (1956)

Federal-Aid Highway Amendments of 1974, Pub. L. No. 93-643, §106, 88 Stat. (1975)

Ghosn, M., Sivakumar, B., & Miao, F. (2013). Development of State-Specific Load and Resistance Factor Rating Method. *Journal of Bridge Engineering*, 18(5), 351-361.

Hayworth, R., Huo, X., & Zheng, L. (2008). Effects of State Legal Loads on Bridge Rating Results Using the LRFR Procedure. *Journal of Bridge Engineering*, 13(6), 565-572.

Jian, Z., & Tabatabai, H. (2012). Evaluation of a Permit Vehicle Model Using Weigh-in-Motion Truck Records. *Journal of Bridge Engineering*, 17(2), 389-392.

Kozikowski, Marek (2009) WIM Based Live Load Model for Bridge Reliability (Doctoral dissertation). University of Nebraska- Lincoln.

Leet, K., & Uang, C. (2011). *Fundamentals of Structural Analysis* (4th ed.). New York, NY: McGraw-Hill

McIlrath, D., Frank, K., Wood, S., & Yura, J. (2000). Improving Bridge Rating and Truck Permitting Procedures through Finite Element Analysis. *Texas Department of Transportation, Research Report 1746-2*.

Megson, T. (2005). *Structural and Stress Analysis* (2nd ed.). Amsterdam: Elsevier Butterworth-Heineman.

Minervino, C., Sivakumar, B., Moses, F., Mertz, D., & Edberg, W. (2004). New AASHTO Guide Manual for Load and Resistance Factor Rating of Highway Bridges. *J. Bridge Eng. Journal of Bridge Engineering*, 9(1), 43-54.

Moses, F. (2001). Calibration of Load Factors for LRFR Bridge Evaluation. *NCHRP, Report 454*.

Nowak, A. (1993). Live load model for highway bridges. *Structural Safety*, (13), 53-66.

Nowak, A., & Hong, Y. (1991). Bridge Live-Load Models. *Journal of Structural Engineering J. Struct. Eng.*, 117, 2757-2767.

Nowak, A., Nassif, H., & Defrain, L. (1993). Effect of Truck Loads on Bridges. *Journal of Transportation Engineering J. Transp. Eng.*, 119(6), 853-867.

Pelphrey, J., Higgins, C., Sivakumar, B., Groff, R., Hartman, B., Charbonneau, J., Rooper, J., Johnson, B. (2008). State-Specific LRFR Live Load Factors Using Weigh-in-Motion Data. *Journal of Bridge Engineering*, 13(4), 339-350.

Rakoczy, Przemyslaw (2011). WIM Based Load Models for Bridge Serviceability Limit States (Doctoral dissertation). University of Nebraska- Lincoln

RIDOT (2011). Guidelines for Load and Resistance Factor Rating (LRFR) of Highway Bridges.

RI DMV/DOT Oversize Overweight Online Permitting System User Guide. (n.d.).

Retrieved July 12, 2015, from

https://www.ri.gov/subscriber/docs/osow/RI_OSOW_User_Guide_v12.pdf

Sivakumar, B., Ghosn, M., Moses, F. (2011). Protocols for Collecting and Using Traffic Data in Bridge Design. *NCHRP, Report 683*.

Sivakumar, B., Moses, F., Fu, G., & Ghosn, M. (2007). Legal Truck Loads and AASHTO Legal Loads for Posting. *NCHRP, Report 575*.

The Manual for Bridge Evaluation (MBE): 2013 Interim Revisions. (2nd. ed.). (2013).

Washington, DC: American Association of State Highway and Transportation Officials.

Zhao, J., & Tabatabai, H. (2012). Evaluation of a Permit Vehicle Model Using Weigh-in-Motion Truck Records. *Journal of Bridge Engineering*, 17(2), 389-392.