SUMMARY**REPORT**

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Correlation of Bridge Deck Deterioration With Truckload Spectra Based on NBI Condition Rating and Weigh-In-Motion Data

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ABSTRACT

Bridge decks, deemed critical components of the infrastructure network, have been observed to have premature deteriorations and shortened service life. Deterioration is usually modeled to depict reduction in bridge condition over time which can assist highway agencies in predicting bridge service life. However, bridge deterioration models are generally based on condition ratings from visual inspection data that do not include quantifiable measures of dominant contributors such as environmental conditions and overweight-truckload spectra.

This paper presents results from a study that established a relationship between truckload spectra and bridge service life at the national, regional, and State levels. Weigh-in-motion data and bridge inspection data were obtained nationwide from the Long-Term Pavement Performance and Long-Term Bridge Performance Programs, respectively. The study used weigh-in-motion data to obtain various truck-loading statistics for all trucks fleet weights, overweight trucks fleet weights, single-axle weights, tandem weights, and tridem-axle weights. Condition ratings from the National Bridge Inventory (NBI) database were used to develop the deck deterioration

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models. The impact of the various truckloads on bridge deterioration were then evaluated. The results of the study indicated that the design load of bridge deck is unable to envelop the actual traffic loadings, thereby imposing risks of premature deterioration of bridge decks. Additionally, the study found that daily axle counts had negative impacts on bridge deck service life and that increases in single-axle and tandem-axle load spectra correlate inversely with bridge deck service lives.

INTRODUCTION

Highway agencies have remitted numerous expenditures on inspection, maintenance, repair, and rehabilitation of infrastructures to ensure their safe load-carrying capacity. Among various factors, overweight trucks have been major contributors in expediting the deterioration processes of various types of bridge decks. Although Federal and State laws legislate legal weight limits, the actual truck loadings do not always conform to legal weight limits due to the loose enforcement.

It is well accepted that reinforced-concrete bridge decks, directly carrying traffic loading, are vulnerable to heavy truck loadings.[1] Their performance has been the subject of many research projects for decades because they are observed to have premature deteriorations due to various reasons, among which the load-driven factors are deemed to make great contributions. Moreover, studies from the early 1990s presented a probabilistic procedure to evaluate the impacts of truckloads on bridges based on limited data from bridge weigh in motion WIM (B-WIM) and truck surveys collected from sites and weigh stations on Michigan highways.[2,3] Nowadays, truck traffic tends to be even greater and heavier. Lou et al. processed consecutive weigh in motion (WIM) data for 20 years and found that both the annual maximum gross vehicle weight (GVW) and the daily number of overweight trucks exhibited increasing trends.[4] With the truck industry's introduction of specialized hauling vehicles (SHVs) in the past two decades, the number of tandem and tridem axles also shows great potential to grow.[5,6] Yang, Lou, and Nassif investigated the statistics of the single-, tandem-, and tridem-axle weights by using 32 nationwide WIM sites.[7] The authors found that design load may not envelop actual load spectra. Additionally, tridem axles are likely to cause higher load effects than do single and tandem axles, since axles with heavier total weight are closely spaced to provide amplified load effects on decks; however, tridem axles are not considered in American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) deck design procedures.[8]

State agencies are under increasing pressure to make optimal funding allocations to maintenance, rehabilitation, and replacement for bridges because of aging structures and funding shortages. Agencies to a great extent rely on the deterioration model to predict future bridge condition and to allocate funding. For the state of practice, deterioration models are, mostly, statistical models originated from visual inspection data, and agencies have successfully used them in bridge management systems.

Because the shortened service lives of bridge decks and the increasing truck loadings were observed together, there could be an inherent relationship between truck loading and bridge deck service life. Lou et al. proved the above statement by correlating the expected service lives of bridge decks and axles per day, equivalent wheel load, and percentage of overweight trucks.[1] However, that study used bridge inspection data and WIM data from New Jersey only, so the conclusion may not be applicable nationally.

On account of the above-mentioned grim facts for bridge decks, the objectives of this study were twofold: The first objective was to quantify truck traffic loading on bridge decks, with a focus on overweight trucks and concentrated axle loads (i.e., single-axle, tandem-axle, and tridem-axle loads). With the development of the Long-Term Pavement Performance (LTPP) Program, nationwide traffic data were accessible to quantify the truckload statistics.[9] After truckload spectra became known, the second objective of this study was to correlate bridge deck service life and load spectra. Taking advantage of the Long-Term Bridge Performance (LTBP) Program, the service life of the bridge decks was quantified, and eventually, the correlation between service life and truckload spectra were developed.[10]

DATABASE

To accomplish the twofold objective of this study, data from both truckload spectra and bridge deck inspection have to be considered. Therefore, the study used two databases supported by the Long-Term Infrastructure Performance (LTIP) Programs: one for truck weight data and another one for bridge inspection data.

WIM Data

Truck axle loads and configurations were obtained from WIM sites available from the LTPP InfoPave™ website.[9] For the design and evaluation of bridges, full truck configurations are of more concern (i.e., axle weights and axle spacings). The LTPP InfoPave collects and stores individual vehicle configuration records in the Ancillary Data Selection and Download function.

Until the date that the authors extracted the WIM data, there were 684 accessible WIM sites from more than 40 States in the United States, and the authors extracted all of them. However, data from many of the WIM sites were deemed not beneficial for this study. The front axle weights (FAWs) of Federal Highway Administration (FHWA) Class 9 trucks (3S2, semi-tractor trailers) are regressed to first-axle spacing by using the WIM data validating approach described by Southgate.(11,12) These Class 9 3S2 type trucks were utilized by Southgate not only because they are typical commercial vehicles but also because the FAW and steering axle spacings are in a steady relationship. The first-axle spacing (S12) and the ratio of the steering axle weight to the first-axle spacing (A1/S12) were established by using this technique as a logarithmic relation. The 12-kip practical weight limit serves as the upper bound, and the minimum requirements for truck manufacturers serve as the lower bound. The quality of the WIM data is deemed satisfactory if most of the class 9 truck data fall within the upper and lower bounds.

After filtering out of all the above-mentioned WIM sites, 203 sites remain from interstate highways, U.S. highways, and State highways across 37 States in the United States. In the later study, bridge deck service life is obtained for nine climate zones.(13) Therefore, the WIM sites were also classified into climate zones to capture regional traffic load variations and to better correlate with deck condition in the same region. The numbers of WIM sites in different climate regions and on different highways are summarized in table 1. It is worth noting that WIM data available in the LTPP database represent only a subset of all of the WIM data collected from agencies nationwide. With more data available in the future, truckload spectra would become more representative and accurate.

Bridge Inspection Data

The bridge inspection data were obtained from the LTBP InfoBridge™ website. The LTBP InfoBridge offers NBI and NBE data, however, this study used only NBI data because it covers an extensive number of historical records.

The NBI database has very detailed information for highway bridges in the United States, including identification and location, structure type and materials, dimensions and clearances, inspections, condition ratings and evaluations, load ratings and postings, and traffic and roadway data. For the purposes of this study, the authors extracted the following information from the NBI database:

Table 1. Number of WIM sites.

Climate Region	Interstate Highway	U.S. Highway	State Highway
Northeast	9	5	7
Upper Midwest	8	11	3
Ohio Valley	20	12	7
Southeast	6	14	2
Northern Rockies and Plains	3	2	4
South	5	13	3
Southwest	8	1	1
Northwest	4	7	7
West	18	4	5

1. State name.
2. Structure number.
3. Record signing prefix.
4. Location.
5. Deck structure type.
6. Deck condition rating.
7. Inspection date.
8. Year built.
9. Year reconstructed.

Items 1 to 4 provide a structure's identification and location. Since this study focused on the reinforced-concrete bridge deck, item 5 is necessary to distinguish deck types. Deck structure type coded as "1," representing a concrete cast-in-place deck, is the target of the study. In the NBI database, bridge deck condition is evaluated as condition rating (CR) on a scale from 9 to 0, and the corresponding condition descriptions are tabulated in Table 2.(14) This inspection scheme rates the deck as a whole component, assigning only one deck rating for one bridge. The aforementioned item 6 provides CR information. Items 7 to 9 are for calculation of bridge age, which counts number of years from either year built or year of reconstruction to year of inspection.

Table 2. Description of NBI condition ratings.[14]

Condition Rating	Condition	Description
9	Excellent	—
8	Very good	No problem noted.
7	Good	Some minor problems.
6	Satisfactory	Structural elements showing some minor deterioration.
5	Fair	All primary structural elements sound but may have minor section loss, cracking, spalling, or scour.
4	Poor	Advanced section loss, deterioration, spalling, or scour.
3	Serious	Loss of section, deterioration of primary structural elements, perhaps fatigue cracks in steel or shear cracks in concrete.
2	Critical	Advanced deterioration of primary structural elements, perhaps fatigue cracks in steel or shear cracks in concrete or scour, which may have removed substructure support, and unless closely monitored, may necessitate closing the bridge until corrective action is taken.
1	Imminent failure	Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement that is affecting structure stability; bridge closed to traffic, but corrective action may put it back in light service.
0	Failed	Out of service; beyond corrective action.

— No data.

DATA PROCESSING

WIM Data Processing

A bridge safety evaluation relies largely on a load demand analysis. The development of WIM technology enhances bridge engineers' understanding of truckload spectra. Nowak, Nassif, and DeFrain applied WIM data to investigate the effects of truckloads on steel bridges.[2] Lou et al. used WIM data to quantify the impact of overweight trucks on bridge girders.[4]

With the prior experience in developing the live-load statistics for bridge decks by using WIM data, the authors have found that tandem- and tridem-axle weights are critical parameters in addition to the single-axle load.[7] Therefore, the axle group statistics were of interest while processing WIM data. To detect the various axle groups, including single, tandem, and tridem axles, a previously developed algorithm was followed.[7]

In addition to the axle group statistics, this paper also investigates overweight-vehicle statistics. For interstate highway bridges across the United States, overweight trucks are defined as vehicles that do not conform to Federal weight limits:[15]

- GVW exceeds 80 kips.
- Single axle exceeds 20 kips.
- Tandem axle exceeds 34 kips.
- Axle configuration does not follow Federal Bridge Formula B (FBF-B).

For non-interstate highways, State weight limits that may or may not be the same as Federal limits are used to restrict truck weight. According to a previous literature review, 20 States follow Federal weight limits, while the 30 other States exceed at least one of the Federal weight limits.[16] However, to derive a standardized overweight-truck statistic, Federal weight limits are applied to both interstate highway and non-interstate highway routes.

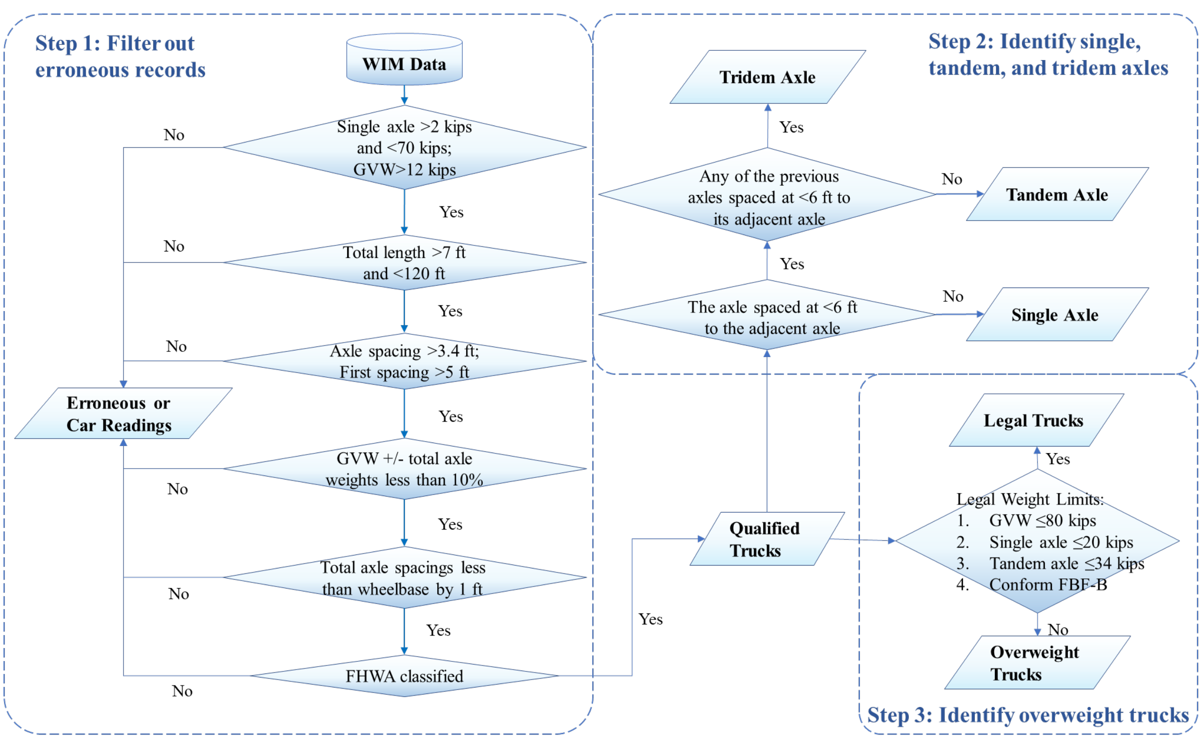
In summary, the WIM data processing program was developed as shown in figure 1. The truckload statistics are presented in a series of box plots from figure 2 to figure 6. In the box plot, the line inside the box is the median value. The top and bottom edges of the box are the upper and lower quartiles, respectively. The vertical whisker lines connect the quartiles to the nonoutlier maximum and minimum values, and the circle markers beyond the maximum and minimum values are the outliers.

As aforementioned, it is well recognized that bridge decks are subjected to truck loading with increasing volume and weight, yet there is a lack of study to quantify how much and how heavy the loads are nationwide. This study hereby intended to provide insight into truckload spectra on bridge decks. The truck traffic information is presented in the following sections. Qualified trucks envelop all truck types passing through WIM stations. The qualified vehicle population were obtained by performing step 1 as shown in figure 1. The average daily truck traffic (ADTT) in different climate zones and for different roadway types is plotted in figure 2. Interstate highways have the highest truck counts, and state highway and U.S. highway carry comparable amount of truck traffic.

The axle group, being regarded as the major contributor to the damage of bridge decks, was extracted from the WIM data by performing step 2 as shown in figure 1. Current AASHTO LRFD Bridge Design Specifications (BDS) prescribe deck design load as a 32-kip single axle or a 50-kip tandem axle(8). However, a National Cooperative Highway Research Program (NCHRP) Project 12-76(17) and Transportation Research Board consensus study report(18) pointed out that actual load spectra could be much heavier than design load. Moreover, tridem axles, emerging along with SHVs, could be even heavier and are not reflected in design loads. Figure 3, figure 4, and figure 5 show the upper-tail mean value of the single-, tandem-, and tridem-axle weights, respectively. The top-5-percent tail was selected to represent the uppertail statistics. The plots indicate the great potential of axle loads to exceed the design load, implying the tendency of load-induced deterioration of bridge decks.

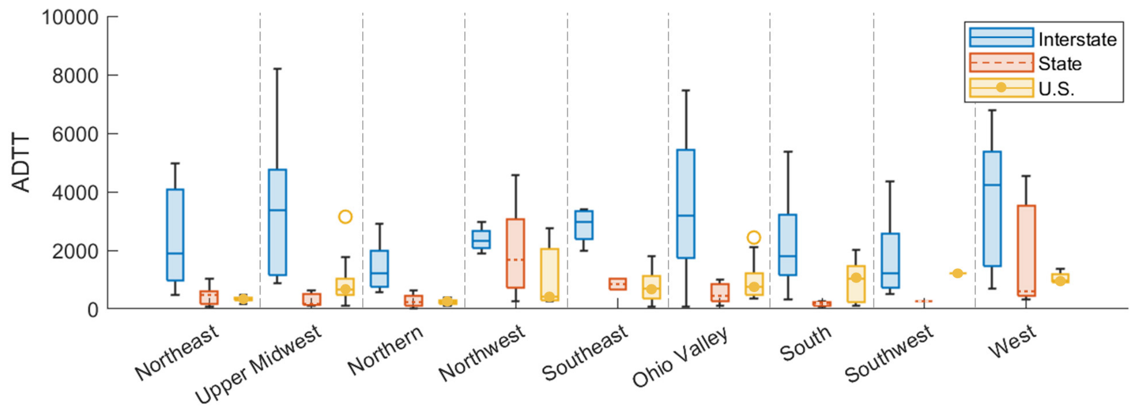
Furthermore, the overweight truck populations are quantified. The overweight trucks were identified from WIM data by performing step 3 as shown in figure 1. Figure 6 depicts the overweight-truck percentage. It is observed that overweight trucks actually take up a great portion of the truck population, thereby alerting State agencies to tighten enforcement on illegal overweight trucks because such trucks could significantly increase the lifecycle cost of bridges and pavements.

Figure 1. Flowchart for WIM Data Processing.



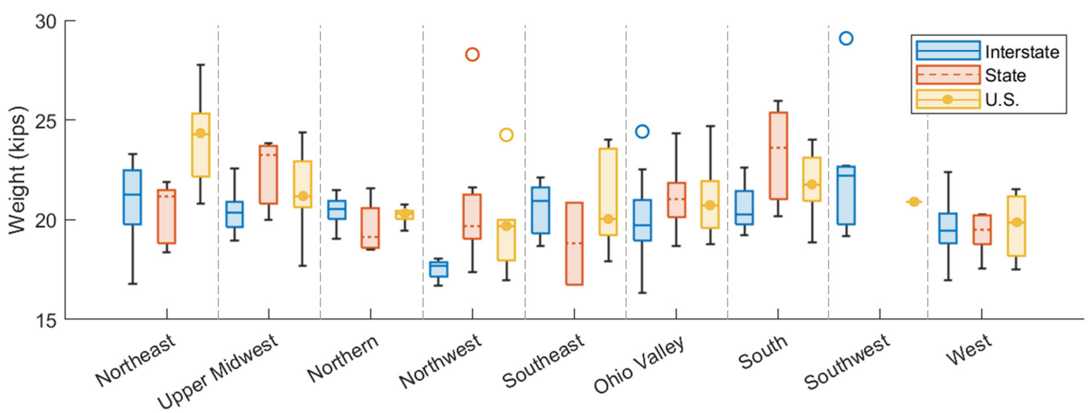
Source: FHWA.

Figure 2. Average Daily Truck Traffic (ADTT).



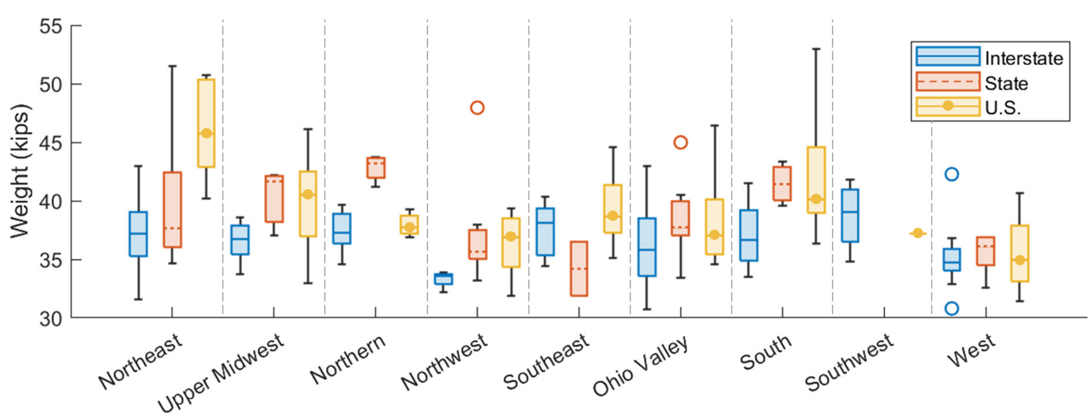
Source: FHWA.

Figure 3. Average of top-5-percent single-axle weight.



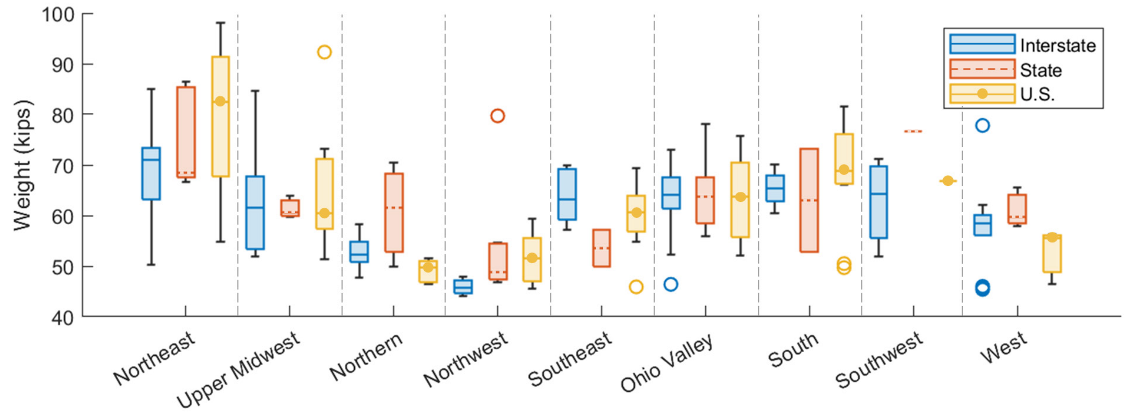
Source: FHWA.

Figure 4. Average of top-5-percent tandem-axle weight.



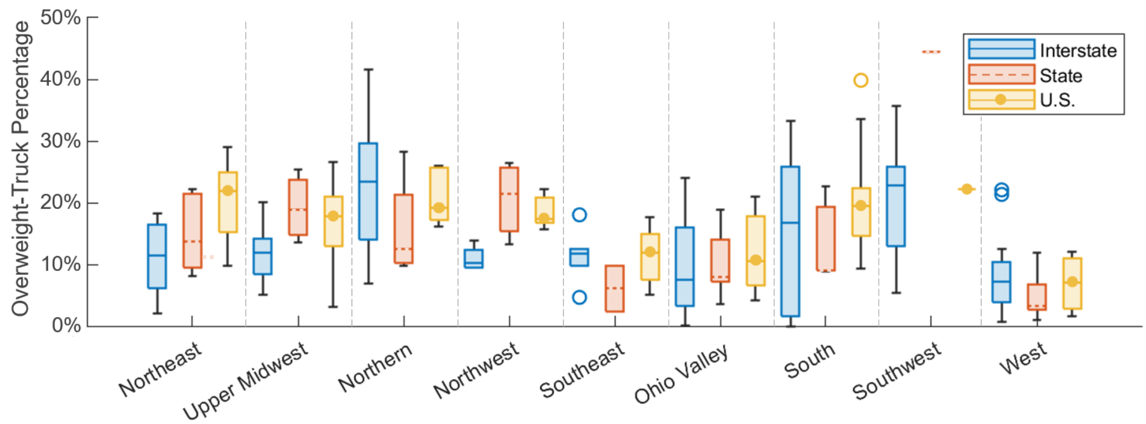
Source: FHWA.

Figure 5. Average of top-5-percent tridem-axle weight.



Source: FHWA.

Figure 6. Percent of overweight trucks.



Source: FHWA.

Bridge Inspection Data Processing

The authors obtained bridge inspection data from LTIP InfoBridge™, and they identified sufficient bridge populations on different highway systems in nine climate zones, thereby ensuring a reliable statistical analysis of deck service life. Before adoption of inspection data for service life analysis, certain filtering works are necessary to eliminate the impact of erroneous or biased data. The detailed explanations are as follows.

There are various reasons for questioning data quality. First, faulty records exist whose CR values are non-integers or larger than nine, whereas correctly recorded CR should be integers from 9 to 0 per FHWA's *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*.[14] Second, there are inspection records earlier than the structure's built year, resulting in a negative bridge age. The authors' experience with agencies' bridge inventory has shown instances in which a newly constructed bridge has been assigned the same structure number of a demolished bridge at the same location. In such a situation, inspection records may be served for the historical bridge that no longer exists, so that the CR records are no longer valuable. Therefore, the records with negative bridge age calculated from the year of reconstruction were filtered out. Last, because a bridge deterioration model intends to capture and predict the natural deterioration of bridge components without interference by repair and rehabilitation work, it is necessary to omit inspection records after preservation work. However, LTBP Info Bridge does not include detailed work history data for individual bridges, and even for agencies' in-house records, maintenance history might not be complete.[19,20] Therefore, in this study, inspection records of bridges whose decks showed improvement in condition were excluded from the analysis. Although that filtering criterion is widely accepted when there are no maintenance histories, its potential defects were pointed out: The first is that maintenance may not improve deck condition but may slow down deterioration rate, and a second is that condition improvement may result from random error rather than preservation work, such as inspector's bias.(21)

After the authors bridge inspection data were filtered and cleaned, the data were grouped into different climate regions because climates are deemed to have an impact on bridge condition.(21) For example, bridge decks in the northern region would experience more chloride-induced rebar corrosion due to the use of deicing salt.

The cleaned data should present particular distribution of bridge age at a rating. For example, figure 7 shows the frequency distribution of the bridge age of bridges in the Interstate Highway System in the southeast region. It is observed that for good conditions (e.g., CR 9 and CR 8) age distributions skew to the left, meaning that newer bridges tend to be in better condition than older bridges are. As bridge deck deteriorates, the skew of the age distribution started to move toward the right, meaning that older bridges tend to be in worse condition.

CORRELATION BETWEEN TRUCK LOADING AND DECK SERVICE LIFE

Truckload Spectra

For bridge decks of slab-on-girder bridges, the truckload-induced load effects result mainly from the concentrated axle loads, so number of loading cycles is defined by daily axle count in this study. Load spectra for single, tandem, and tridem axles, which are deemed influential to bridge decks, are extracted respectively. Equation 1 converted wheel load spectra into one value—namely, the equivalent wheel load. In addition, the authors collected daily overweight counts to analyze the potential impact of overweight loadings on bridge deck service life. The statistics of the truckload spectra are presented in a later section.

$$P = \sum f_i(p_i) \times p_i, \qquad (1)$$

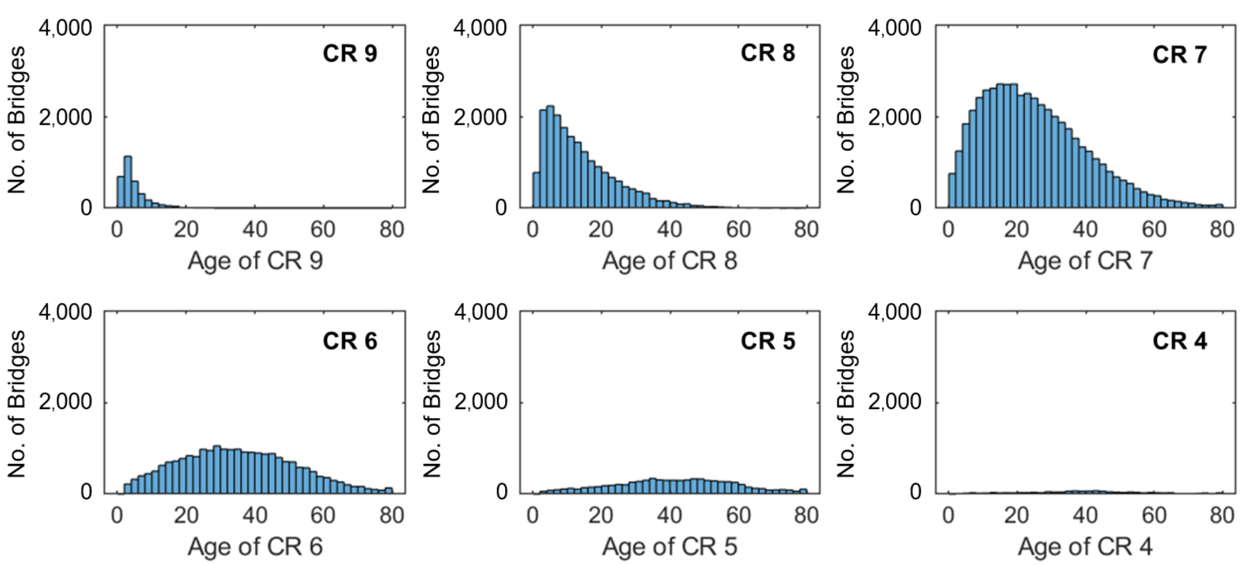
Where:

P = equivalent wheel load from weight distribution.

p_i = value of wheel weight in wheel weight distribution (kips).

$f_i(p_i)$ = frequency for that wheel load.

Figure 7. Frequency distribution of bridge age at different conditions: Southeast region interstate highway bridges.



Source: FHWA.

Bridge Deck Service Life

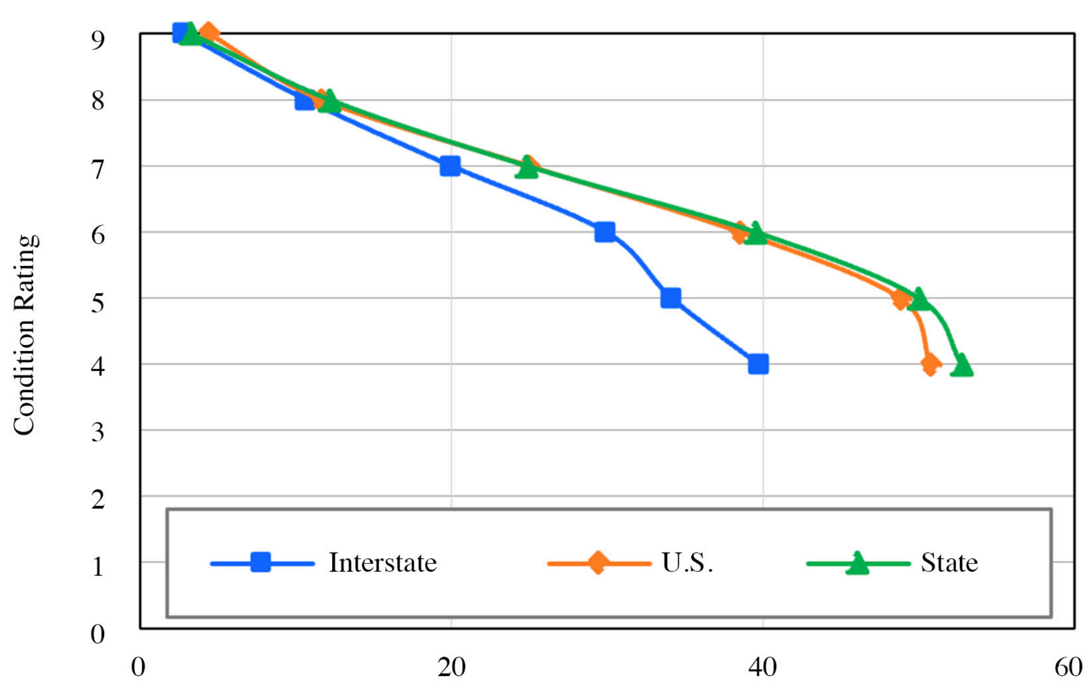
State agencies have widely used deterioration models that present condition rating (CR) versus bridge age to predict bridge service life. Previous studies concluded that a bridge deck would be planned for major repair or rehabilitation when its condition rating was downgraded to 4.[22,23] In addition, NBI data have few records with CR equal to or smaller than 4, indicating that agencies are not willing to allow their structure to downgrade to "poor condition" or "critical condition" (i.e., CR 4 or CR 3). As a result, in this study, bridge deck service life is defined as the age when a deck is downgraded to CR 4.

To derive the deterioration model, the average age of each condition rating is obtained. For example, bridge records of the Interstate Highway System in the southeast region, as a continuation of figure 7, are plotted in figure 8. It is observed that the bridge deck on the interstate highway route deteriorates faster than the others. This phenomenon resulted from the larger truck volume on the interstate highway, as shown in figure 2. Additionally, figure 8 shows that the deck smoothly downgrades from CR 9 to CR 6, and then the deterioration starts to accelerate when the deck is in worse condition. That deterioration trend is observable among all the other cases under investigation. Such a phenomenon could be explained by the fact that once cracks formed on the deck, cyclic truck loading accelerates deterioration by expediting the transport of chloride ions through the developed deck cracks rather than by regular diffusion of chlorides in a good-condition deck. The experimental test proved that cyclic loading stimulates crack opening on bridge decks, allowing water penetration and eventually compromising ultimate strength.[24] From a microscopic view, rebar corrosion rate in an acidic environment also exhibits an accelerating rate, being smooth in the crack initiation phase and aggressive in the crack propagation phase.[25]

To capture the nature of the deck deterioration rate, the third-order polynomial was adapted to develop the deterioration model, and figure 9 shows the fitted models. While fitting the data with the regression curve, CR4 records were not taken into consideration due to their small population. The R-squared (R^2) value is presented in the plot to show how well the data fit the regression model. R^2 values range from 0 to 1. A value of 1 indicates a perfect goodness of fit, and a value of 0 indicates that the model could not explain the variability of the variable. In the fitted model, all of the R^2 values are close to 1, indicating adequate strength of the relationship between the fitted model and the real measurement.

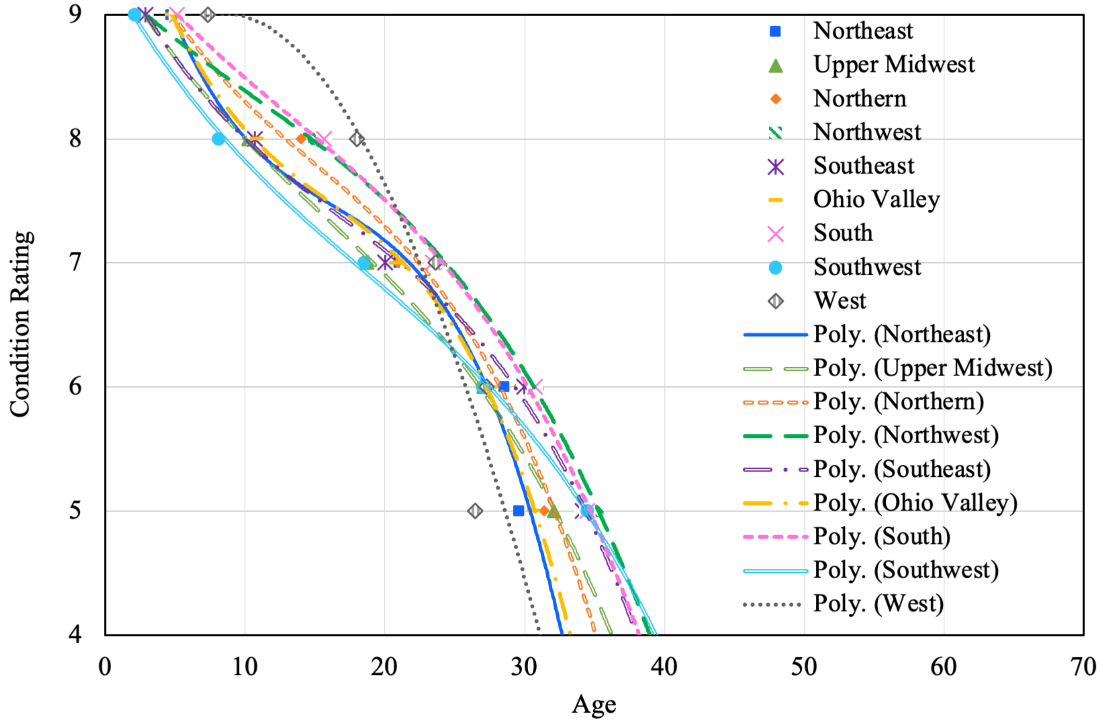
The third-order polynomial fitted well with the data except for State highway bridges in the west region. In the west region, the regression model bounces back to good condition as age increases, overfitting the actual data and overlooking the nature of the deterioration trend. Thus, the data point from the west region on the State highway was disregarded from the later analysis.

Figure 8. Average age of bridge deck at different conditions.

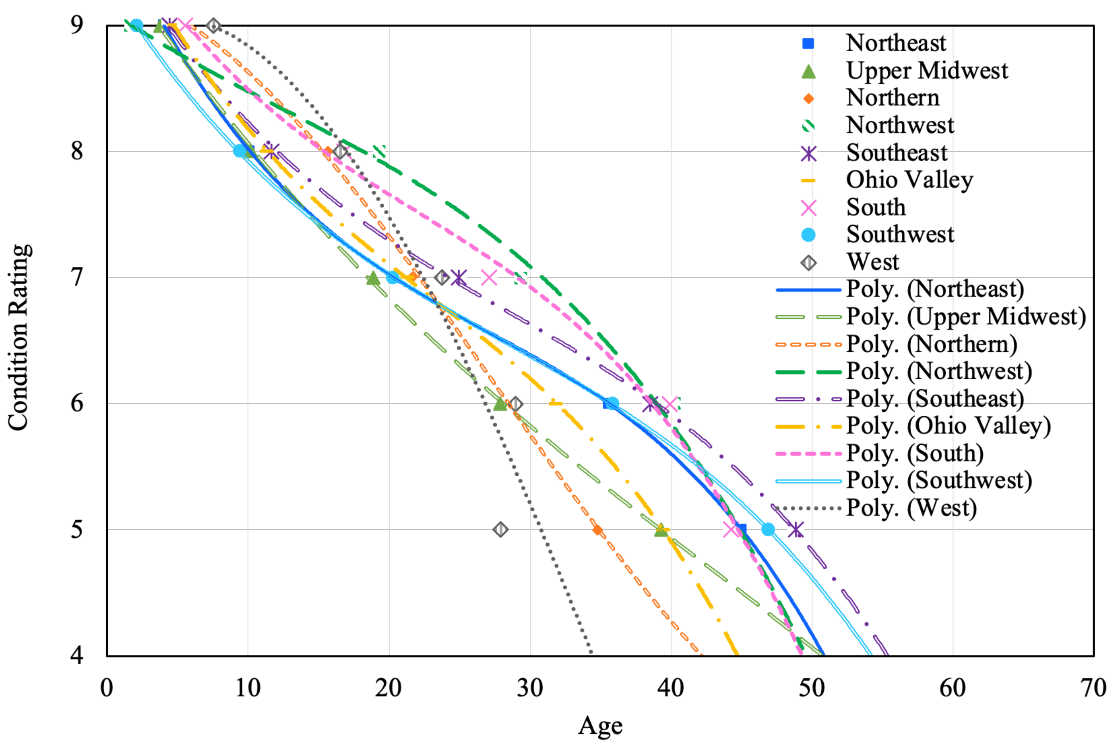


Source: FHWA.

Figure 9. Deterioration model (A) Interstate highway, (B) U.S. highway, (C) State highway.



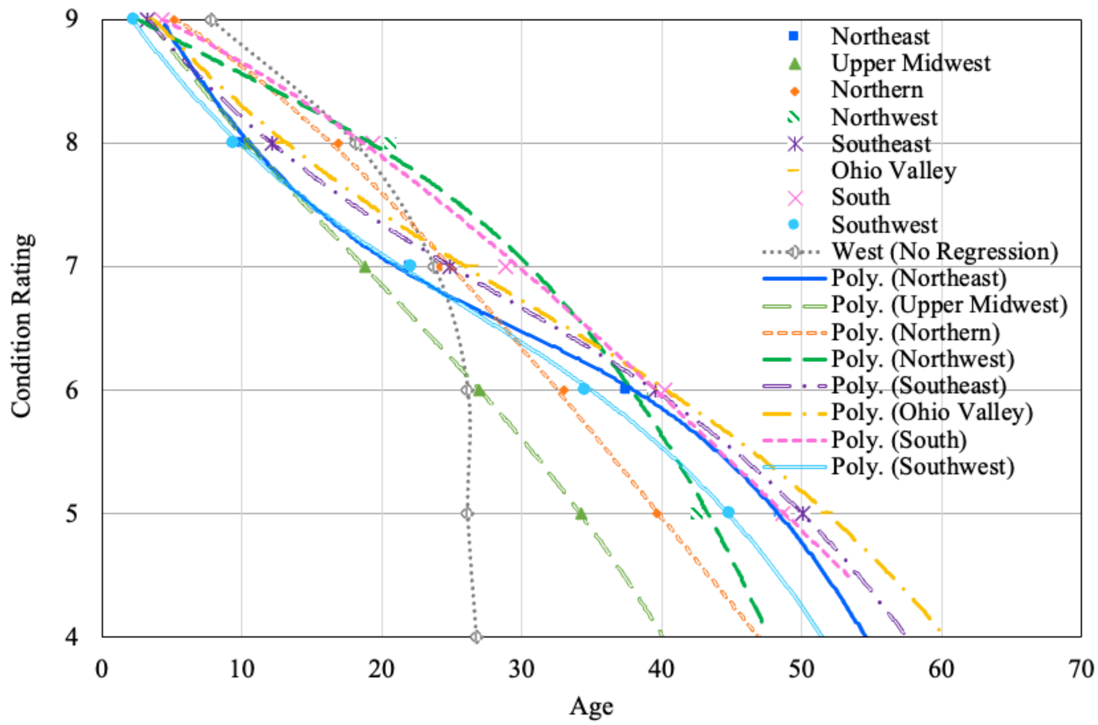
A. Interstate highway.



B. U.S. highway.

Source: FHWA.

Figure 9. Deterioration model (A) Interstate highway, (B) U.S. highway, (C) State highway. (Continued)



C. State highway.

Source: FHWA.

Correlation Between Deck Service Life and Truckload Spectra

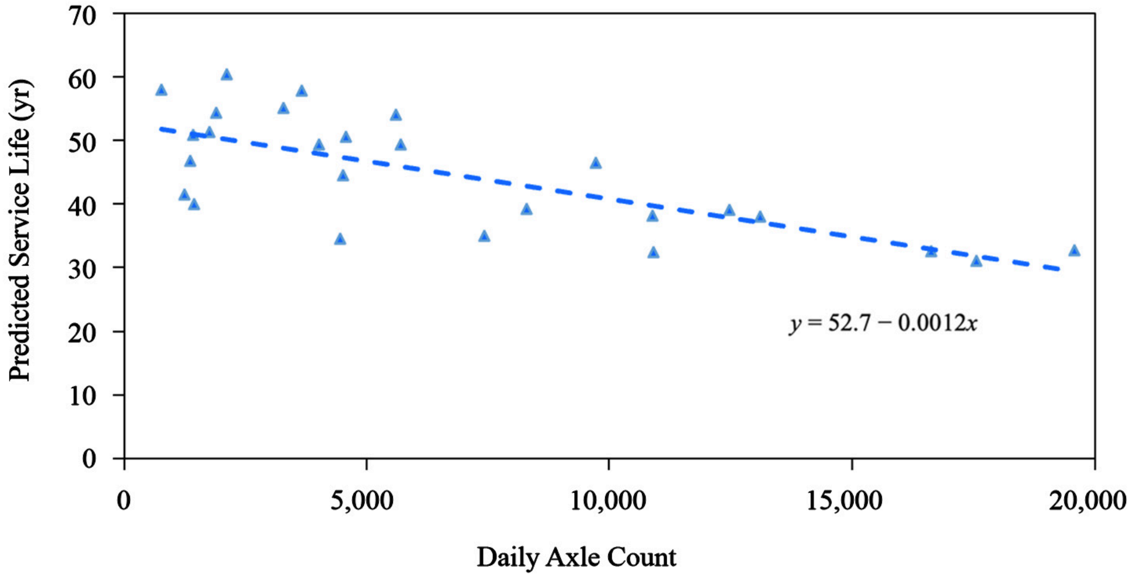
Load spectra and expected service life obtained from the previous analysis are tabulated in table 3. For visualization, the relationship between load parameters and service life is plotted in figure 10. From figure 10(A), the daily axle count was observed to have a clearly negative relationship to service life, indicating that load cycles reduce service life. According to the linear regression line, an increment of 1,000 axle counts would reduce service life 1.2 years. From figure 10(B) and figure 10(C), the single and tandem axle equivalent loads also adversely affect service life, indicating that heavier axle loads are more likely to damage concrete decks. Similarly, the overweight axle count was also found to have a negative relationship with service life, further confirming the inverse impact of heavy, overweight axles on bridge decks. The tridem axle load spectra were not found to have a strong correlation with deck service life, possibly due to the insufficient population of tridem axles.

Table 3. Load spectra and expected service life.

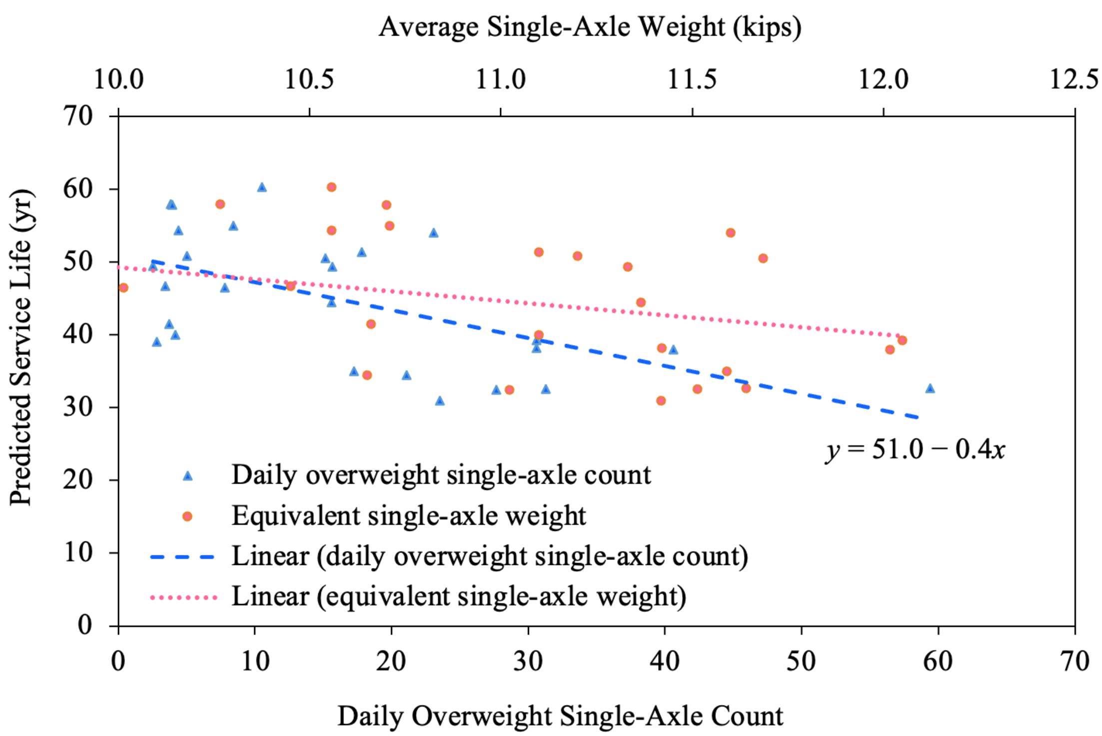
Route—Region		Deck Service Life (yr)	Daily Axle Count	Single Axle: Equivalent Weight (kips)	Single Axle: Daily Overweight Count	Tandem Axle: Equivalent Weight (kips)	Tandem Axle: Daily Overweight Count
Interstate	Northeast	32.4	7,284	11.5	16.9	21.7	133.1
	Upper Midwest	35.0	13,882	11.8	9.6	25.1	159.3
	Northern	39.0	5,868	9.9	1.4	20.6	26.2
	Northwest	32.7	5,088	11.6	26.4	22.1	181.5
	Southeast	38.2	6,507	12.0	20.3	23.5	254.2
	Ohio Valley	38.0	14,548	12.2	19.5	22.9	182.3
	South	39.2	16,221	12.4	18.4	24.9	148.3
	Southwest	32.5	6,507	12.0	17.4	22.5	149.1
	West	31.0	17,477	11.9	15.1	23.0	131.6
United States	Northeast	50.8	4,406	11.9	3.3	22.9	33.8
	Upper Midwest	41.5	5,136	10.6	1.4	22.8	24.0
	Northern	49.4	7,961	9.9	7.1	20.1	49.4
	Northwest	44.5	9,900	11.8	6.6	22.5	57.5
	Southeast	49.3	6,200	11.6	8.8	23.3	96.3
	Ohio Valley	55.0	6,496	11.0	3.9	21.0	44.8
	South	54.0	12,374	12.5	16.1	26.0	118.7
	Southwest	50.5	6,200	12.1	8.2	22.9	65.5
	West	34.5	4,758	10.8	7.9	21.8	24.0
State	Northeast	54.3	3,755	11.2	1.8	21.4	17.6
	Upper Midwest	46.7	11,236	9.8	2.1	23.3	27.9
	Northern	46.5	8,473	10.7	14.1	21.2	106.7
	Northwest	60.3	10,646	10.7	3.9	20.2	26.0
	Southeast	58.0	4,705	10.6	1.5	20.8	12.3
	Ohio Valley	57.8	2,057	11.0	3.2	20.2	17.7
	South	51.3	5,494	11.7	10.6	22.4	41.9
	Southwest	40.0	4,705	11.5	2.0	22.8	20.5
	West	—	7,849	11.1	6.4	21.4	86.8

—No data.

Figure 10. Relationship between expected service life and truckload (A) Daily axle count, (B) Single-axle-load spectra, (C) Tandem-axle-load spectra.



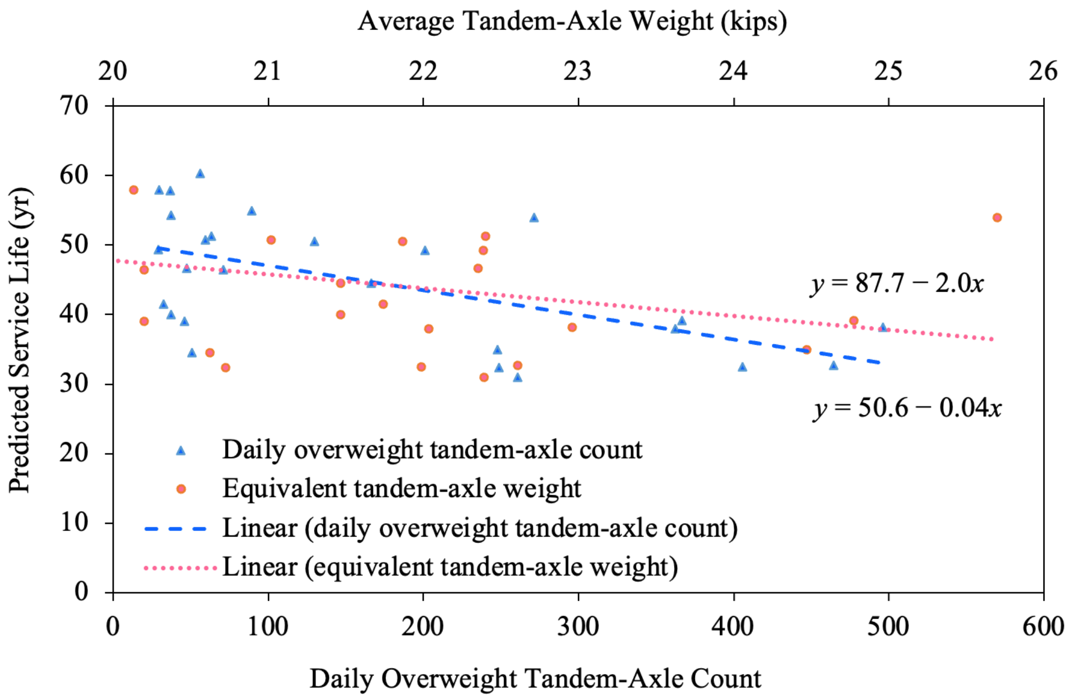
A. Daily axle count. 1



B. Single-axle-load spectra.

Source: FHWA.

Figure 10. Relationship between expected service life and truckload (A) Daily axle count, (B) Single-axle-load spectra, (C) Tandem-axle-load spectra. (Continued)



C. Tandem-axle-load spectra.

Source: FHWA.

CONCLUSIONS

This study used WIM data to identify truck traffic loading spectra for bridge decks, and it used condition ratings from the NBI database to derive deck deterioration models. The correlation between truckload spectra and bridge deck service life was quantified. The results of this study led to the following conclusions:

- Interstate highway bridge decks are subjected to more truck volume, resulting in shorter service life than decks located on the other routes.
- Bridge decks are subjected to single and tandem loads that are heavier than the design load as specified in the AASHTO LRFD BDS.[8] Additionally, a large number of heavy, tridem axles are not well accounted for in the BDS. There is a need to reassess design axle loads for bridge decks.
- All of the highway systems are subjected to overweight trucks, accounting for more than 15 percent, on average, of total truck traffic, on average, damaging bridges and roadways.
- The deterioration rate for bridge decks between good and satisfactory conditions (CR 9 to CR6) is relatively steady and smooth; however, the deterioration rate accelerated when decks downgraded to worse conditions—below CR 6.
- The authors found that based on data from all regions, truckload spectra closely correlated with bridge deck service life. In particular, an increment of 1,000 axle counts would reduce deck service life 1.2 years. Single- and tandem-axle load spectra are also inversely related to deck service life.

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