State-Specific LRFR Live Load Factors Using Weigh-in-Motion Data

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Abstract: The *LRFR Manual*, within commentary Article C6.4.4.2.3, contains provisions for development of site-specific live load factors. In Oregon, truck weigh-in-motion (WIM) data were used to develop live load factors for use on state-owned bridges. The factors were calibrated using the same statistical methods that were used in the original development of LRFR. This procedure maintains the nationally accepted structural reliability index for evaluation, even though the resulting state-specific live load factors were smaller than the national standard. This paper describes the jurisdictional and enforcement characteristics in the state, the modifications used to described the alongside truck population based on the unique truck permitting conditions in the state, the WIM data filtering, sorting, and quality control, as well as the calibration process, and the computed live load factors. Large WIM data sets from four sites were used in the calibration and included different truck volumes, seasonal and directional variations, and WIM data collection windows. Finally policy implementation for actual use of the factors and future provisions for maintenance of the factors are described.

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Introduction and Background

Transportation agencies are beginning to transition from the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Condition Evaluation of Bridges* (AASHTO 1994) to the AASHTO *Load and Resistance Factored Rating (LRFR) Specifications* (AASHTO 2003) for bridge rating and evaluation. The LRFR specifications extend the limit states design philosophy from AASHTO load and resistance factor design (LRFD) (AASHTO 2004) to evaluation of existing bridges. Employing structural reliability principles, the specifications provide the flexibility to attain uniform target safety levels by reducing uncertainty (Minervino et al. 2004) and further provide a means of incorporating advancements in analysis methods, load models, and material and member characterization in the evaluation process. For evaluation of existing bridges, site-specific information can be collected to characterize the local uncertainty, rather than relying on generalized information. One area where it is possible to reduce uncertainty is in the live loads through collection and characterization of site-specific traffic data. The generalized load factors given in the LRFR specifications are representative of bridges nationwide with similar traffic volumes. The LRFR specifications provide procedures for calculating site-specific load factors using truck weight data collected from weigh-in-motion (WIM) sites that follows the same format used in the derivation of LRFD live load factors. Site-specific load factors are more refined because they are characteristic of a particular bridge site, route, or jurisdiction and reflect the actual truck traffic and likely maximum loadings over the exposure period.

Following the methodology developed in NCHRP Project No. 12-46 (Moses 2001) and incorporated in the LRFR specifications, live load factors for strength evaluation were developed for state-owned bridges in Oregon using WIM data from sites across the state. Adaptation of the methods was necessary to account for unique characteristics of truck loads and permitting regulations in the state. Live load factors were developed using WIM data from four sites, including state and interstate routes, considering possible seasonal variations, and different WIM data collection windows. This paper describes the analysis methods used to determine the site-specific live load factors based on WIM data, the resulting live load factors, policy implementation, and plans for updating factors in the future.

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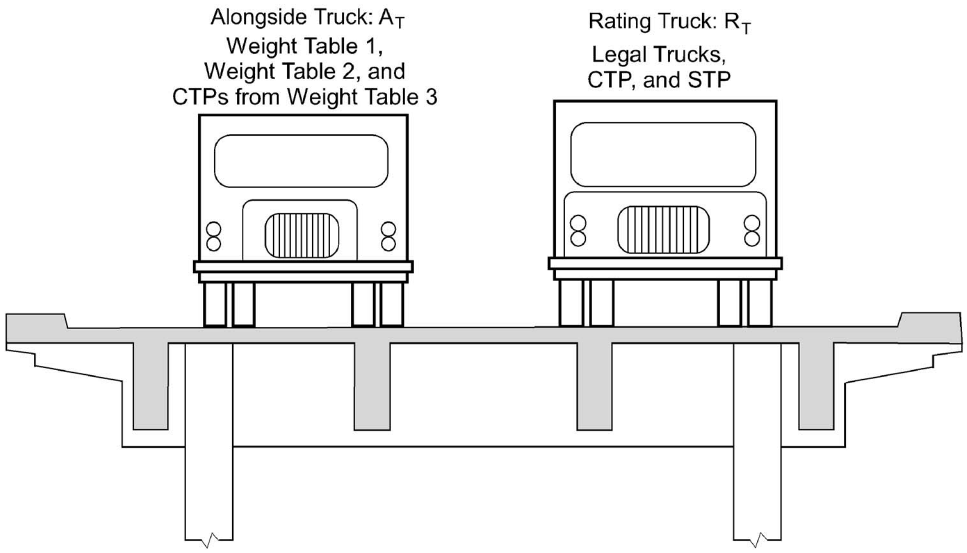

Fig. 1. Maximum loading event for calibration of live load factors

Live Load Factor Methodology and Analysis

The *LRFR Manual* provides a procedure for calculating site-specific load factors using truck weight data from WIM sites that follow the format used in the derivation of live load factors contained in the LRFD specifications. The LRFR approach is to determine the statistics associated with the 3S2 truck population to characterize the uncertainty associated with the alongside truck. The Ontario truck weight data used in calibration of the LRFR specifications were reasonably matched by a 3S2 truck with a normal distribution and a mean of 68 kips and standard deviation of 18 kips. The weight parameters fit the heaviest one fifth of the truck weight population and it was assumed that the remaining trucks have no influence on the maximum loading events. The maximum loading event for calibration assumes a legal truck or a permit truck in one lane and a random truck (referred to as the alongside vehicle) in the adjoining lane as illustrated in Fig. 1. Therefore, the load factor applied to the permit vehicle depends on the random alongside truck. Live load factors are higher for spans with higher average daily truck traffic (ADTT) and smaller for heavier permitted vehicles. Live load factors for permit loads are smaller compared with legal load rating values to account for the reduced probability of simultaneous crossing events and also reduced likelihood that a permit truck will be significantly overloaded.

In the LRFD calibration, Novak (1999) showed that the maximum expected lifetime loading in each lane for two-lane loading is 0.85 times the single lane expected maximum lifetime loading. Therefore, in a two-lane loading situation, the extreme occasional overloads that may be present within the various truck categories are not influential in the calibration of live load factors. This also suggests that data for long periods of time to identify such loads would not be very beneficial for calibration purposes. The key to reliable calibration statistics is the quality and not necessarily the quantity of data. Additionally, the WIM data should represent site-to-site variations in traffic within a state.

Significant differences in permitting requirements exist in the State of Oregon, compared to other jurisdictions as illustrated in Table 1. These include a legal gross vehicle weight (GVW) of 80,000 lbs, large numbers of continuous trip permit (CTP) vehicles, and extended legal weight CTP vehicles to 105,500 lbs on state highways. As a result, the 3S2 truck population statistics alone may not necessarily characterize the alongside truck variability. Therefore, the alongside truck population in Oregon was taken as consisting of legal trucks (Weight Table 1), Extended Weight Table 2 (105,500 lbs maximum), and 98,000-lb CTP vehicles from Weight Table 3. Inclusion of permitted trucks (the CTPs) in the alongside truck population is a conservative departure from past load factor calibration work, but characteristic of the jurisdiction.

WIM data were used to develop the state-specific live load factors based on the characteristic vehicle population in the state. Three major variables were considered in the selection of WIM data. These included length of the WIM data collection window, truck volume, and seasonal variability. Each is described in additional detail below.

WIM Data Collection Windows

Typically, in practice, 2 weeks of WIM data are used to compute site specific live load factors; however no established standard of time or quantity of WIM data has previously been established. To

Table 1. ODOT Rating Vehicle Classifications

Rating vehicle	Live load factor designation	GVW (kips)
Legal Type 3	Oregon legal loads	50
Legal Type 3S2		80
Legal Type 3-3		80
OR-CTP-2A	CTP-2A,2B	105.5
OR-CTP-2B		105.5
OR-CTP-3	CTP-3	98
OR-STP-3	STP-3	120.5
OR-STP-4A	STP-4A	99
OR-STP-4B	STP-4B	185
OR-STP-5A	STP-5A	150.5
OR-STP-5B	STP-5B	162.5
OR-STP-5C	STP-5C	258
OR-STP-5BW	STP-5BW	204

Table 2. Selected WIM Sites, Locations, and ADTT

Corridor	Site location	Site designation	ADTT	ADTT percent of ADT (%)	Winter 2005	Spring 2005	Summer 2005	Fall 2005
I-5	Woodburn NB	WBNB	5,550	13	January	Apr	June	October
US97	Bend NB	BNB	607	8	December	—	June	October
OR58	Lowell WB	LWB	581	7	January	April	June	October
I-84	Emigrant Hill WB	EHWB	1,786	36	November	April	May	October

assess the effect of different WIM data collection windows on the corresponding live load factors, three different windows of time were considered in each month: (1) data from the entire month; (2) 2 weeks of data from 1st to 14th; and (3) 2 weeks of data from 15th to 28th. Comparisons were made between each of the 2-weeks data windows and further compared with the 4-weeks data windows (all-month factors).

Traffic Volume

There are four highways/interstates of interest in Oregon that collect WIM data. These are Interstate-5, Interstate-84, Oregon State Highway-58, and US Highway-97. From these highways, individual WIM data collection sites were selected based on ADTT volume. The WIM sites chosen are shown in Table 2 and Fig. 2. These sites enabled calculation of live load factors considering different truck volume conditions.

Seasonal Variation

To assess possible variations in the data occurring at different periods of the year, four "seasons" were selected for each WIM site. WIM sites are intended to collect a continuous record of data for vehicles crossing the WIM scales. However, due to local conditions such as roadway construction or hardware or electronics problems, data were not always continuous over an entire month. Therefore, the months selected for analysis were chosen based on availability of complete months of data within each "season." These included: November–January for winter, April for spring, May and June for summer, and October for fall. Some months strayed outside of traditional "seasonal" boundaries, but only when necessary due to noncontinuous data sets. Table 2 lists the specific months from which WIM data were available for each of the sites. Site specific live load factors were computed for each of these timeframes. Data collection for Bend NB did not begin until June, 2005. Therefore, live load factors could not be calculated for spring, but these were computed when data became available.

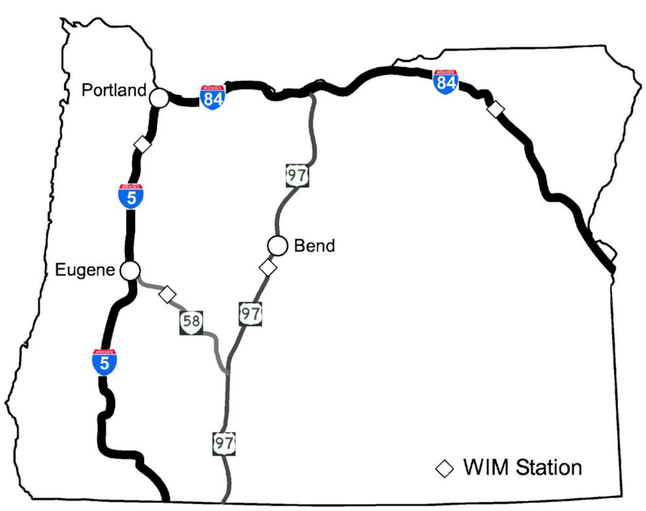

Fig. 2. Map of Oregon WIM sites used in study

WIM Data Cleaning, Filtering, and Weight Table Sorting Methodology

The raw WIM records from each collection site were provided in text format for subsequent data processing. The data were cleaned and filtered to remove records with formatting mistakes, spurious data, and other errors. Error types that were removed in the cleaning process were as follows:

1. Record where the GVW value is equal to 0.0;
2. Record does not follow the general record pattern; this could be any inconsistency in the time stamp, words out of place from the status quo, incomplete records, etc.;
3. Records with misplaced characters, such as a letter where a number should be or a number where a letter should be;
4. Record where an individual axle is greater than 50 kips;
5. Record where the speed is less than 10 mi/h.
6. Record where the speed is greater than 99 mi/h;
7. Record where the length is greater than 200 ft.
8. Record where the sum of the axle spacing lengths are greater than the length of the truck;
9. Record where the sum of the axle spacing lengths are less than 7 ft;
10. Record where the first axle spacing is less than 5 ft;
11. Record where the number of axles is greater than 13;
12. Record where the GVW is greater than 280 kips;
13. Record where any axle spacing is less than 3.4 ft;
14. Record which has a GVW $\pm$ the sum of the axle weights by more than 7%; and
15. Record which has a GVW less than 2.0 kips.

Classifying and sorting the WIM data into the appropriate permit weight table classification is a key step in developing site live load factors. Data processing should remove permitted trucks from the WIM data representing the alongside truck population. Two separate sorting methods for the WIM data were investigated and compared. These are defined as "conventional sort" and "modified sort."

The conventional sort method sorts vehicles based on their GVW, axle group weights, and length (GVW+axle group sort). It is the method currently used by the Motor Carrier Transportation Division (MCTD) of ODOT to classify vehicles into Weight Tables 1, 2, 3, 4, and 5, or Table *X* (the overflow table classification). ODOT currently uses a suite of 13 trucks to represent these permit categories for rating purposes, and the axle weights and configurations are illustrated in Fig. 3. Permits are issued based on a vehicle's weight table classification. This method accounts

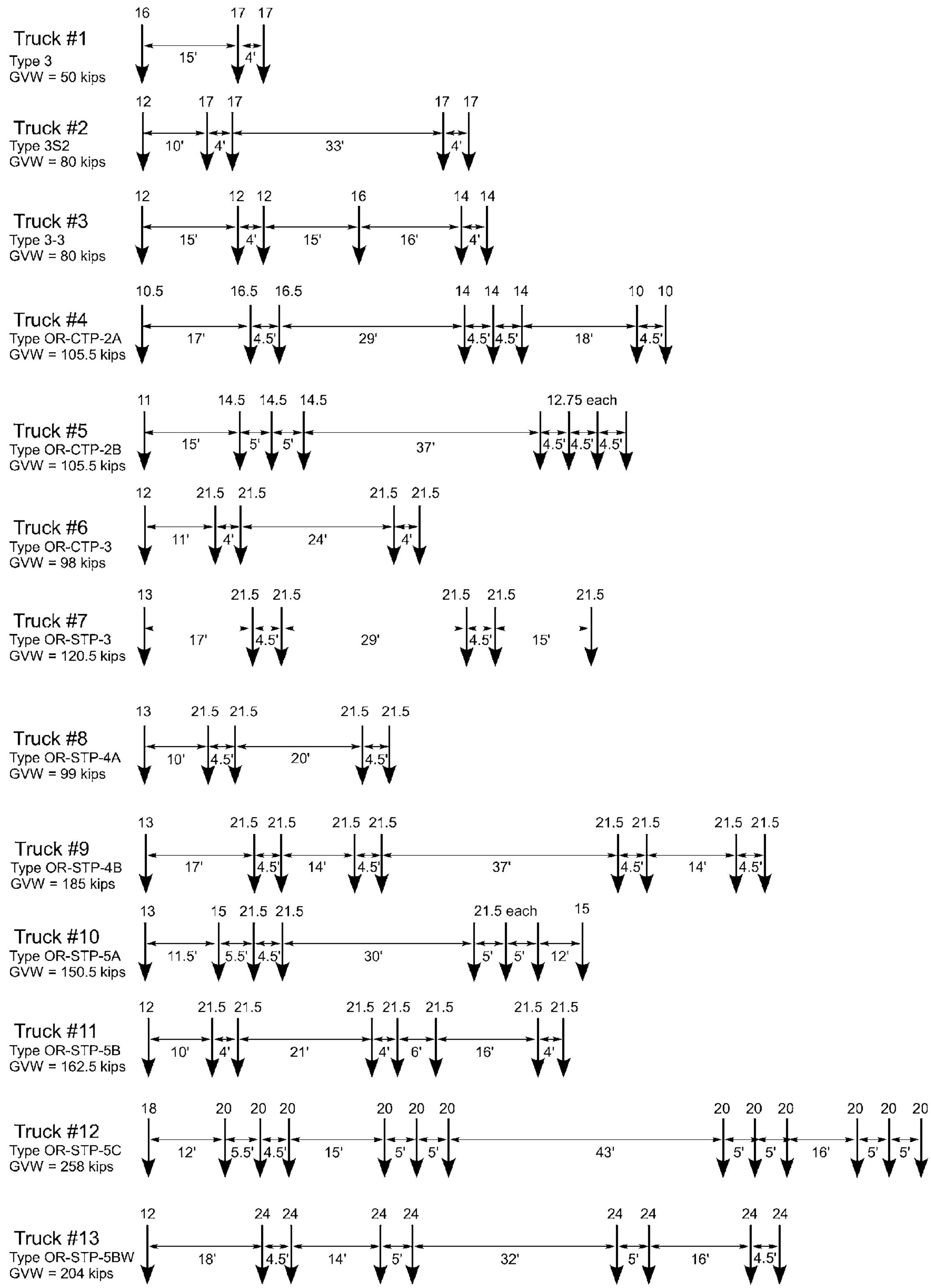

Fig. 3. Suite of 13 rating vehicles used to represent various weight classifications in Oregon for bridge rating

for the axle weights and spacing in assigning each vehicle to an appropriate weight table and assigns more vehicles to higher weight tables than the modified sort (described subsequently). Proportionately more heavy vehicles that could have been interpreted as "rogue" legal vehicles are assigned to Weight Table 3 and above and are thus considered as legitimate permit vehicles. The sort yields lower coefficients of variation and as seen subsequently yields lower live load factors compared to the modified sort. While it is less conservative than the modified sort, it is thought to better represent the permitted truck population in Oregon as will be discussed later.

The modified sort method sorts vehicles based only on their GVW and rear-to-steer axle length, and it does not account for axle groupings (GVW+truck length sort). The method assigns

Table 3. Results of Sorting Methods for Weight Table Classification

	Site	Sort method[a]	Table 1	Table 2	Table 3	Table 4	Table 5	Table *X*	Total records	CTP from WT3 to WT2[b]	STP per day[c]
Winter	I-5 WBNB	*C*	124,062	13,175	1,788	44	1	32	139,102	477	45
		M	125,014	13,690	366	29	2	1	139,102	—	—
	US97 BNB	*C*	9,776	411	398	9	0	1	10,595	185	7
		M	9,954	535	105	1	0	0	10,595	—	—
	OR58 LWB	*C*	15,157	469	30	3	0	0	15,659	4	1
		M	15,164	477	17	1	0	0	15,659	—	—
	I-84 EHWB	*C*	43,416	2,224	72	2	0	0	45,714	14	2
		M	43,447	2,253	14	0	0	0	45,714	—	—
Spring	I-5 WBNB	*C*	136,364	13,065	1,835	57	1	25	151,347	609	44
		M	137,374	13,554	392	21	2	4	151,347	—	—
	US97 BNB	*C*	—	—	—	—	—	—	0	—	—
		M	—	—	—	—	—	—	0	—	—
	OR58 LWB	*C*	17,455	433	17	3	0	0	17,908	3	4
		M	17,460	442	6	0	0	0	17,908	—	—
	I-84 EHWB	*C*	37,249	3,433	7,177	73	2	77	48,011	3,688	121
		M	39,846	5,964	2,191	9	1	0	48,011	—	—
Summer	I-5 WBNB	*C*	143,018	13,684	4,713	89	4	47	161,555	1,938	97
		M	145,524	15,001	1,004	19	6	1	161,555	—	—
	US97 BNB	*C*	15,676	763	2,304	9	1	20	18,773	1,616	24
		M	16,640	1,811	314	7	1	0	18,773	—	—
	OR58 LWB	*C*	24,765	954	95	12	1	3	25,830	45	2
		M	24,813	982	32	3	0	0	25,830	—	—
	I-84 EHWB	*C*	45,109	4,206	1,057	13	0	8	50,393	596	16
		M	45,450	4,563	378	0	0	0	50,393	—	—
Fall	I-5 WBNB	*C*	135,964	12,136	3,912	93	14	46	152,165	1,436	85
		M	137,776	13,298	1,025	47	19	0	152,165	—	—
	US97 BNB	*C*	18,028	708	304	12	4	11	19,067	117	7
		M	18,167	831	60	7	2	0	19,067	—	—
	OR58 LWB	*C*	25,235	1,278	202	9	1	13	26,738	141	3
		M	25,388	1,309	36	5	0	0	26,738	—	—
	I-84 EHWB	*C*	48,426	3,084	49	0	0	1	51,560	10	1
		M	48,447	3,101	12	0	0	0	51,560	—	—

[a]*C*=conventional sort, *M*=modified sort.

[b]CTP from WT3 to WT2 are records of CTP trucks in Weight Table 3 that were moved into Weight Table 2 to be included in the alongside truck population.

[c]STP per day computed as total number of vehicles in Weight Tables 3 (minus the CTPs moved into Weight Table 2), 4 and 5 and *X* divided by the number of days in the month.

more vehicles to lower weight tables than the conventional sort. Proportionately more heavy vehicles that could have been interpreted as legitimate permit vehicles are conservatively assigned to Weight Tables 1 and 2 and are thus considered "rogue" legal vehicles. The sort produces higher coefficients of variation and higher live load factors compared to the conventional sort. While it is more conservative, it may unfairly penalize Oregon's regulatory and enforcement policies, than the conventional sort.

Oregon has a well established permitting process that contributes to reduced overloads on state highways. These include minimal cost of overweight permits, large numbers of such permits authorized, the ease of access in obtaining them (such as through the Internet), a weight-mile tax that results in lower taxes for loads placed on more axles, development and fostering of the "trusted carrier" program which enhances cooperation and load compliance by trucking companies, and the significant enforcement and cost of penalties imposed on vehicles and drivers that are noncompliant. The compliance to weight limits for trucks in Oregon was verified in a study by Strathman and Theisen (2002) that demonstrated there was no statistically significant evidence of overweight truck scale avoidance. Further, there are few detour routes available to skirt scales on the major state highways.

The two different sorting methods were used on the WIM data sets and results are shown in Table 3 for the weight table breakdown. The live load factors herein were calculated based on the conventional sort method because it better represents the regulatory and enforcement procedures in Oregon. In contrast to some other states where truckers generally know the vehicle GVW but may not know their axle grouping weights, MCTD of ODOT report that Oregon truckers are generally aware of their axle and tandem weights, usually to within 2,000 lbs, which proves beneficial in obtaining a continuous trip permit.

Table 4. Statistics from Controlling WIM Data Sets Used in Live Load Factor Calibration

Vehicle	Statistic	Site I-5 WBNB	I-84 EHWB	US97 BNB	OR58 LWB
Legals	W^*	75.06	71.32	76.66	69.17
(type 3, 3S2, 3-3)	σ^*_{3S2}	1.98	3.40	1.25	2.93
	W^*_{along}	83.90	80.84	80.78	75.79
	σ^*_{along}	9.73	8.53	8.38	8.46
CTP-3	W^*_{along}	84.01	80.82	80.78	75.79
	σ^*_{along}	9.85	10.23	8.38	8.46
CTP-2A	W^*_{along}	84.01	80.82	80.78	75.79
CTP-2B	σ^*_{along}	9.85	10.23	8.38	8.46
STP-3	W^*_{along}	83.90	80.82	80.78	75.79
	σ^*_{along}	9.73	10.23	8.38	8.46
STP-4A	W^*_{along}	83.90	80.82	80.78	76.11
	σ^*_{along}	9.73	10.23	8.38	8.04
STP-4B	W^*_{along}	83.90	80.82	80.78	75.79
	σ^*_{along}	9.73	10.23	8.38	8.46
STP-5A	W^*_{along}	83.90	80.82	80.78	75.79
	σ^*_{along}	9.73	10.23	8.38	8.46
STP-5B	W^*_{along}	83.90	80.82	80.78	75.79
	σ^*_{along}	9.73	10.23	8.38	8.46
STP-5C	W^*_{along}	83.90	80.82	80.78	75.79
	σ^*_{along}	9.73	10.23	8.38	8.46
STP-5BW	W^*_{along}	83.90	80.82	80.78	75.79
	σ^*_{along}	9.73	10.23	8.38	8.46

After careful quality control measures and independent checks were performed on the WIM data cleaning, filtering, and sorting routines, statistics were generated based on GVW for the rating truck and the alongside truck using only the top 20% of the truck weight data from each category. This was consistent with the projection of the upper tail of the weight histogram (Novak 1999; AASHTO 2003). Statistical parameters were calculated for the alongside truck population from Weight Tables 1 and 2, and CTPs from Weight Table 3. Additionally, statistical parameters were calculated for just the 3S2 truck population. The statistical parameters are reported in Table 4 for the controlling data sets. Using these statistical values, live load factors were determined for each of the ODOT rating vehicles for the different WIM sites, data windows, and seasons.

The LRFR live load factor for rating is given in Eq. (39) of NCHRP Report 454, as

$$\gamma_L = 1.8\frac{W_T}{240} \times \frac{72}{W} \tag{1}$$

where W=gross weight of vehicle (legal truck or permit truck with units of kips) and W_T=expected maximum total weight of rating and alongside vehicles, computed as

$$W_T = R_T + A_T \tag{2}$$

where R_T=rating truck and is computed for legal loads as

$$R_T = W^* + t_{\text{ADTT}}\sigma^*_{3S2} \tag{3a}$$

or for permit loads as

$$R_T = P + t_{\text{ADTT}}\sigma^*_{\text{along}} \tag{3b}$$

where W^*=mean value of the top 20% of legal trucks taken from the 3S2 population, σ^*_{3S2}=standard deviation of the top 20% of legal trucks; P=weight of permit truck; and σ^*_{along}=standard deviation of the top 20% of the alongside trucks. The alongside truck, A_T, is computed as

$$A_T = W^*_{\text{along}} + t_{\text{ADTT}}\sigma^*_{\text{along}} \tag{4}$$

where W^*_{along}=mean of the top 20% of alongside trucks (taken from Weight Tables 1 and 22, as well as CTPs from Weight Table 3 for the Oregon data). In the above expressions, t_{ADTT} =fractile value corresponding to the number of side-by-side events, N. The number of side-by-side crossings is computed as

$$N(\text{legals}) = (\text{ADTT}) \times (365\ \text{days/year}) \times (\text{evaluation period}) \times (P_{s/s}) \times (\%\,\text{of record}) \tag{5a}$$

$$N(\text{permits}) = (N_P) \times (365\ \text{days/year}) \times (\text{evaluation period}) \times (P_{s/s}) \tag{5b}$$

for legal trucks and permit trucks, respectively, where N_P =number of observed single trip permits (STPs) in the WIM data extrapolated over the evaluation period and $P_{s/s}$=probability of side-by-side concurrence. LRFD and LRFR calibrations assumed a 1/15 (6.7%) probability of side-by-side events for truck passages. This assumption was based on visual observations and is conservative for most sites. Recent WIM studies completed under NCHRP 12-63 indicate much lower multiple-presence probabilities even for very high ADTT sites. In the NCHRP study, very accurate time stamps were collected and analyzed for WIM sites on I-84 in Idaho and I-75 in Ohio to estimate the number of side-by-side events over several days in 2004 and 2005. Results showed a maximum side-by-side probability of 3.35% for a three-lane site with >5,000 ADTT (Ohio) and 1.37% for a two-lane site with >2,500 ADTT (Idaho). These calculated probabilities considered all trucks within a headway separation of 60 ft to constitute a side-by-side event. This larger and more conservative definition of headway separation may produce a higher multiple presence but may have a lower total moment on most spans. The I-5 site in the current study is comparable to the three-lane >5,000 ADTT site reported above. For the calibration purposes, a 1/30 (3.4%) probability of side-by-side events was adopted as being more representative of likely concurrence for the sites in Oregon.

The ADTT values specific to each site were used in calculating the t_{ADTT} statistic and were listed previously in Table 2. The number of permits per day used in calculating the t_{ADTT} statistic was derived from the conventional sort method as shown in Table 3. Once the data were sorted according to the ODOT table classification, the number of Weight Table 3 CTP vehicles with five axles and GVW less than 99 kips were removed and placed into Weight Table 2, thereby including them as part of the routine traffic stream. The number of permits was then calculated by summing the remaining trucks in Weight Table 3 as well as those in Weight Tables 4 and 5, and X, and then dividing by the number of days in the WIM record. This represents the average number of STP vehicles passing the WIM site each day.

Considering a 5 year evaluation period for which the bridge rating would be considered valid, the LRFR live load factors were computed for the four WIM sites that reflect the site-to-site vari-

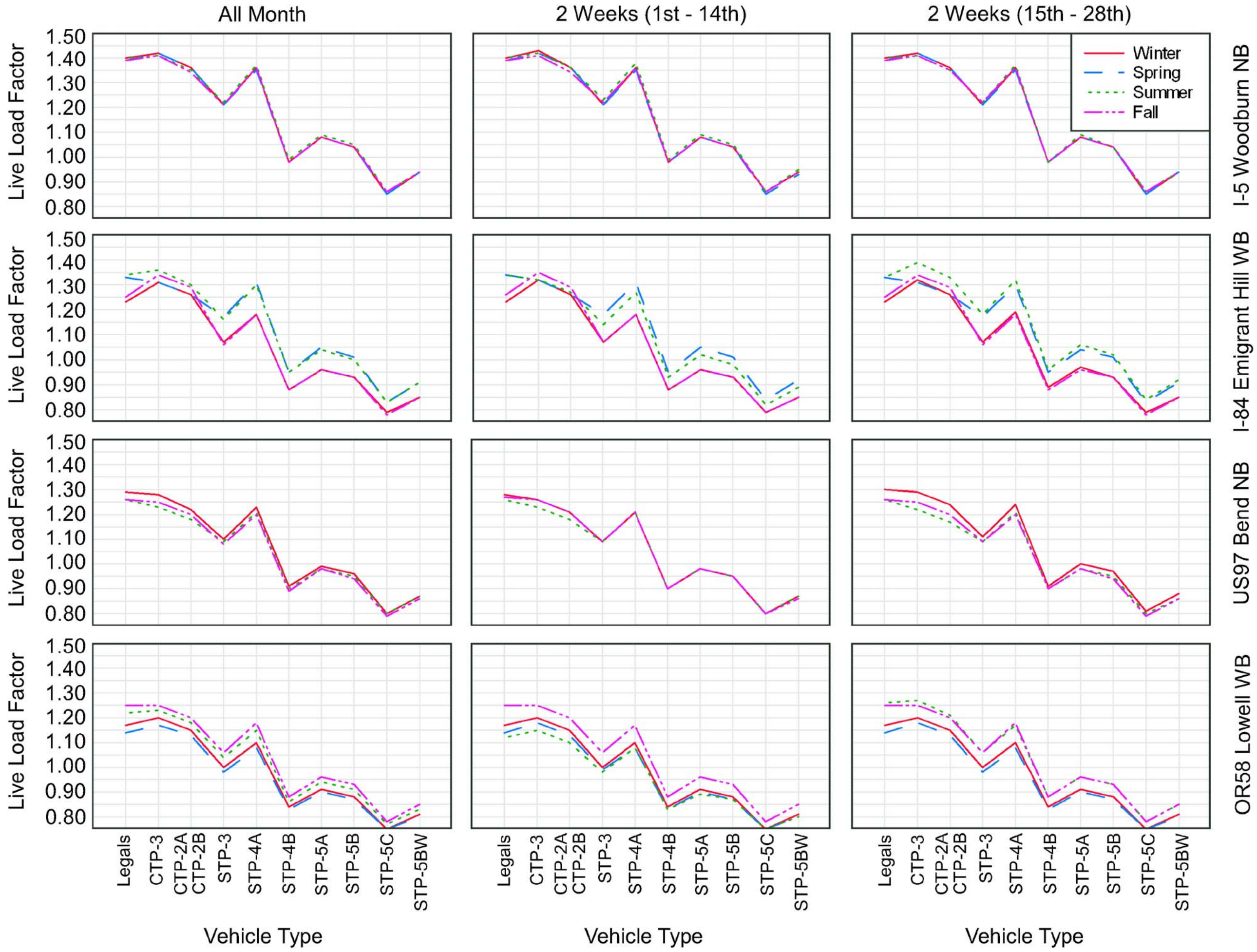

Fig. 4. Live load factors for WIM sites at different seasons and different WIM data windows

ability in the state and an example calculation procedure is shown in the Appendix. The state-specific load factors represent a target reliability index level corresponding to the operating level of 2.5.

Live Load Factor Results

The computed live load factors for all sites, for all seasons, and for all ODOT rating vehicles are shown in Fig. 4. The data used for this calibration process included over 930,000 individual WIM records spanning over 4 months of the year and represents significantly more data than was used in the original calibration of the national specifications.

The computed live load factors are intended to replace Table 6-5 and Table 6-6 (upper portion) in the LRFR manual with the Oregon-specific values based on the actual population of trucks on the state highways. For each rating vehicle and represented truck traffic volume level, the live load factors were conservatively chosen as the upper bound of all the factors from each of the four seasons and each of three data sampling periods. These selected live load factors are lower than the values found in the LRFR manual as shown in Tables 5 and 6. ODOT's MCTD issues STPs in large numbers on a routine basis without specific structural review and as a result, they are treated the same as "routine or annual" in Table 6 (upper portion of LRFR Table 6-6). Several of the controlling live load factors were shared by more than one season and/or time frame and illustrates the degree of consistency between data sets over the period considered. Full data sets, statistics, and details are reported by Pelphrey and Higgins (2006).

Significant Findings from Calibration Process

Significant findings based on results of this calibration process are presented below. These include information on seasonal, directional, and traffic-volume variations between sites, interstate versus noninterstate traffic, and WIM data collection windows.

The variation of live load factors for the different seasons at all four sites can be seen in Fig. 2. I-5 Woodburn NB and US97 Bend NB show very little change from season to season, while OR58

Table 5. Computed Oregon-Specific Live Load Factors for Legal Loads and LRFR Table 6-5 values

Traffic volume (one direction)	Load factor	
	LRFR	Oregon-specific
Unknown	1.80	1.40
ADTT$\geq$5,000	1.80	1.40
ADTT=1,500	1.67	1.34
ADTT$\leq$500	1.51	1.30

Table 6. Computed Oregon-Specific Live Load Factors for Permit Loads and Upper Portion of LRFR Table 6-6 Values

					Live load factor γ_L by ADTT (one direction)					
					>5,000		=1500		<500	
Permit type	Frequency condition	Loading condition	DF	Permit vehicle	LRFR	Oregon specific	LRFR	Oregon specific	LRFR	Oregon specific
Continuous trip (annual)	Unlimited crossings	Mix w/traffic (other vehicles may be on the bridge)	Two or more lanes	CTP-2A	1.75	1.36	1.58	1.33	1.45	1.24
				CTP-2B	1.75	1.36	1.58	1.33	1.45	1.24
				CTP-3	1.80	1.43	1.63	1.39	1.49	1.29
Single trip	Route-specific limited crossings	Mix w/traffic (other vehicles may be on the bridge)	Two or more lanes	STP-3	1.60	1.23	1.46	1.18	1.35	1.11
				STP-4A	1.80	1.38	1.63	1.32	1.49	1.24
				STP-4B	1.30	0.99	1.21	0.96	1.14	0.91
				STP-5A	1.30	1.09	1.21	1.06	1.14	1.00
				STP-5B	1.30	1.05	1.21	1.02	1.14	0.97
				STP-5C	1.30	0.86	1.21	0.84	1.14	0.81
				STP-5BW	1.30	0.95	1.21	0.92	1.14	0.88

Lowell WB and I-84 Emigrant Hill WB show a slight variation between select seasons. The greatest variation for OR58 is for the Oregon legal load (2 weeks, 1st–14th) from a Summer live load factor of 1.12 to a Fall live load factor of 1.25 (12% change). The greatest variation for I-84 is for the STP-4A (2 weeks, 15th–28th) from a Fall live load factor of 1.18 to a Summer live load factor of 1.32 (13% change). Some of these seasonal variations are attributed to movement of construction equipment and agricultural products in the summer and fall.

To investigate if there were directional influences in the calibrated factors, another site—Woodburn SB for January 2005—was investigated and compared to its counterpart, Woodburn NB. The live load factors for Woodburn NB and SB in each WIM data window during January, 2005 are shown in Table 7. The results show that the computed live load factors were not sensitive to the direction of travel.

Interstate traffic produced higher ADTT values, which in turn produced higher live load factors. This follows the national trend of higher live load factors for higher ADTT values. Calibration of the live load factors for different ADTT volume sites across the state permits them to be used statewide for both interstate and noninterstate routes on state-owned bridges.

Live load factors were calculated for three different windows of time in each month: (1) all month; (2) 2 weeks: 1st–14th; and (3) 2 weeks: 15th–28th. This was done to determine if results would change significantly if more WIM data were used to develop the factors. As shown in Fig. 3, there was little difference between the WIM data collection windows. This would suggest that reasonable characterization of the WIM sites (even the lower ADTT volume sites) could be made from any 2 continuous weeks of data within the month of interest. Here, again it is important to note that high quality data an required rather than a large quantity of data.

A sensitivity analysis was performed to determine how changes in the mean and standard deviation values of the alongside vehicles (Weight Tables 1 and 2 and CTP's <99 kips from Weight Table 3) affect the live load factors. All four sites were investigated for the summer season using the first 2 weeks of data (1st–14th). The analysis determined the magnitude of change required in the alongside vehicle mean and standard deviation to result in the live load factor increasing by 0.05. The two statistical parameters were assessed independent of each other (first, changing only the mean for a live load factor change of 0.05, and then changing only the standard deviation for a live load factor change of 0.05). The results of this analysis are shown in Table 8. As seen in this table, the mean would have to change by about 10% for all sites, and the standard deviation by about 15% on the interstates, and approximately 25% on the state highways.

A sensitivity analysis was also performed for the statistics on the 3S2 population. The live load factor for legal vehicles is the only factor affected by these statistics. Results from this analysis were similar to that observed for the alongside vehicle population, except that the standard deviation would have to be more than twice as large as that for the alongside population. Increasing mean GVW indicates a shift in truck weights while an increase in standard deviation indicates higher dispersion in the data. Changes in these parameters may be caused by changes in policy, compliance, or enforcement, as well as truck weight regulations, economic growth, or the type of freight being moved would indicate a need to recalibrate the load factors.

Table 7. Directional Influence for Live Load Factors at I-5 Woodburn NB and SB Sites for January, 2005

Location	Time frame	Legals	CTP-3	CTP-2A/2B	STP-3	STP-4A	STP-4B	STP-5A	STP-5B	STP-5C	STP-5BW
I-5 WBNB	All month	1.40	1.42	1.36	1.21	1.36	0.98	1.08	1.04	0.85	0.94
I-5 WBSB	All month	1.39	1.42	1.36	1.22	1.37	0.98	1.09	1.05	0.86	0.94
I-5 WBNB	1st–14th	1.40	1.43	1.36	1.21	1.36	0.98	1.08	1.04	0.86	0.94
I-5 WBSB	1st–14th	1.38	1.42	1.36	1.22	1.37	0.98	1.08	1.04	0.86	0.94
I-5 WBNB	15th–28th	1.40	1.42	1.36	1.21	1.36	0.98	1.08	1.04	0.85	0.94
I-5 WBSB	15th–28th	1.39	1.43	1.36	1.23	1.38	0.99	1.09	1.05	0.86	0.95

Table 8. Sensitivity Analysis for Alongside Vehicle Variability for Select Rating Vehicles during Summer Season (2 Weeks—1st–14th)

Site info		Original statistics[a]		Increase W to increase γ_L by 0.05		Increase σ to increase γ_L by 0.05	
		W (kips)	σ (kips)	W (kips)	Percent change (%)	σ (kips)	Percent change (%)
I-5 WBNB	Legals $\gamma_L=1.40-1.45$	83.9	9.7	91.3	9	11.5	18
	CTP-3 $\gamma_L=1.42-1.47$	83.9	9.7	93.0	11	10.9	12
	STP-4A $\gamma_L=1.38-1.43$	83.9	9.7	93.1	11	11.0	13
US97 BNB	Legals $\gamma_L=1.26-1.31$	81.7	6.5	89.1	9	8.5	31
	CTP-3 $\gamma_L=1.23-1.28$	81.7	6.5	90.8	11	7.9	21
	STP-4A $\gamma_L=1.21-1.26$	81.7	6.5	90.7	11	7.9	22
OR58 LWB	Legals $\gamma_L=1.12-1.17$	68.2	6.3	75.6	11	8.3	32
	CTP-3 $\gamma_L=1.15-1.20$	68.2	6.3	77.3	13	7.7	22
	STP-4A $\gamma_L=1.08-1.13$	68.2	6.3	77.4	13	8.2	30
I-84 EHWB	Legals $\gamma_L=1.34-1.39$	80.8	8.5	88.2	9	10.4	22
	CTP-3 $\gamma_L=1.32-1.37$	80.8	8.5	89.9	11	9.8	15
	STP-4A $\gamma_L=1.27-1.32$	80.8	8.5	90.0	11	10.0	17

[a]Statistics derived from WT1, WT2, and CTP's <99.0 kips from WT3 (alongside vehicle).

Discussion of Results

As described earlier, calibration of the LRFR specifications was performed using Ontario vehicle weight data of 1975 which were reasonably described by a 3S2 truck with a normal distribution and a mean of 68 kips and standard deviation of 18 kips for the top 20% of the truck weight population. The corresponding parameters for the Oregon weight data, calibrated using large WIM data sets, had higher mean but reduced standard deviations for the alongside truck population at each of the sites. The parameters indicate that there were significantly more overloads in the Ontario random truck data than are present in the Oregon legal loads or in the truck population grouped as the alongside truck. The maximum loading event for the LRFR calibration of load factors was controlled by the overloaded random trucks. It was shown that even when a permit truck of known weight up to 125 kips crosses the bridge, the expected maximum loading is lower compared with the maximum random legal loading event due to the many overloads in the random traffic (Moses 2001). That is, most routine permits do not affect the critical loading, which was governed by the nonpermit overloads. The reduced overloads in the Oregon data explain the reduced site-specific load factors. For example, the LRFR live load factor for legal loads is 1.80 for ADTT$\geqslant$5,000, while the Oregon-specific value is 1.40. Similar reductions in live load factors were seen for lower ADTT ranges, as well as for permit vehicles (Oregon's CTP and STP vehicles). These results are the outcome of the regulatory and enforcement environment in Oregon. The permit issuance and regulatory environment encourages the routine operation at above-legal load levels by means of low-cost continuous trip permits, and inhibits the operation of heavily overloaded "legal" vehicles within the traffic stream. The major factors affecting this condition include low cost and ease of obtaining permits, a weight-mile tax system that encourages loads spread onto more axles, development of the "trusted carrier" program that enhances cooperation and load compliance by trucking companies, and significant enforcement and hefty penalties for noncompliance. Previous research showed no statistically significant evidence of overweight truck scale avoidance (Strathman and Theisen 2002). The ability to minimize uncertainties in the truck population through the effective means described above has the effect of reducing the live load factors.

Policy Implementation

The ODOT Bridge Engineering Section plans to implement the AASHTO LRFR Specifications for rating and evaluation of state-owned bridges. The agency expects this implementation will preserve the safety of the traveling public in Oregon and to the greatest extent possible, facilitate the unrestricted movement of freight on Oregon's highways. These stated purposes are best served by assessing the load carrying capacity of Oregon's bridges as accurately as possible, to avoid the unnecessary restriction of freight movements while maintaining the nationally accepted reliability index. The large and diverse WIM data sets used in the live load factor calibration process produced consistent results and allowed establishment of Oregon specific versions of Tables 6-5 and 6-6 in the *LRFR manual*. The results are appli-

Table 9. ODOT Adaptation of LRFR Table 6-5 Generalized Live-Load Factors for Legal Loads: γ_L

Traffic volume (one direction)	Liveload factor γ_L by ADTT[a] (one direction)[b]			
	Unknown	$\geq$5,000	=1,500	$\leq$500
Liveload factor γ_L	1.40	1.40	1.35	1.30

[a]Interpolate the liveload factor by ADTT values. Liveload factors from this table should not be used when advanced methods of analysis are employed.

[b]If there are two directions of traffic, use only half of the structure ADTT to determine the liveload factors.

cable only to bridges on Oregon's state-owned highway system and provide an operational rating condition corresponding to the nationally accepted reliability index of 2.5. Live load factors from the I-5 Woodburn Northbound site (ADTT of 5,500) were taken to represent ADTT$\geq$5,000, and factors from the I-84 Emigrant Hill site (ADTT of 1,786) were taken to represent ADTT =1,500. The worst case of the factors from the sites on OR 58 at Lowell (ADTT of 581) and US 97 at Bend (ADTT of 607) was taken as representative of ADTT$\leq$500.

The calibrated live load factors described previously were adjusted for use in the ODOT policy implementation. It is recognized that calibrated live load factors in LRFR are merely statistical adjustments to the load effects to maintain a uniform level of structural reliability, and are not traditional amplification load factors as were used to provide a margin of safety in the AASHTO standard design specifications (AASHTO 2004). However, to assure additional conservatism where the calibration process resulted in very low live load factors, a minimum value of 1.0 was used. Additionally, the statistical calibration process used to compute the live load factors does not provide precision to the 100th decimal place. Therefore, rounding was applied to the live load factors, generally to the next higher 0.05 increment. The final tables for use in Oregon are shown in Tables 9 and 10.

To investigate possible changes in the truck population in the state, at 3 year intervals starting in 2008 until 2011 and every 5 years thereafter, ODOT will review the calibration process using 2-week windows of WIM data for each of the same four sites for each season, or will follow nationally accepted protocols that may emerge. If the mean or standard deviation values change enough to cause any live load factor to change by 0.05 or greater, based on the sensitivity analysis study, the Federal Highway Administration will be notified and a complete recalibration of the live load factors will be performed. This is a much more stringent standard of calibration data currency than has been applied to the calibration in the *LRFR manual*. In addition to these scheduled reviews, the Oregon-specific live load factors will be reviewed any time a significant statutory or administrative rule change occurs in the vehicle permit regulatory structure (how permits are issued and the fine structure for ticketed overloads) or if a significant change occurs in overweight vehicle enforcement procedures.

In the event that a future review or regulatory change triggers a decision to recalibrate the Oregon-specific live load factors, the calibration procedure will be repeated as described in the above methodology, or in accordance with any nationally accepted protocols that may have been established. The revised Oregon-specific live load factors will be applied to all subsequent load ratings. If the new live load factors are higher (more conservative) than before, ODOT will assess the accumulated body of LRFR load ratings and determine a minimum rating factor threshold to warrant rerating of bridges. Conservatively, this threshold would be set to match the upper bound percentage increase in the calibrated live load factors for any rating vehicle. Any bridges that have rating factors below this threshold will have the load ratings updated and load restrictions applied, as required. Additional detail regarding the implementation plans are reported by Groff (2006).

Conclusions

The first ever statewide calibration of live load factors for LRFR bridge evaluation and rating has been performed. This calibration employed the methodology described in the *LRFR manual* commentary Article C6.4.4.2.3 for development of site-specific live

Table 10. ODOT Adaptation of Upper Portion of LRFR Table 6-6 for ODOT Routine Permits

Permit type	Frequency	Loading condition	DF[a]	Permit vehicle	Liveload factor γ_L by ADTT[b] (one direction)[c]			
					Unknown	$\geq$5,000	=1,500	$\leq$500
Continuous trip (annual)	Unlimited crossings	Mix w/traffic (other vehicles may be on the bridge)	Two or more lanes	CTP-2A	1.35	1.35	1.35	1.25
				CTP-2B	1.35	1.35	1.35	1.25
				CTP-3	1.45	1.45	1.40	1.30
Single trip	Route-specific limited crossings	Mix w/traffic (other vehicles may be on the bridge)	Two or more lanes	STP-3	1.25	1.25	1.20	1.10
				STP-4A	1.40	1.40	1.35	1.25
				STP-4B	1.00	1.00	1.00	1.00
				STP-5A	1.10	1.10	1.05	1.00
				STP-5B	1.05	1.05	1.05	1.00
				STP-5C	1.00	1.00	1.00	1.00
				STP-5BW	1.00	1.00	1.00	1.00

[a]DF=LRFD liveload distribution factor. When one-lane distribution factor controls for an exterior girder, the built-in multiple presence factor for one lane (1.2) should be divided out of the distribution factor.

[b]Interpolate the liveload factor by ADTT values. Liveload factors from this table should not be used when advanced methods of analysis are employed.

[c]If there are two directions of traffic, use only half of the structure ADTT to determine the liveload factors.

[d]DF=LRFD liveload distribution factor. When a one-lane distribution factor is used, the built-in multiple presence factor for one lane (1.2) should be divided out of the distribution factor.

load factors. WIM data were used to develop the live load factors for evaluation and rating of state-owned bridges. The factors were calibrated using the same statistical methods used in the original development of the LRFR specifications. Due to the unique jurisdictional and enforcement characteristics in the state, modifications were used to described the alongside truck population and conservatively included continuous trip permit vehicles in this population. WIM data were filtered, sorted, and checked for quality as part of the calibration process. Using the statistical data from four WIM sites with different ADTT volume, at different times of the year, and over different WIM data collection windows, live load factors were computed. The Oregon-specific live load factors were smaller than those in the LRFR specification. The factors were smaller for the lower volume sites and smaller for the heavier permit trucks. The high volume site showed little seasonal variation, was insensitive to direction of travel, and 2 weeks of data were sufficient to produce consistent factors. For the lower volume sites, some seasonal variation was observed with higher load factors during summer and fall due to agricultural and construction transport. In all cases, the largest computed live load factor from each data set was used to describe the WIM site. By employing the procedures used to develop the LRFR specification, the resulting live load factors maintain the nationally accepted structural reliability index for evaluation, even though the resulting state-specific live load factors were smaller than the national standard. The large WIM data sets used in the state-specific calibration process were significantly larger than that used in the original LRFD or LRFR calibration process. Finally, policy implementation for the Oregon-specific factors included rounding the computed values to the next highest 0.05, setting a lower limit of 1.0 for the live load factors, and establishing provisions for maintenance of the factors into the future.

Appendix. Example Calculation of Live Load Factors

The following section provides a detailed example for calculating live load factors. Data from the I-5 Woodburn NB site for June 2005 (2 weeks, 1st–14th) are used to illustrate the procedure. Live load factors are calculated for Oregon legal loads, CTP-2A, CTP-2B, CTP-3, and STP-3. The statistics used in demonstration of the calculation for the live load factors are shown in the following table and the loading scenario is illustrated in Fig. 1.

Statistics for I-5 Woodburn NB, June 2005 (2 weeks, 1st–14th)

	Using the top 20% of the WIM record		
Vehicle	Max GVW	Mean W^*	σ^*
3S2-legal	80^K	75.1^K	2.0^K
Alongside truck	105.5^K	83.9^K	9.7^K

1. *Load factor for Oregon legal loads*. Using a $1/30$ probability of side-by-side events for two legal trucks, a 5 year evaluation period, an ADTT=5,550, and taking the top 20% of the record, the number of side-by-side events N

$$N=(5{,}550)(365)(5)(1/30)(1/5)=67{,}525$$

$$1/N=1.4809\times10^{-5}$$

From NCHRP 454, Appendix: $t_{\text{ADTT}}=4.18$

$$R_T=75.1+4.18\times2.0=83.3^K$$

$$A_T=83.9+4.18\times9.7=124.5^K$$

$$W_T=83.3^K+124.5^K=207.8^K$$

$$\gamma_L=1.8\times\frac{207.8}{240}\times\frac{72}{80}=\mathbf{1.40}$$

→ This is the controlling value for ADTT ⩾ 5,000

2. *Load factors for continuous trip permits (CTP)*. ODOT has estimated that CTPs are about 30% of legal truck traffic on I-5 for determining the number of side-by-side events, N (CTP adjacent to a legal truck)

$$N=67{,}525+0.30=20{,}258$$

$$1/N=4.9364\times10^{-5}$$

From NCHRP 454, Appendix: $t_{\text{ADTT}}=3.89$

$$A_T=83.9+3.89\times9.7=121.8^K$$

a. For 105.5^k CTP (CTP-2A/2B)

$$R_T=105.5+3.89\times9.7=143.4^K$$

$$W_T=143.4^K+121.8^K=265.2^K$$

$$\gamma_L=1.8\times\frac{265.2}{240}\times\frac{72}{105.5}=\mathbf{1.36}$$

→ This is the controlling value for ADTT ⩾ 5,000

b. For 98^k CTP (CTP-3A)

$$R_T=98+3.89\times9.7=135.9^K$$

$$W_T=135.9^K+121.8^K=257.7^K$$

$$\gamma_L=1.8\times\frac{257.7}{240}\times\frac{72}{98}=\mathbf{1.42}$$

3. *Load factor for* 120.5^K *STP-3 (same method for all STP vehicles)*. From Table 3, $N_P=97$

$$N=(97)(365)(5)(1/30)=5{,}901$$

$$1/N=1.6947\times10^{-4}$$

From NCHRP 454, Appendix: $t_{\text{ADTT}}=3.58$

$$A_T=83.9^K+3.58\times9.7^K=118.8^K$$

$$R_T=120.5+34.7=155.4^K$$

$$W_T=155.4^K+118.8^K=274.1^K$$

$$\gamma_L=1.8\times\frac{274.1}{240}\times\frac{72}{120.5}=\mathbf{1.23}$$

→ This is the controlling value for ADTT ⩾ 5,000

where N=number of concurrence events during evaluation period; t_{ADTT}=normal variate for $1/N$ level; A_T=GVW of the alongside truck; R_T=GVW of the reference or rating truck; W_T=GVW of the alongside and reference trucks on both lanes; and γ_L=two-lane loaded live load factor for evaluation and rating of state-owned bridges in Oregon.

References

AASHTO. (1994). *Manual for condition evaluation of bridges*, Washington, D.C.

AASHTO. (2003). *Manual for condition evaluation and load and resistance factor rating (LRFR) of highway bridges*, Washington, D.C.

AASHTO. (2004). *LRFD bridge design specifications*, 3rd Ed., Washington, D.C.

Groff, R. (2006). "ODOT LRFR policy report: Liveload factors for use in load and resistance factor rating (LRFR) of Oregon's state-owned bridges." *Rep.*, Oregon Department of Transportation, Salem, Ore.

Minervino, C., Sivakumar, B., Moses, F., Mertz, D., and Edberg, W. (2004). "New AASHTO guide manual for load and resistance factor rating of highway bridges." *J. Bridge Eng.*, 9(1), 43–54.

Moses, F. (2001). "Calibration of load factors for LRFR bridge evaluation." *NCHRP Rep. No. 454*, Transportation Research Board, National Research Council, Washington, D.C.

Novak, A. (1999). "Calibration of LRFD Bridge Design Code." *NCHRP Rep. No. 368*, Transportation Research Board, National Research Council, Washington, D.C.

Pelphrey, J., and Higgins, C. (2006). "Calibration of LRFR live load factors for Oregon state-owned bridges using weigh-in-motion data." *Kiewit Center for Infrastructure and Transportation Rep.*, Dept. of Civil Engineering, Oregon State Univ., Corvallis, Ore.

Strathman, J. G., and Theisen, G. (2002). "Weight enforcement and evasion: Oregon case study." *Rep.*, Center for Urban Studies, College of Urban and Public Affairs, Portland State Univ., Portland, Ore.