MEPDG Traffic Loading Defaults Derived from Traffic Pooled Fund Study

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FOREWORD

The *Mechanistic-Empirical Pavement Design Guide (MEPDG), Interim Edition: A Manual of Practice* requires detailed axle loading information in the form of normalized axle load spectra (NALS), number of axles per truck class and axle group types, and axle spacing inputs as part of traffic loading inputs.[1] These data are obtained from weigh-in-motion (WIM) sites.

The objectives of this project were to evaluate the applicability of the existing MEPDG global traffic loading defaults and to use research-quality WIM data from the *Long-Term Pavement Performance (LTPP) Specific Pavement Study (SPS) Traffic Data Collection* pooled fund study to revise and improve the global default axle loading values.[2] This report provides an assessment of the original MEPDG axle loading defaults, describes WIM data selection criteria, including data reliability assessment, presents findings from the LTPP SPS traffic pooled fund study traffic data review, describes a methodology to generate new MEPDG traffic loading defaults, and provides a description of the new traffic loading defaults and recommendations for their use.

The report also discusses a sensitivity analysis of MEPDG pavement performance models to NALS. Significant differences found in the MEPDG outcomes support the need for axle loading characterization beyond a simple default value for heavy trucks that dominate vehicle class distributions, especially for class 9 trucks. The effect of WIM accuracy on axle weight measurements, NALS estimates, and the associated MEPDG outcomes was also investigated.

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16. Abstract
As part of traffic loading inputs, the *Mechanistic-Empirical Pavement Design Guide (MEPDG), Interim Edition: A Manual of Practice* requires detailed axle loading information in the form of normalized axle load spectra (NALS), number of axle per truck class and axle group types, and axle spacing inputs.(1) These data are obtained from weigh-in-motion (WIM) sites.

The objective of this project was to evaluate the applicability of the existing MEPDG global traffic loading defaults and to use research-quality WIM data from the *Long-Term Pavement Performance (LTPP) Specific Pavement Studies (SPS) Traffic Data Collection* pooled fund study to revise and improve the global default axle loading values.(2) This report provides an assessment of the original MEPDG axle loading defaults, describes WIM data selection criteria, including data reliability assessment, presents findings from the LTPP SPS traffic pooled fund study traffic data review, describes a methodology to generate new MEPDG traffic loading defaults, and provides a description of the new traffic loading defaults and recommendations for their use.

The report also discusses a sensitivity analysis of MEPDG pavement performance models to NALS. Significant differences found in the MEPDG outcomes support the need for axle loading characterization beyond a simple default value for heavy trucks that dominate vehicle class distributions, especially for class 9 trucks. The effect of WIM accuracy on axle weight measurements, NALS estimates, and the associated MEPDG outcomes was also investigated. It was found that drift in WIM system calibration leading to over 5 percent bias in mean error between true and WIM-measured axle weight could lead to significant differences in MEPDG design outcomes. In addition, two new statistical parameters were developed in this study: (1) a summary statistic used to describe traffic loads for comparison and grouping of similar NALS called the relative pavement performance impact factor and (2) a parameter used to quantify errors associated with NALS and to assess NALS reliability called the pooled weighted load error.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

AADTT	average annual daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
APC	axle per class
AVC	automatic vehicle classification
CF	confidence factor
CL	confidence level
DOW	day of the week
ESAL	equivalent single-axle load
ETG	expert task group
FHWA	Federal Highway Administration
GP	load cluster group
GPS	General Pavement Studies
GVW	gross vehicle weight
HMA	hot mix asphalt
IRI	International Roughness Index
JPCP	jointed plain concrete pavement
LTAS	Long-Term Pavement Performance Traffic Analysis Software
LTPP	Long-Term Pavement Performance
MEPDG	*Mechanistic-Empirical Pavement Design Guide*
M.P.	Milepost
NALS	normalized axle load spectra
NCHRP	National Cooperative Highway Research Program
PCC	portland cement concrete
PLUG	*Pavement Loading User Guide*
PWLE	pooled weighted load error
PVR	per vehicle record
QA	quality assurance
QC	quality control
RANALS	representative annual normalized axle load spectra
RI	rural interstate
ROPA	rural other principal arterial

RPPIF	relative pavement performance impact factor
SDR	Standard Data Release
SHRP	Strategic Highway Research Program
SPS	Specific Pavement Studies
TPF	transportation pooled fund
TTC	truck traffic classification
VCD	vehicle class distribution
WIM	weigh-in-motion

CHAPTER 1—INTRODUCTION

BACKGROUND

The *Mechanistic-Empirical Pavement Design Guide* (MEPDG) methodology was developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A, and the *MEPDG Manual of Practice* was balloted affirmatively through the American Association of State Highway and Transportation Officials (AASHTO) in 2008 at the Joint Technical Committee on Pavements annual meeting.(3,1) Currently, many State highway agencies are evaluating and implementing the new pavement design procedures.

This report focuses on traffic inputs that support the MEPDG method. As a result, the abbreviation "MEPDG" is used extensively throughout this report. This abbreviation does not refer to a specific publication; rather, it is used to define parameters, models, and computational procedures that support the MEPDG method.

The MEPDG requires actual traffic inputs, rather than the number of 18-kip equivalent single-axle loads (ESALs) determined through the use of the AASHTO equivalency factors.(4) The MEPDG traffic inputs are normalized axle load spectra (NALS) for each truck class and axle group type, number of axles of each type per vehicle class, percentile truck class volume distribution, truck volume, and truck growth.

NALS are percentile distributions of axle counts by load level. Individual NALS are computed for each axle group type and truck class. The axle group types included in the MEPDG design procedure are single, tandem, tridem, and quad.(4) Truck classes are vehicle classes 4 through 13 based on the Federal Highway Administration (FHWA) vehicle classification scheme F-13. For the design, NALS representative of axle load distribution for a typical day of the month are used. For roads that do not show significant seasonal variations, the same NALS are used for all calendar months.

Out of all MEPDG traffic inputs, NALS are the most challenging to collect due to the high data collection costs, the time needed to collect an adequate quantity of data, and weigh-in-motion (WIM) equipment calibration and maintenance requirements. Therefore, the majority of pavement designs in accordance with the MEPDG rely on regional, agency-wide, or national NALS traffic loading defaults. It is important that default NALS values are as representative of the actual truck loading along the project site as possible.

The default traffic datasets included in the MEPDG were developed during NCHRP Project 1-37A and based on Long-Term Pavement Performance (LTPP) traffic data collected by State highway agencies prior to 1999.(3) At that time, these data represented the best available and most comprehensive national set of WIM and automatic vehicle classification (AVC) data. However, some concerns existed regarding the lack of documented quality of the data that were used to determine the truck traffic default values—specifically, the NALS values for each axle group type within a truck class. More importantly, many agency personnel have also questioned the quality of their own truck traffic data.

Since 1999, the *LTPP Specific Pavement Study (SPS) Traffic Data Collection* transportation pooled fund (TPF) study, TPF-5(004) (SPS TPF study) has generated high-quality traffic loading information for 26 LTPP SPS TPF WIM sites.(2) These data were collected using uniform protocols for data quality assurance (QA) and in accordance with the LTPP vehicle classification scheme. These new data provide an opportunity to evaluate the applicability of the MEPDG NALS defaults and to provide alternate NALS.

RESEARCH OBJECTIVES AND OUTCOMES

The primary purpose of this project was to revise axle loading defaults based on data from SPS TPF WIM sites, compare new defaults with the existing MEPDG global NALS defaults, and provide recommendations for use of the new axle loading defaults. This research project addresses the following specific objectives:

- Examine improvements since the original issue of the traffic data for the MEPDG to develop new design defaults for traffic inputs.
- Develop additional default NALS for the MEPDG using SPS TPF data.
- Develop a procedure for estimating the reliability of the traffic load data using confidence levels (CLs).

The following are the outcomes and deliverables of this study:

- An alternate set of default NALS for the MEPDG.
- Practical guidelines for generation and use of MEPDG traffic loading defaults in the form of a stand-alone guide, *LTPP Pavement Loading User Guide*, known as LTPP-PLUG.(5)
- A procedure for estimating the reliability of the traffic loading data used in pavement design.
- A final report summarizing the study findings and outcomes, including a description of the new default traffic datasets for the MEPDG and an assessment of the sensitivity of MEPDG pavement design models to differences in NALS and to the accuracy of WIM data.
- A software tool (LTPP-PLUG) for the development of NALS input files for the MEPDG and DARWin-ME™ software using the new LTPP SPS TPF defaults as well as user-supplied defaults or site-specific NALS.(5)
- The following two new statistical parameters intended to help simplify analyses involving NALS while also allowing pavement analysts to easily summarize and communicate the relative size of traffic loads being experienced by roadways:
    - **Relative pavement performance impact factor (RPPIF)**: A summary statistic for comparison and grouping of similar NALS. This statistic converts NALS to a single

value, considering both the frequency of load applications and the relative effect of different load magnitudes on pavement performance.

- **Pooled weighted load error (PWLE)**: A parameter to quantify the potential for error associated with using several NALS to compute a single group NALS. This summary can be used to assess potential errors when computing an average monthly or an average annual NALS at a specific site using different data availability scenarios or when computing a single NALS that is intended to represent a group from the NALS measured at multiple sites within that group. The PWLE statistic, computed for a selected CL, can also be used to assess the reliability of a summary NALS. It takes into consideration both the variation in relative percentage of the traffic at each axle load level and the relative importance of each load level on the MEPDG-based pavement performance predictions.

REPORT ORGANIZATION

This report consists of two parts. Part I (chapters 1 through 7) focuses on a review of the MEPDG traffic loading data requirements, data assessment, and development of data selection criteria. Part II (chapters 8 through 11) focuses on the development of alternate MEPDG traffic loading defaults and recommendations for use of those alternate defaults.

CHAPTER 2—REVIEW OF MEPDG TRAFFIC LOADING DEFAULTS

This chapter covers the following topics:

- A review of the original MEPDG NALS defaults and the methodology used to estimate or determine global defaults.
- An assessment of the applicability and limitations of the current MEPDG traffic defaults.
- Recommendations for enhancement of MEPDG traffic loading defaults.

ASSESSMENT OF METHODOLOGY USED FOR ORIGINAL TRAFFIC LOADING DEFAULTS

The research team reviewed the original methodology for generating MEPDG traffic loading defaults, and the results of that review are summarized in this section.

Data Selection Criteria for Development of MEPDG Defaults

The researchers used the following data selection criteria to identify data for the development of the original MEPDG traffic defaults:

- Availability of at least 210 days of AVC data to develop truck volume-based defaults.
- Availability of at least 1 weekday and 1 weekend of WIM data per quarter (preferably at least 1 week per quarter) to develop axle loading defaults.
- Availability of above data items for at least 2 years in a 5-year period.

Development of the default axle load spectra was based on data from 134 sites. Defaults for axle spacing in tandem and tridem axle configurations were based on data from 26 sites, and axles per truck type defaults were based on data from 16 sites. All the defaults were based on LTPP data collected up to 1999 for General Pavement Studies (GPS) sites that passed rudimentary LTPP quality checks.

Summary of Traffic Loading Defaults and Methods Used

WIM data were used to generate the following global traffic loading defaults when sufficient traffic weight data were unavailable:

- One set of default NALS for each axle group type (single, tandem, tridem, and quad axles) and FHWA vehicle classes 4 through 13, as applicable. The default NALS included in the MEPDG were determined based on the following points and hypotheses:
    - Functional classification was initially used to segregate the LTPP sites for computing NALS. It was found that NALS were independent of functional class, so one set of values was determined for NALS for each axle group type and truck class.

- The site-specific NALS or the annualized axle load spectra were based on WIM data.
- Researchers calculated a representative NALS for each site that satisfied sufficient data criteria and passed rudimentary LTPP quality checks and then averaged NALS across similar sites to develop the global NALS default.
- Assumptions when weight data were not available to generate the traffic loading defaults include the following:
  - NALS by axle group type for each vehicle class remain constant from year-to-year unless there are regulatory or economical changes that affect the maximum axle or gross vehicle loads.
  - NALS by axle group type and vehicle class do not change throughout the time of day or over the week (weekday versus weekend and night versus day).
  - NALS for each axle group type and vehicle class do not change from site-to-site within a specific region or roadway functional classification.

- One set of typical axle spacing for each of the FHWA vehicle classes 4 through 13 (i.e., tandem and tridem axle configurations).
  - Based on per vehicle counts from WIM data.
  - Comparison of truck industry values to the values calculated from WIM data.
  - Where axle spacing does not change over time for a site or roadway.
  - When there are no quad defaults.
- One set of axles per truck type (i.e., single, tandem, and tridem) for each of the FHWA vehicle classes 4 through 13.
  - Based on spacing reported in per vehicle records (PVRs) obtained from WIM data.
  - Where number of axles for each axle group type was reviewed from the individual truck record data for a sample of sites.
  - Where numbers of each axle group type were summed for each vehicle class. The total number of each axle group type (i.e., single, tandem, and tridem) was divided by the total number of trucks/vehicles to determine the average number of axles for each axle group type for each truck/vehicle class.
  - The number of axle group types per truck class does not change over time for a site or roadway.
  - When there are no quad defaults.

Determination of Expected Errors in Traffic Estimates Using Original Methodology

The NCHRP Project 1-37A report includes a procedure to estimate the expected error of the site-specific traffic estimates based on the amount of data collected at a site, given the variation in the data and the selected confidence interval.[3] The following equation was used to calculate the expected error in estimating the daily number of trucks for each vehicle class.[6]

$$e(VC_k)_j = \frac{Z}{n^{0.5}}\left(\frac{\sigma}{\mu}\right)_{k,j}$$

Figure 1. Equation. Expected error in estimating the daily number of trucks for each vehicle class.

Where:

$e(VC_k)_j$ = Expected error for vehicle class k in season j.
Z = Confidence interval coefficient.
n = Number of sampling days.
σ = Standard deviation of the number of class k vehicles in the population during season j.
μ = Mean number of class k vehicles in the truck traffic population during season j.

This approach accounts for errors in truck volume estimates associated with data availability and variability of data due to natural fluctuations in truck volumes during the season. However, it does not account for the errors associated with WIM equipment performance or expected level of accuracy of WIM systems, nor does it provide an estimate of expected errors in axle loads.

APPLICABILITY OF THE ORIGINAL MEPDG TRAFFIC LOADING DEFAULTS

The research team identified, reviewed, and compiled studies published prior to 2009 that evaluated the reasonableness of the original MEPDG traffic defaults or MEPDG sensitivity to traffic inputs. (See references 7–10.) Most of the identified studies focus on sensitivity of pavement design to MEPDG defaults (level 3 inputs) versus site-specific or regional traffic data (level 1 inputs) and present State-sponsored research projects with the focus on State implementation of the MEPDG. Depending on pavement type, distress type, climatic region, State, and functional type of road, the effect of load spectra on pavement design or performance prediction ranged from low to high.

Understanding the Physical Meaning of the Original Default NALS

Some of the criticism regarding the original MEPDG traffic loading defaults comes from unusual shapes reported as a default NALS. The following example demonstrates that the use of the average NALS for each axle group type for a specific truck class is the reason why some NALS do not exhibit some of the typical loading features or patterns that have been reported for specific roadway segments (i.e., appearing like a “stretched” distribution with longer tail of the distribution (higher percentages of overloads and higher percentage of light loads)).

Figure 2 compares the default NALS for tandem axle for truck class 9 to the loading patterns from three loading spectra for SPS TPF sites within the same functional classification (rural other principal arterial (ROPA)). As shown, site-specific NALS are significantly different, and one may question the applicability or adequacy of the default tandem spectra.

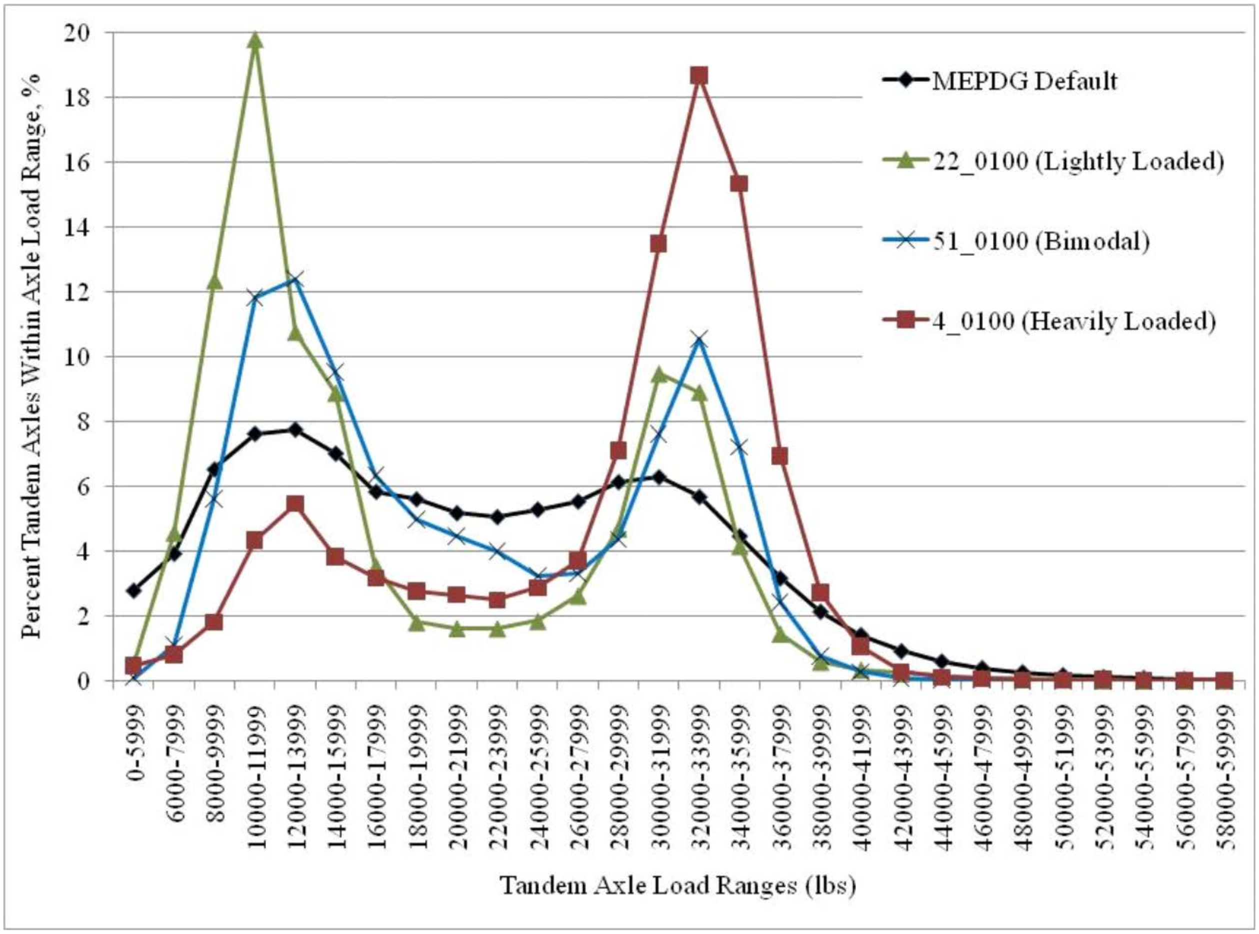

Figure 2. Graph. Comparison of three tandem axle loading patterns to the MEPDG default NALS for tandem axles for truck class 9.

The NCHRP 1-37A research team computed an average NALS for each axle group type and truck class using data from all available sites.[(3)] The averaging method is used in figure 3, where three different SPS TPF NALS for the same road functional class are averaged and compared to the default NALS for tandem axles. The average of the three site-specific distributions has bi-modal distribution and shows more resemblance to MEPDG defaults.

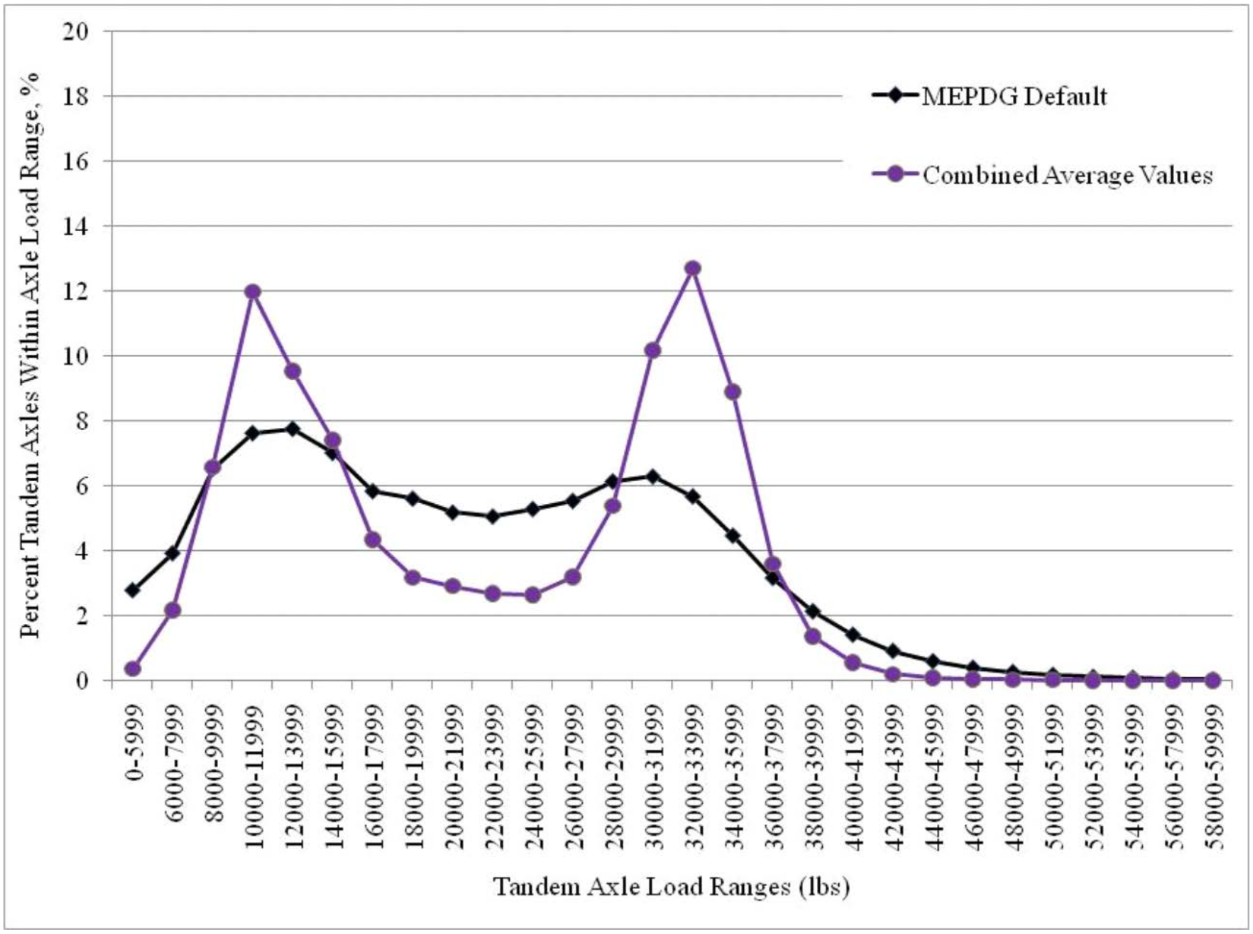

Figure 3. Graph. Average tandem axle loading patterns for truck class 9.

In summary, the MEPDG default values represent an average NALS from multiple sites across the United States, including light, bi-modal, and heavy loading patterns. These defaults are based on data collected using a variety of data collection equipment with various maintenance and calibration procedures applied. Thus, the bi-modal distribution for tandem axles shown in figure 3 is somewhat smoothed out because of the averaging process. The averaging process was used because the amount of variation within the same functional classification found during NCHRP 1-37A was about the same as between all functional classifications, and only one global set of defaults was developed. However, the question still remains—are these overloads real or a result of measurement errors or improper calibration of the WIM equipment? This question was not addressed during NCHRP Project 1-37A; it was assumed that the overloads were real values.(3)

Applicability of Default NALS

The current state of knowledge does not provide a conclusive answer whether the original defaults could be used successfully by States that move forward with MEPDG implementation. Early findings suggest that while some States find the NALS defaults applicable for their local conditions, others find a need for regional defaults or some other groupings of NALS for improving on the accuracy of pavement design. States that have percentages of heavy and overloaded axles (over 75 percent of legal weight limit) similar to the ones used in default NALS are more likely to benefit from the defaults than States that have significantly different percentages of heavy and overloaded axle loads.

Applicability of Axles per Truck Numbers and Axle Spacing

The values computed under the NCHRP 1-37A study and included in MEPDG software were based on data from 16 LTPP sites that did not have well-documented vehicle classification algorithms.(3) Additionally, some differences existed in State-defined vehicle classification schemes. Therefore, it is expected that some inconsistencies or truck misclassifications are present in the data used to determine the average number of axles per truck type by axle group and the average axle spacing.

CONCERNS AND LIMITATIONS OF THE ORIGINAL MEPDG TRAFFIC DEFAULTS

The following lists provide a summary of concerns and issues found in application of the original MEPDG traffic defaults.

Data processing and data quality concerns include the following:

- The quality of WIM data was not well known at the time of this study. The extent and results of WIM equipment validation and calibration activities was not documented partly because LTPP traffic data collection and processing were shared between participating States and FHWA. WIM equipment type, performance requirements, calibration protocols, and data collection algorithms varied from State to State.
- Data collected by highway agencies were not of uniform or defined quality. For many sites, it was impossible to determine if WIM scales were calibrated and what the outcomes of calibration procedures were.
- Although not a concern, a constraint of the analysis was that the data format and processing time made the task of data assessment and defaults development time consuming and labor intensive.
- Inclusion of sites with very low axle counts in underrepresented vehicle classes resulted in choppy distributions that do not follow expected shapes. This applies to vehicle classes 6–8 and 10–13.

Issues associated with the methodology include the following:

- Only one set of global default NALS exists for a given vehicle class, limiting pavement designers' ability to analyze different pavement loading conditions and the effect of these different loading conditions on pavement response and performance.
- Loading data were collected using different vehicle classification algorithms, and the consequences of aggregation of the data collected from the States utilizing multiple vehicle classification algorithms were not investigated.

- Applicability of the defaults for the States that are using different classification schemes was not investigated.

- The data quality was unknown, and the NCHRP 1-37A panel requirement to determine the default NALS values using roadway functional classification caused high variability and challenges in identifying different loading patterns.

- The data were not selected randomly and may not represent typical traffic loading conditions observed on U.S. roads.

- Very few of the sites used to determine the truck default values, especially NALS, were located on minor arterial and collector highways and on urban highways, which limits the application of the global NALS.

- Sensitivity of pavement performance prediction models to variability in NALS was estimated based on using the equivalent annual modulus concept for rutting and fatigue or alligator cracking (bottom-up cracking) for new flexible pavements because the pavement performance prediction models or transfer functions based on the incremental damage concept were not yet programmed at the time traffic defaults were generated.

RECOMMENDATIONS FOR ENHANCEMENT OF THE ORIGINAL MEPDG TRAFFIC LOADING DEFAULTS

Several recommendations for enhancements or alternatives for the default NALS are as follows:

- **Use of new SPS TPF WIM data to develop alternate NALS defaults**: One of the limitations associated with the original NALS defaults was lack of knowledge of WIM data quality and the multitude of different data collection practices implemented by States that supplied WIM data to LTPP. Utilization of data from SPS TPF WIM sites will have a major benefit with respect to known data quality and uniformity in vehicle classification algorithm. However, data are available for only 26 WIM sites located in 22 States, so the new NALS defaults may not be applicable to all loading conditions across the United States.

- **Use of loading patterns in defining new default NALS**: An improvement in the application of NALS default values within the MEPDG would be the analyst's ability to specify how the loading patterns can vary in terms of loads and truck volumes by type of truck for a given design scenario. While a default or typical distribution should be used if the loading condition for a particular pavement design location is unknown, the availability of alternative loading conditions is highly beneficial for "what if" sensitivity analyses and for sites that are expected to have either heavier or lighter than default loading conditions. SPS TPF data should be used to investigate if different axle loading patterns can be identified. These patterns should be assessed using the MEPDG to quantify the significance of pavement design and analysis outcomes for different NALS from these 26 sites. Based on the results of the analysis, NALS representing different axle loading conditions should be developed for different vehicle classes and axle group types.

- **Focus on heavy loads and MEPDG predictions**: The amount of heavy and overloaded axles drives pavement design decisions. Therefore, heavier load bins should be used in judging whether NALS are different or statistically the same for pavement design purposes. Similarly, greater emphasis should be placed on the accuracy of data for the heavier load bins. The MEPDG can be used to determine and compare the difference in predicted distress and/or expected service life. Based on the results, the sites can be grouped into those that result in similar predictions and those that are different.

- **Comparison of MEPDG outcomes**: Both the original defaults and the alternate defaults should be used in the MEPDG analysis to quantify the difference in pavement design outcomes using the NCHRP 1-37A and SPS TPF default NALS.[3,2]

- **Variability in NALS for the road functional classes**: In the NCHRP 1-37A study, large differences of the NALS within the same functional classification were observed.[3] There was as much variation in the normalized values of the heavier load intervals within the same functional classification as between all functional classifications. This can be attributed partly to the limited amount of high-quality traffic data used in that analysis. It would be important to evaluate if the same high loading variability is observed for the loading spectra obtained for sites within the same road functional class.

- **Axle per class (APC) coefficients using SPS TPF data**: The number of axles per vehicle class should be determined for the 26 SPS TPF sites, compared to the default values, and used to develop new default values, if needed. This would indicate whether the LTPP vehicle classification algorithm leads to different APC numbers.

- **Axle spacing using SPS TPF loading data**: Average axle spacing or wheelbase information is used for MEPDG applications involving top-down slab cracking failure in jointed plain concrete pavements (JPCPs). The MEPDG considers wheelbase of the tractor unit on vehicles in classes 8 through 13 in the form of three inputs: percentage of tractor units with short, medium, and long wheelbases. By default, the MEPDG software assumes an even distribution of short, medium, and long axle spacing occurrences at 33, 33, and 34 percent, respectively. Axle spacing and tractor wheelbase information should be obtained from per-vehicle records for SPS TPF sites and analyzed to provide updates to the default values. In addition, axle spacing for tandem, tridem, and quad axle groups should be computed and compared with the existing MEPDG default values.

CHAPTER 3—SUMMARY OF IMPROVEMENTS IN LTPP TRAFFIC DATA SINCE ORIGINAL MEPDG DEFAULTS

A number of improvements to LTPP WIM data have occurred within the last 13 years, as summarized in the following sections.

OVERVIEW OF SPS TPF STUDY

Study Objective

Since the original defaults were developed, LTPP undertook the SPS TPF study that focused on installing highly reliable permanent WIM systems and collecting axle loading data using a uniform vehicle classification scheme and rigorous quality control (QC) procedures to produce research-quality traffic data (classification and weight) to support LTPP analysis projects.(2) The SPS TPF study was designed with the support of the Transportation Research Board Traffic Expert Task Group (ETG). The effort consisted of two principal elements: shifting the data collection from highway agencies to a national, centralized effort and standardizing data collection equipment and procedures. Additionally, guidelines for pavement smoothness, equipment calibration checks, equipment model specifications, and LTPP vehicle classification scheme were developed and implemented for SPS TPF sites.(2)

WIM Equipment

Table 1 provides the location, road type, and WIM technology description for each SPS TPF site. Two types of weighing sensors typically were used for the sites: bending plate and quartz piezo. Both sensors have a proven history of reliable performance. In addition, two Ohio sites use load cell technology.

Table 1. SPS WIM site locations.

State	SPS Site	Route and Site Location	WIM Sensor	Road Functional Class
1. Arizona	040100	US-93 North at M.P. 52.62	Bending plate	Rural principal arterial—other
2. Arizona	040200	I-10 East at M.P. 108.6	Quartz piezo	Rural principal arterial—interstate
3. Arkansas	050200	I-30 North of SR74 overpass	Bending plate	Rural principal arterial—interstate
4. California	060200	SR-99 at M.P. 32.5	Bending plate	Rural principal arterial—other
5. Colorado	080200	I-76 East at M.P. 39.7	Bending plate	Rural principal arterial—interstate
6. Delaware	100100	US-113 Southbound north of SR 579	Quartz piezo	Rural principal arterial—other
7. Florida	120100	US-27 at M.P. 12.03	Quartz piezo	Rural principal arterial—other
8. Florida	120500	US-1	Quartz piezo	Rural principal arterial—other
9. Illinois	170600	I-57 at M.P. 225.6	Bending plate	Rural principal arterial—interstate
10. Indiana	180600	US-31 North at M.P. 216.9	Bending plate	Rural principal arterial—other

State	SPS Site	Route and Site Location	WIM Sensor	Road Functional Class
11. Kansas	200200	I-70 West at M.P. 287.48	Bending Plate	Rural principal arterial—interstate
12. Louisiana	220100	US-171 at M.P. 8.4	Quartz piezo	Rural principal arterial—other
13. Maine	230500	I-95 at M.P. 200.1	Quartz piezo	Rural principal arterial—interstate
14. Maryland	240500	US-15 North at M.P. 4.62	Bending plate	Rural principal arterial—other
15. Michigan	260100	US-27 South	Quartz piezo	Rural principal arterial—other
16. Minnesota	270500	US-2 at M.P. 91.8	Quartz piezo	Rural principal arterial—other
17. New Mexico	350100	I-25 North at M.P. 36.1	Quartz piezo	Rural principal arterial—Interstate
18. New Mexico	350500	I-10 East at M.P. 50.2	Quartz piezo	Rural principal arterial—interstate
19. Ohio	390100	US-23 at M.P. 19.7	Load cell	Rural principal arterial—other
20. Ohio	390200	US-23 at M.P. 19.7	Load cell	Rural principal arterial—other
21. Pennsylvania	420600	I -80 at M.P. 158.2	Quartz piezo	Rural principal arterial—interstate
22. Tennessee	470600	I-40 West at M.P. 91.67	Quartz piezo	Rural principal arterial—interstate
23. Texas	480100	US-281 South	Bending plate	Rural principal arterial—other
24. Virginia	510100	US-29 bypass at M.P. 12.8	Bending plate	Rural principal arterial—other
25. Washington	530200	US-395 at M.P. 93.01	Quartz piezo	Urban principal arterial—other freeways or expressways
26. Wisconsin	550100	US-29 at M.P. 189.8	Bending plate	Urban principal arterial—other

M.P. = Milepost.

Study Coverage

Figure 4 shows the distribution of SPS TPF sites on a map, illustrating good coverage across the United States. However, only two functional road types have adequate representation in the SPS TPF study: rural principal arterial interstate and rural principal arterial other non-interstate highways. No SPS TPF site was located on an urban interstate or on minor arterials and collectors, and only two sites were located on urban roads (principal arterial other and expressways). This is a limitation in developing alternate NALS for the MEPDG. In other words, the alternate NALS developed from these sites may be restricted to certain truck traffic conditions.

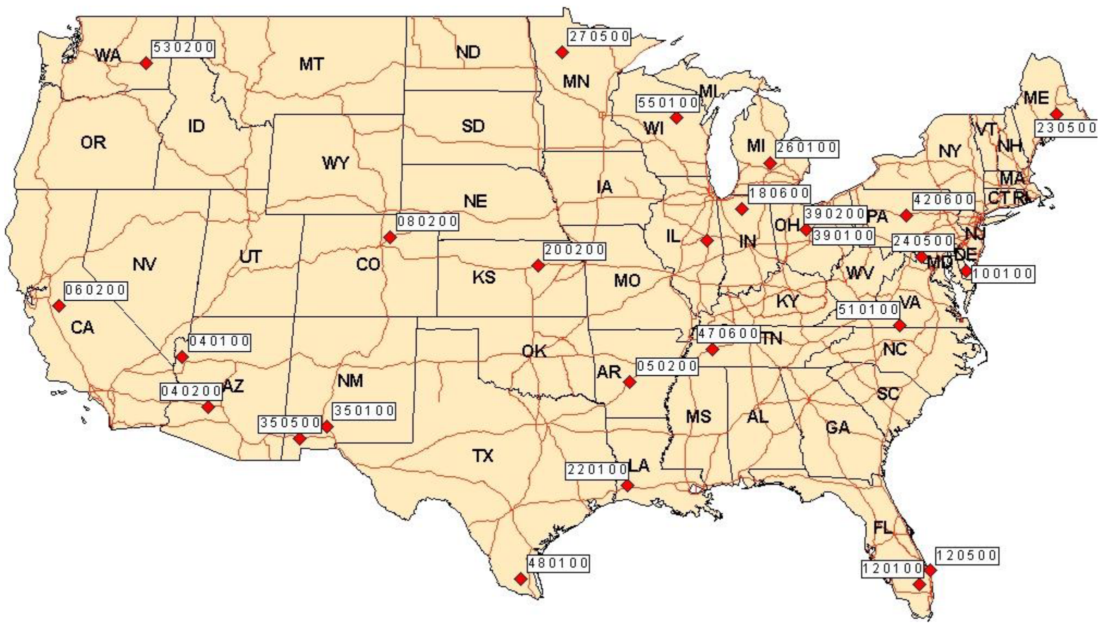

Figure 4. Illustration. Map of SPS TPF study sites.

AXLE LOADING DATA FROM SPS TPF STUDY

LTPP Definition of Research-Quality Traffic Data

Under the LTPP SPS TPF study, *research-quality traffic data* are defined as at least 210 days of data (in a year) of known calibration meeting LTPP's precision requirements for single axles, axle groups, gross vehicle weight (GVW), vehicle length (bumper-to-bumper), vehicle speed, and axle spacing, as detailed in table 2.(2)

Table 2. LTPP WIM system performance requirements.

SPS TPF Factors	95 Percent Confidence Limit of Error
Loaded single axles	±20 percent
Loaded axle groups	±15 percent
GVW	±10 percent
Vehicle length	greater of ±1.5 ft or ±3 percent
Vehicle speed	±1 mi/h
Axle spacing length	±0.5 ft

As a result of enforcing the criteria for research-quality data, the SPS TPF sites have had more direct calibration and performance monitoring reviews performed as part of the data collection effort than any other WIM sites in the United States. Because LTPP requires regional contractors to periodically download and verify the collected traffic data, anomalies are identified quickly, and actions are taken to ensure accurate performance of WIM systems. That is, if performance problems are noted in the equipment, the repair/calibration is performed, and problem data are not processed and stored. The SPS TPF WIM equipment is also installed in pavement that supports accurate WIM system performance, ensuring the accuracy of the collected data. This means that the SPS TPF dataset is among the most trustworthy WIM data in the country.

LTPP Traffic Data QC Process

The LTPP data processing and QA programs ensure that WIM data being collected at SPS TPF sites are reviewed in a timely manner using a systematic, comprehensive, and well-documented internal process. Implementation of the new and improved LTPP Traffic Analysis Software (LTAS) for traffic data QC and processing, along with rigorous and systematic WIM scale validation and calibration process for SPS TPF sites, has greatly improved the quality of WIM data.

For equipment measurements, QC procedures include routine calibrations, data checks during acquisition, and data checks prior to loading data into the LTAS database. Once WIM data are downloaded to LTAS, they undergo several levels of data QC checks developed by the LTPP Program for completeness and validity.

Overview of Relevant LTPP Data Tables

LTPP Standard Data Release (SDR) 24 was the primary source of data for this study.[(11)] The LTAS DD* series of tables contain daily axle load (DD_AX table) and truck volume (DD_WT_CT table) data for all SPS TPF sites. Axle load and vehicle volume data in these tables have one-to-one correspondence on a daily basis, which is important for computing APC coefficients. These daily data were used as the primary source of data.

The DD_AX table contains axle data by site, year, month, day of the month, day of the week (DOW), lane, direction, vehicle class, axle group, and load bin. This table was created by accumulating the axle distributions over all hours by vehicle class in a calendar day. The data are summarized in 1,000-lb bins for single axles, 2,000-lb bins for tandem axles, and 3,000-lb bins for tridems and quads. (Quad axles are any axle group with four or more axles.)

The DD_WT_CT table summarizes the number of vehicles by class. This table contains count data by site, year, month, day, lane, and direction for each day for which weight data exist for estimating loads. This table uses the calendar day to define a day of data.

CONCLUSIONS

SPS TPF data represent a unique national traffic loading data sample. Currently, this dataset is the best quality national loading data sample available in the United States. The primary benefit of the SPS TPF data is that they are collected using WIM devices that are routinely monitored and periodically calibrated using uniform procedures to monitor changes in load spectra over time. Additional benefits of these data are the extended periods of data collection (using continuously operating WIM scales). Also, a uniform vehicle classification scheme is used at most sites (some minor deviations from the algorithm are observed in data from Florida, Ohio, and Washington).

The SPS TPF data provide an opportunity to improve the MEPDG traffic loading defaults. The quality and quantity of data affect the reliability of loading defaults, as do consistency in data collection and data processing protocols and the uniformity of the vehicle classification scheme. However, the limited scope of SPS TPF WIM data may limit the utility of the alternate NALS defaults. Currently, data are available for only 26 sites, and they do not cover all road types.

CHAPTER 4—IMPORTANCE OF AXLE LOADS FOR PAVEMENT DESIGN USING THE MEPDG

PURPOSE OF INVESTIGATION

Understanding the sensitivity of MEPDG outputs to traffic loads is an important step in the development of procedures for computing axle loading inputs and defaults as well as axle loading data reliability procedures. The main reason is that the load level does not have a linear relationship with pavement performance—heavier loads have a greater impact on performance. Thus, accurate representation of heavier loads is more important than lighter load levels.

No universal damage factor is available that indicates how much more damaging heavy axles are in comparison to lighter axles in accordance with the MEPDG method. This is in part because the MEPDG method is complex, and the influence of traffic loads varies by site features, distresses, and pavement type. Nonetheless, the ability to quantify the relative importance of axle loads would be beneficial for comparing different axle load spectra.

In this study, the research team investigated the relative effect of different axle load levels on pavement performance using different pavement distress prediction models to develop RPPIFs (or importance factors), *W*, that would provide measure of relative importance of different axle loads for pavement design using MEPDG method.

RPPIF

A new parameter was developed for this study—RPPIF, or *W* factor. The intent of *W* factors is to provide a measure of the relative importance of one load level against another with regard to sensitivity of MEPDG outcomes to different loads. These factors are intended to be used as generalized weights of relative importance for different load magnitudes to aid in comparing different load spectra. They are not intended to be used in a direct correlation with a particular pavement deterioration model, as different pavement deterioration mechanisms and pavement design types are expected to have different sensitivities to various load levels.

To develop *W* factors, the research team conducted a series of MEPDG analyses by applying axle loads of different magnitudes—one axle load level and axle group type per MEPDG design scenario—to several typical pavement structures and evaluated the number of load applications of a given magnitude to cause the pavement structure to reach a terminal condition or failure in major load-associated distresses. Initially, the International Roughness Index (IRI) was considered as a pavement performance parameter, but it was dropped from further investigation as it became evident that IRI, in addition to load related distresses, was also affected by pavement material aging and environment.

The scope of MEPDG analysis was limited to eight flexible pavement scenarios and eight rigid pavement scenarios representing different classes of pavement structures located on road facilities with different functional use (rural interstates (RIs) and ROPA) and in different climatic zones. For flexible pavements, pavement design scenarios were developed based on a 15-year design life to achieve terminal values in one of the major distresses; a 20-year design period was used for rigid pavements. Design life values were selected based on average values observed for

LTPP GPS sections. MEPDG default inputs, along with truck traffic classification (TTC) and average annual daily truck traffic (AADTT) levels typical for RI and ROPA roads were used to develop adequate pavement structures. Climatic conditions used in the MEPDG analyses included wet-freeze, wet-no freeze, dry-freeze, and dry-no freeze. Table 3 summarizes the pavement structures and climatic scenarios used in the sensitivity study.

Table 3. Pavement structures and climatic scenarios used in the sensitivity study.

Pavement and Climate Scenarios					Highway Functional Class, AADTT, and TTC
Pavement Type	**Wet-Freeze**	**Wet-No Freeze**	**Dry-Freeze**	**Dry-No Freeze**	
Flexible	AC thickness: 6 inches	AC thickness: 7 inches	AC thickness: 7.8 inches	AC thickness: 7 inches	RI, AADTT = 2,000, TTC 1
	Base type/thickness: crushed stone/11-inch subbase	base type/thickness: crushed stone/11-inch subbase	base type/thickness: crushed stone/ 11-inch subbase	base type/thickness: crushed stone/ 11-inch subbase	
	Type/thickness: A-1-a/12 inches	Type/thickness: A-1-a/12 inches	Type/thickness: A-1-a, 12 inches	Type/thickness: A-1-a, 12 inches	
	Soil type: A-1-b	Soil type: A-1-b	Soil type: A-1-b	Soil type: A-1-b	
Flexible	AC thickness: 4.2 inches	AC thickness: 4 inches	AC thickness: 5 inches	AC thickness: 4 inches	ROPA, AADTT = 500, TTC 6
	Base type/thickness: crushed stone/ 8 inches	Base type/thickness: crushed stone/ 8 inches	Base type/thickness: crushed stone/ 8 inches	Base type/thickness: crushed stone/ 8 inches	
	Soil type: A-1-b	Soil type: A-1-b	Soil type: A-1-b	Soil type: A-1-b	
Rigid	PCC thickness: 10 inches	PCC thickness: 11 inches	PCC thickness: 11 inches	PCC thickness: 11 inches	RI, AADTT = 2,000, TTC 1
	Dowel diameter/ spacing: 1.25 inches/ 12 inches	Dowel diameter/ spacing: 1.25 inches/ 14 inches	Dowel diameter/ spacing: 1.25 inches/ 12 inches	Dowel diameter/ spacing: 1.25 inches/ 14 inches	
	Erodibility Index: 2	Erodibility Index: 2	Erodibility Index: 2	Erodibility Index: 2	
	Base type/ thickness: cement stabilized/6 inches	Base type/ thickness: cement stabilized/6 inches	Base type/ thickness: cement stabilized/6 inches	Base type/ thickness: cement stabilized/6 inches	
	Subbase type/ thickness: A-6/12 inches	Subbase type/thickness: A-6/12 inches	Unknown	Unknown	
	Soil type: A-6	Soil type: A-6	Soil type: A-6	Soil type: A-6	

Rigid	PCC thickness: 9 inches	PCC thickness: 9 inches	PCC thickness: 9 inches	PCC thickness: 10 inches	ROPA, AADTT = 700, TTC 2
	Dowel diameter/ spacing: 1.25 inches/ 12 inches	Dowel diameter/ spacing: 1.25 inches/ 14 inches	Dowel diameter/ spacing: 1 inch/ 10 inches	Dowel diameter/ spacing: 1 inch/ 12 inches	
	Erodibility index: 4	Erodibility index: 3	Erodibility index: 3	Erodibility index: 4	
	Base type/ thickness: soil cement/6 inches	Base type/ thickness: A-6/ 6 inches	Base type/ thickness: cement stabilized/6 inches	Base type/ thickness: soil cement/6 inches	
	Soil type: A-6	Soil type: A-6	Soil type: A-6	Soil type: A-6	

AC = Asphalt concrete; PCC = Portland cement concrete.

In each MEPDG sensitivity run, one axle load level and axle group type was used to determine the number of load applications to failure in major load-associated distresses for a given pavement structure and climatic scenario. For flexible pavements, the following pavement performance parameters were considered: rutting and fatigue cracking or bottom-up alligator cracking. For rigid pavements, cracking and faulting were considered.

For each pavement type, climate zone, road type, axle group type, and load level, the number of load applications to failure was found for each pavement performance parameter from MEPDG runs, and the minimum number of loads to failure was determined among all pavement performance parameters at each load level. An example plot is shown in figure 5 for flexible and rigid pavements and for RI and ROPA design scenarios for the wet-freeze zone.

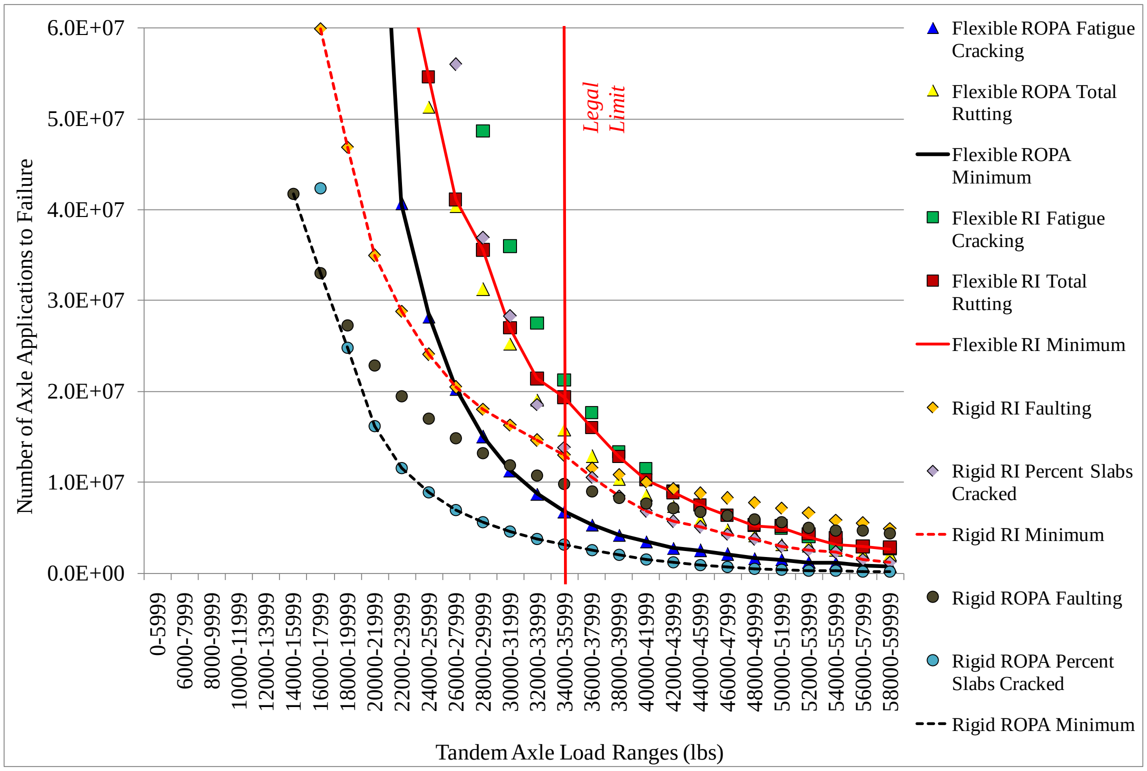

Figure 5. Graph. Example of MEPDG sensitivity results for different load levels.

For each pavement design scenario, the inverse of the minimum number of load application to failure was computed for each load level and normalized with respect to the inverse value computed at the legal load level (34,000 lb) for tandem axle loads. These values represent *W* factors at individual load levels. Results of MEPDG analyses for each pavement design scenario were then used to compute single, tandem, tridem, and quad axle loads by averaging pavement performance impact factors, as shown in table 4. The decision to average *W* factors over different pavement design types was based on the need to have a single set of *W* (importance) factors that would provide a means for evaluating the relative importance of different load levels and for comparing different axle load spectra, rather than to have a series of precise curves designed for different pavement scenarios or pavement types. Graphical representation of these factors is provided in figure 6.

Table 4. Pavement performance impact *W* factors.

Load Bin	Single		Tandem		Tridem		Quad	
	Load Range (lb)	Weight Factor	Load Range (lb)	Weight Factor	Load Range (lb)	Weight Factor	Load Range (lb)	Weight Factor
BIN_01	0–999	0.00	0-1,999	0.00	0-2,999	0.00	0-2,999	0.00
BIN_02	1,000–1,999	0.00	2,000-3,999	0.00	3,000-5,999	0.00	3,000-5,999	0.00
BIN_03	2,000–2,999	0.00	4,000-5,999	0.00	6,000-8,999	0.00	6,000-8,999	0.00
BIN_04	3,000–3,999	0.00	6,000-7,999	0.00	9,000-11,999	0.00	9,000-11,999	0.00
BIN_05	4,000–4,999	0.00	8,000-9,999	0.00	12,000-14,999	0.00	12,000-14,999	0.00
BIN_06	5,000–5,999	0.00	10,000-11,999	0.00	15,000-17,999	0.04	15,000-17,999	0.00
BIN_07	6,000–6,999	0.00	12,000-13,999	0.01	18,000-20,999	0.09	18,000-20,999	0.02
BIN_08	7,000–7,999	0.00	14,000-15,999	0.04	21,000-23,999	0.15	21,000-23,999	0.05
BIN_09	8,000–8,999	0.02	16,000-17,999	0.08	24,000-26,999	0.21	24,000-26,999	0.09
BIN_10	9,000–9,999	0.04	18,000-19,999	0.14	27,000-29,999	0.28	27,000-29,999	0.14
BIN_11	10,000–10,999	0.08	20,000-21,999	0.22	30,000-32,999	0.35	30,000-32,999	0.20
BIN_12	11,000–11,999	0.12	22,000-23,999	0.30	33,000-35,999	0.43	33,000-35,999	0.27
BIN_13	12,000–12,999	0.18	24,000-25,999	0.40	36,000-38,999	0.53	36,000-38,999	0.34
BIN_14	13,000–13,999	0.24	26,000-27,999	0.51	39,000-41,999	0.64	39,000-41,999	0.42
BIN_15	14,000–14,999	0.31	28,000-29,999	0.62	42,000-44,999	0.76	42,000-44,999	0.52
BIN_16	15,000–15,999	0.40	30,000-31,999	0.75	45,000-47,999	0.92	45,000-47,999	0.62
BIN_17	16,000–16,999	0.49	32,000-33,999	0.89	48,000-50,999	1.10	48,000-50,999	0.73
BIN_18	17,000–17,999	0.59	34,000-35,999	1.04	51,000-53,999	1.32	51,000-53,999	0.85
BIN_19	18,000–18,999	0.71	36,000-37,999	1.21	54,000-56,999	1.58	54,000-56,999	0.99
BIN_20	19,000–19,999	0.85	38,000-39,999	1.40	57,000-59,999	1.90	57,000-59,999	1.14
BIN_21	20,000–20,999	1.01	40,000-41,999	1.63	60,000-62,999	2.27	60,000-62,999	1.30
BIN_22	21,000–21,999	1.19	42,000-43,999	1.90	63,000-65,999	2.71	63,000-65,999	1.47
BIN_23	22,000–22,999	1.41	44,000-45,999	2.23	66,000-68,999	3.22	66,000-68,999	1.66
BIN_24	23,000–23,999	1.67	46,000-47,999	2.63	69,000-71,999	3.82	69,000-71,999	1.87
BIN_25	24,000–24,999	1.99	48,000-49,999	3.13	72,000-74,999	4.51	72,000-74,999	2.10
BIN_26	25,000–25,999	2.38	50,000–51,999	3.74	75,000–77,999	5.30	75,000–77,999	2.35
BIN_27	26,000–26,999	2.85	52,000–53,999	4.49	78,000–80,999	6.20	78,000–80,999	2.63
BIN_28	27,000–27,999	3.43	54,000–55,999	5.42	81,000–83,999	7.22	81,000–83,999	2.93

Load Bin	Single		Tandem		Tridem		Quad	
	Load Range (lb)	**Weight Factor**	**Load Range (lb)**	**Weight Factor**	**Load Range (lb)**	**Weight Factor**	**Load Range (lb)**	**Weight Factor**
BIN_29	28,000–28,999	4.12	56,000–57,999	6.56	84,000–86,999	8.37	84,000–86,999	3.26
BIN_30	29,000–29,999	4.96	58,000–59,999	7.95	87,000–89,999	9.66	87,000–89,999	3.62
BIN_31	30,000–30,999	5.97	60,000–61,999	9.64	90,000–92,999	11.09	90,000–92,999	4.02
BIN_32	31,000–31,999	7.18	62,000–63,999	11.67	93,000–95,999	12.68	93,000–95,999	4.46
BIN_33	32,000–32,999	8.62	64,000–65,999	14.11	96,000–98,999	14.44	96,000–98,999	4.94
BIN_34	33,000–33,999	10.33	66,000–67,999	17.00	99,000–101,999	16.37	99,000–101,999	5.47
BIN_35	34,000–34,999	12.35	68,000–69,999	20.43	102,000–104,999	18.48	102,000–104,999	6.06
BIN_36	35,000–35,999	14.72	70,000–71,999	24.47	105,000–107,999	20.78	105,000–107,999	6.71
BIN_37	36,000–36,999	17.48	72,000–73,999	29.19	108,000–110,999	23.28	108,000–110,999	7.42
BIN_38	37,000–37,999	20.70	74,000–75,999	34.68	111,000–113,999	25.98	111,000–113,999	8.20
BIN_39	38,000–38,999	24.41	76,000–77,999	41.04	114,000–116,999	28.90	114,000–116,999	9.06
BIN_40	≥ 39,000	28.70	≥ 78,000	48.37	≥ 117,000	32.03	≥ 117,000	10.01

Note: this table was developed to work with LTPP DD_AX tables. DARWin-ME™ has a different definition of the first load range. For DARWin-ME™, the first load bin range is 0–2,999 lb for single axles, 0–5,999 lb for tandem axles, and 0–11,999 lb for tridem and quad axles. Impact factors for the first three or four bins depending on axle group type should be averaged. For single and tandem axles, value from BIN_04 corresponds to DARWin-ME™ BIN_02 and so on. For tridem and quad axles, value from BIN_05 corresponds to DARWin-ME™ BIN_02 and so on.

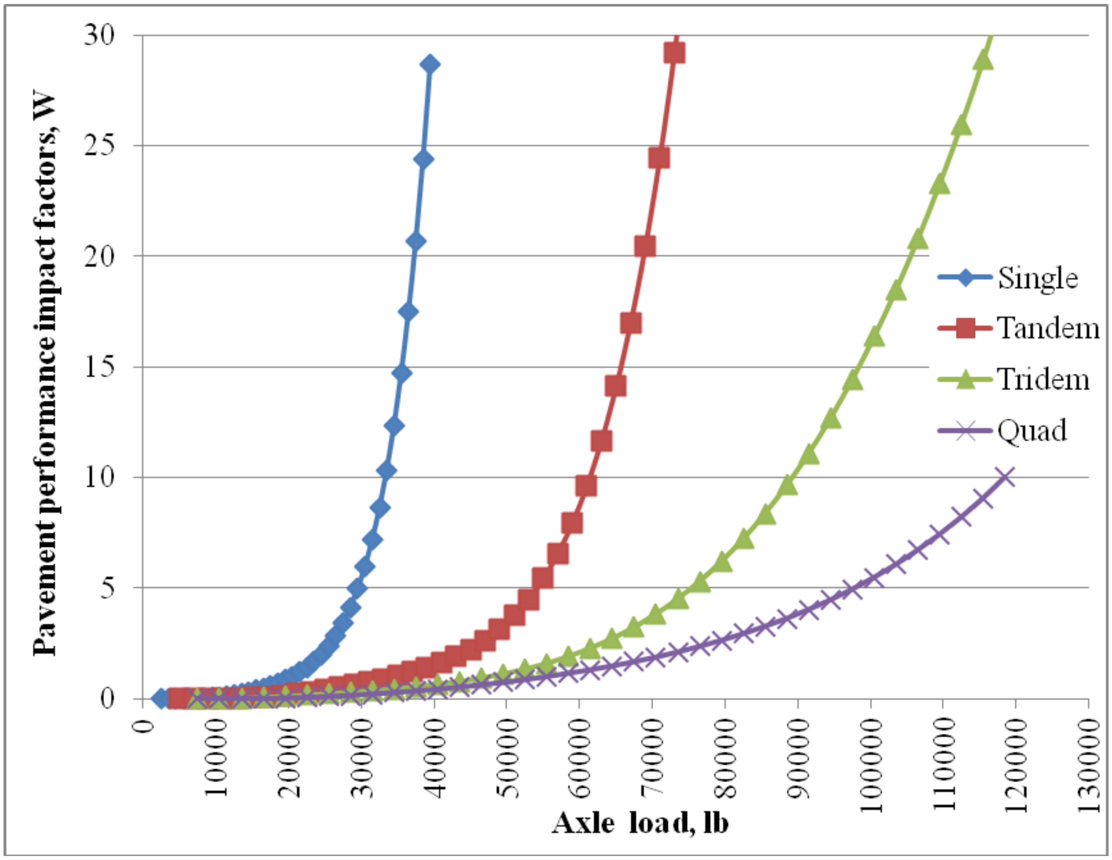

Figure 6. Graph. Pavement performance impact *W* factors.

CONCLUSIONS BASED ON MEPDG ANALYSIS OUTCOMES

Based on findings from MEPDG sensitivity analyses, the *W* factor is very low or zero for low load ranges, especially below 50 percent of the legal load limit, and it increases rapidly as load ranges go over the legal limit. This conclusion is valid for pavement structures designed for typical truck flows (vehicle class distributions (VCDs) and truck volumes) observed on RI and ROPA roads based on observation of MEPDG-predicted load-related distresses for typical flexible and rigid pavement structures.

EXAMPLE DEMONSTRATING IMPORTANCE OF HEAVY AXLE LOADS FOR PAVEMENT DESIGN

From the pavement design perspective, an evaluation of the entire NALS is not necessary since it is the higher load intervals of the NALS where the decisions need to be made in establishing default NALS for pavement design. The following example demonstrates this concept. Figure 7 shows four distinctly different NALS for class 9 tandem axles. Two of the sites are from the SPS TPF WIM study, and two are from the LTPP GPS. All data were obtained from LTPP MEPDG traffic tables for sites that passed minimum data availability requirements for research-quality data and LTPP traffic QC checks designed for SPS and GPS sites. Loading patterns at these four sites are summarized as follows:

- **Site 1—SPS 35-0500**: Loading distribution characterized by high presence of heavy loads under legal limit with cumulative percentage of overloads equal to 8 percent (lowest overloads of the four sites).

- **Site 2—SPS 12-0100**: Loading distribution characterized by presence of both light and heavy axle loads with cumulative percentage of overloads equal to 18 percent (second lowest overloads of the four sites).

- **Site 3—GPS 50-1004**: Loading distribution characterized by high presence of light axle loads with cumulative percentage of overloads equal to 22 percent (second highest overloads of the four sites).

- **Site 4—GPS 44-7401**: Loading distribution characterized by high presence of light axle loads with cumulative percentage of overloads equal to 35 percent (highest overloads of the four sites).

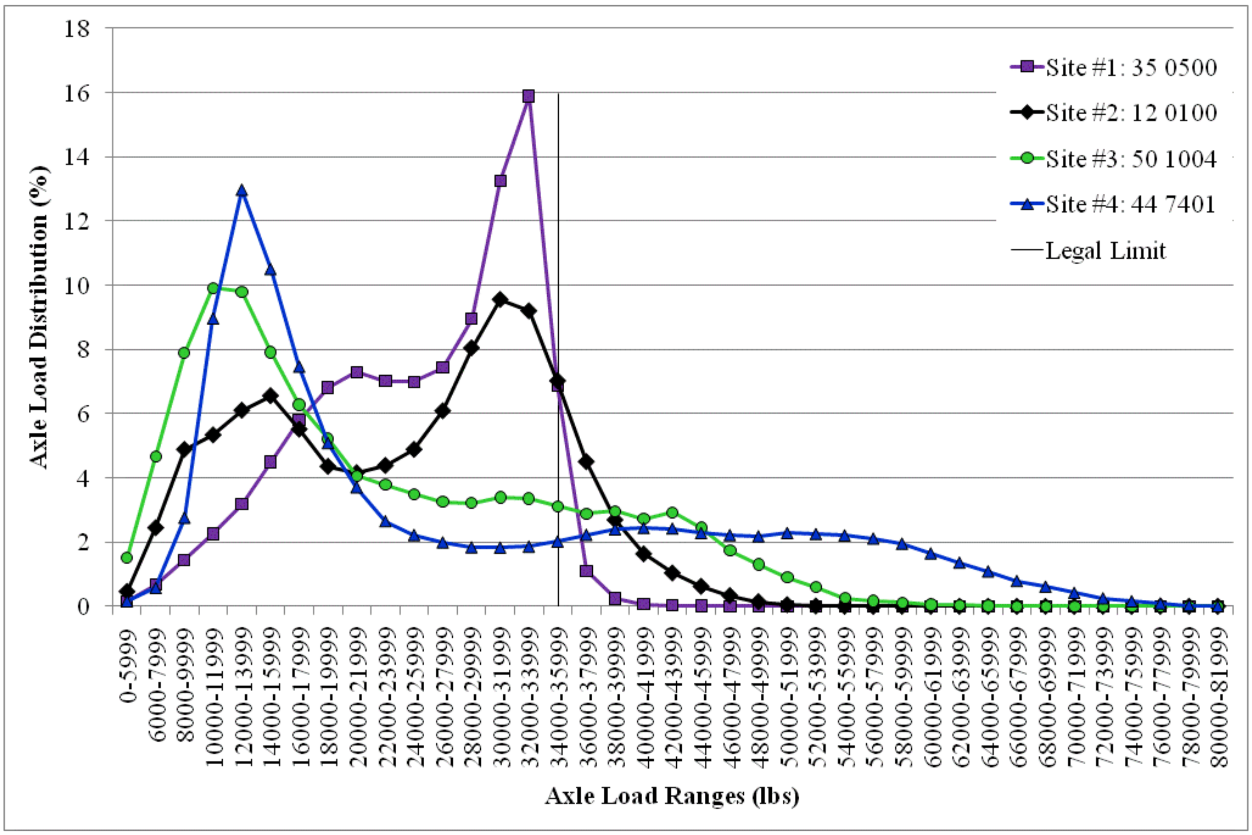

Figure 7. Graph. Tandem NALS for class 9 vehicles for four LTPP sites.

If one considers the portion of NALS distribution below the legal limit for tandem axle loads, then looking at load distribution, site 1 would be considered the heaviest, followed by sites 2, 3, and 4. However, if one considers the portion of NALS distribution above legal limit for tandem axle loads, then the opposite trend would be observed.

Another important observation is that GPS sites (sites 3 and 4) have the longer tail for the heavier load bins, which was noted as a reason why the MEPDG global NALS was questioned—MEPDG NALS are based on data from GPS sites. NALS for sites 3 and 4 result in higher levels of predicted distress and require thicker pavement layers than the MEPDG default NALS (discussed in the following paragraphs).

These four loading patterns were used in the MEPDG software to predict bottom-up alligator cracking, rutting, and IRI for a typical AC pavement section located in a southern climate (Alabama SPS-6). Figure 8 through figure 10 show the predicted load-related distresses and IRI against the number of tandem axle load applications. As can be seen in the plots, site 4 consistently performed the worst, followed by sites 3, 2, and 1. This would be opposite to the expected trend if load spectra characterizations would be based on the loading distributions observed below legal load limits but in line with the loading distributions above the legal limit. The sudden jumps in predicted distresses are caused by seasonal environmental effects and annual truck volume growth function.

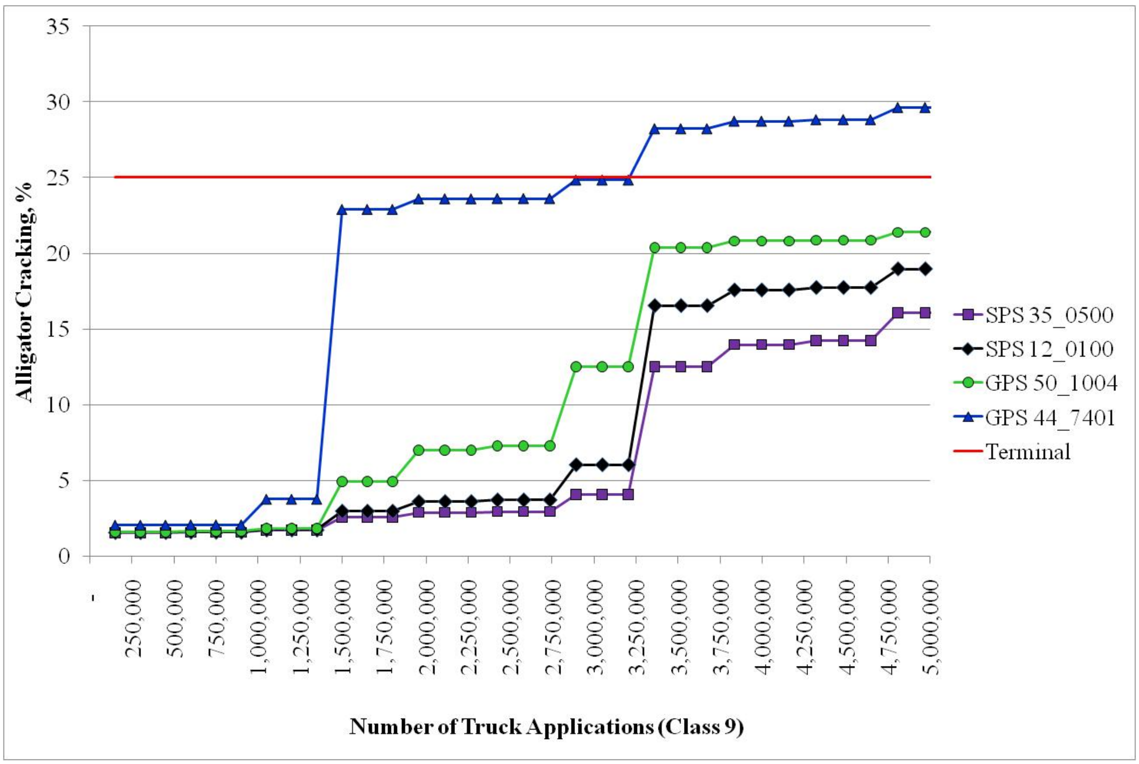

Figure 8. Graph. MEPDG alligator cracking prediction.

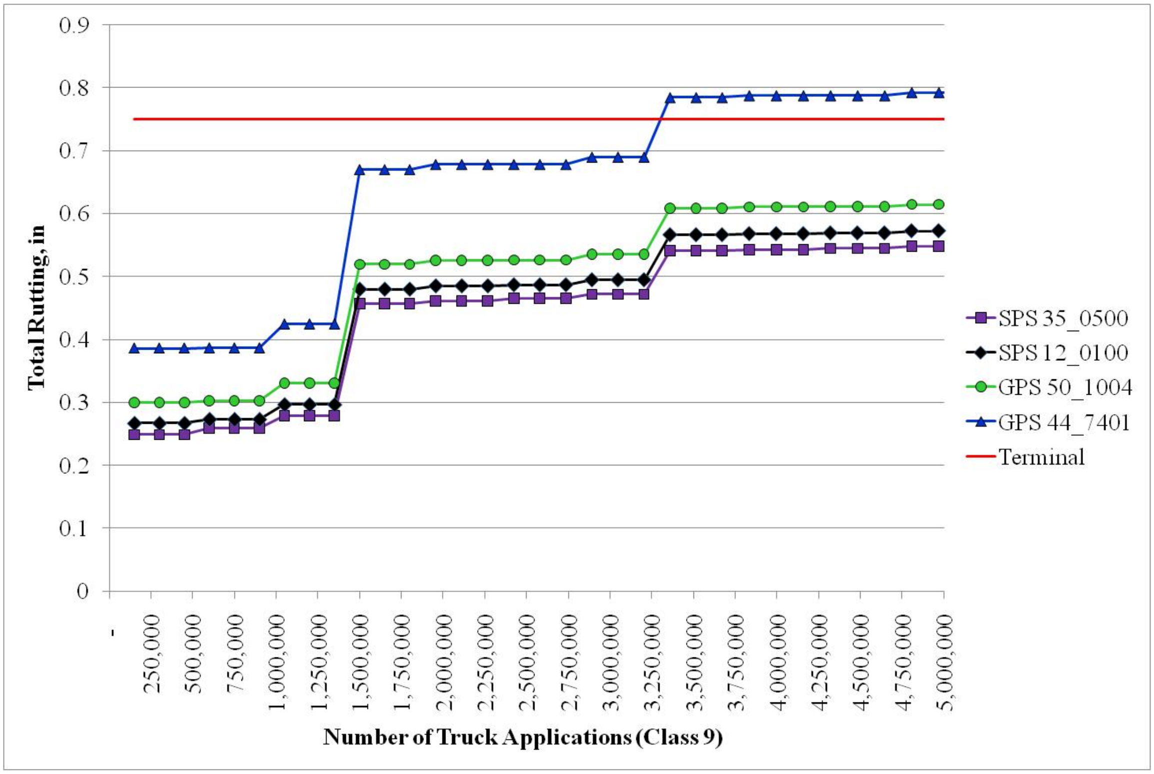

Figure 9. Graph. MEPDG total rutting prediction.

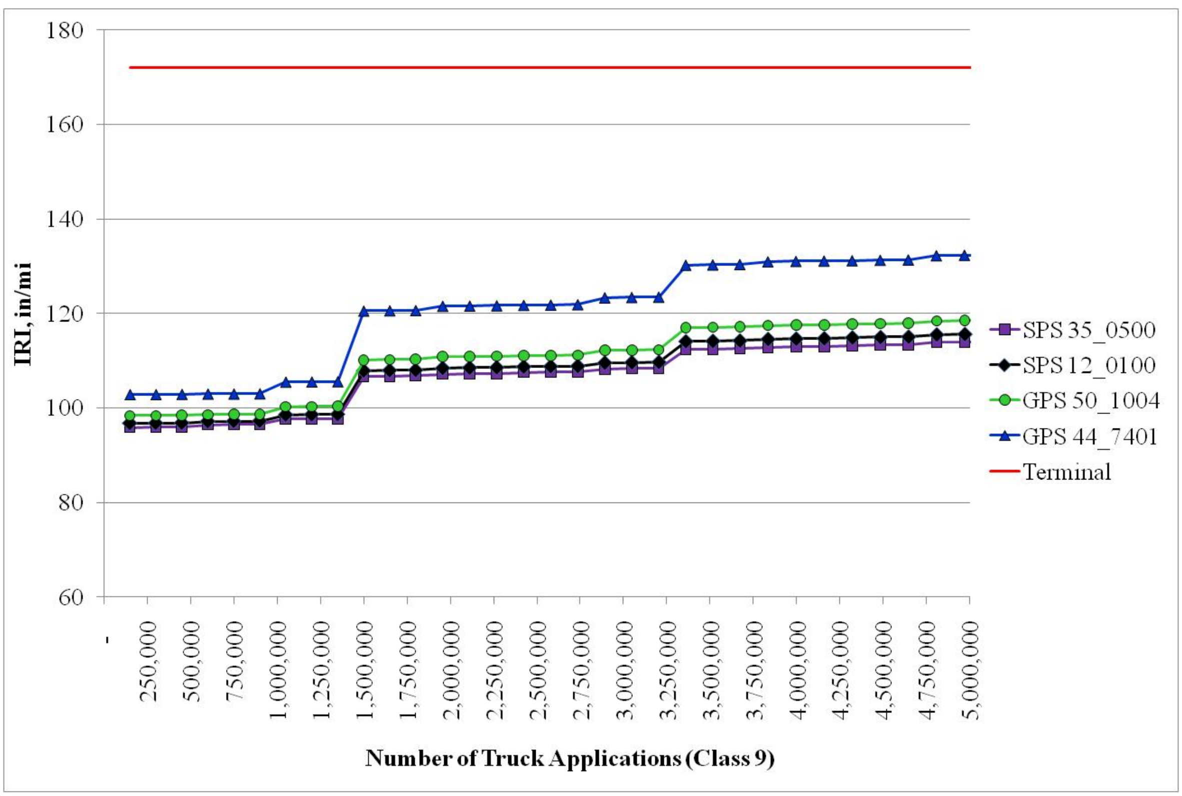

Figure 10. Graph. MEPDG IRI prediction.

These results clearly demonstrate the importance of heavy loads (or overloads, in this example) for pavement design and the relative unimportance of lighter loads. More importantly, the error within the heavier load intervals is what impacts pavement design and where the emphasis on accuracy needs to be focused. Large errors within the lighter load intervals are likely to have a negligible impact on pavement thickness design.

The key question is, what load level significantly impacts pavement thickness design? Based on limited sensitivity analysis, the 75th percentile level of the legal axle load and the number or percentage of axles exceeding the axle load limit can be used as a rule-of-thumb criterion. However, this load level or interval can depend on material, structure, climate, and MEPDG transfer function (the relationship between stress or strain and the resulting pavement damage).

It should be noted that this example is provided for illustrative purposes only. Traffic input data obtained for the GPS sites may be incorrect. For example, for site 1, (SPS site 1) there are few tandem axles exceeding 40,000 lb, the maximum allowable weight on split tandem axles. However, over 10 percent of tandem axles for site 4 exceed 50,000 lb. Such high occurrence of extreme overloads is very unusual, and the data may be suspect.

CHAPTER 5—METHODOLOGY FOR ESTIMATING RELIABILITY OF TRAFFIC LOADING DATA

RESEARCH OBJECTIVE

One of the objectives of this study was to develop a procedure for estimating the reliability of the traffic load data used for pavement design. In this study, traffic loading data reliability was estimated in terms of the maximum expected error in percentages of axles in NALS used for pavement design for a given CL.

Based on the reliability approach used in the MEPDG, there is no direct relationship between the reliability of MEPDG outcomes and the accuracy of the specific inputs. The measurement error of all inputs is included indirectly through the standard error of each transfer function. The standard errors used to define reliability in the MEPDG are distress-specific and were derived from the calibration of the transfer functions. The standard error represents the total model error. It is difficult to consider or evaluate the effect of an individual measurement error (measurement of axle load) on performance predictions. Specifically, there is no means within the MEPDG to directly consider traffic load data reliability as a direct pavement design input. However, knowledge of traffic loading data reliability is useful in developing data selection criteria for generating accurate traffic loading inputs for the MEPDG.

In this study, the research team developed a traffic loading data reliability procedure to facilitate the evaluation of WIM data accuracy and to aid in the development of data selection criteria for generating MEPDG traffic loading inputs and defaults. In other words, the procedure addresses the issue of quantifying and/or reducing the variability of WIM data for making a decision on the input to the MEPDG.

SOURCES OF ERROR AND VARIABILITY IN TRAFFIC LOADING DATA

Sources of Error

To develop NALS for pavement design, it is necessary to estimate the percentage of loads for each axle group type within each load range (load bin) of the load spectrum. In the case of global traffic loading defaults, such percentages typically represent normalized load distribution for a typical day of the year. In the case of site-specific traffic loading inputs, such percentages should represent the load distribution for a typical day of each calendar month. These NALS estimates are computed using the number of axle counts within each load range collected over a certain period of WIM monitoring.

The number of axle counts per load range (bin) can be represented using the following equation:

$$N_{ij} = Nact_{ij} + \sum \varepsilon_{ijk}$$

Figure 11. Equation. Number of axle counts per load range (bin).

Where:

N_{ij} = WIM-measured number of counts within load range i for axle group type j.
$Nact_{ij}$ = Actual number of counts within load range i for axle group type j.
ε_{ijk} = Error associated with factor, k, for load range i for axle group type j.

Some typical factors (k) causing errors in load counts include the following:

- Equipment-related factors:
  - Accuracy of axle load measurements (WIM precision and bias).
  - Equipment malfunction or improper calibration.
- Data interpretation or the incorrect placement of measured values in the correct bins (i.e., inaccurate axle group type or vehicle class assignment).
- Small sample size (number of monitoring days and their distribution over time).
- Procedure to estimate the percentages of axle loads.

Each of these factors has a different importance for the NALS estimation process. Some may have significant impacts on the estimates, and criteria for gathering and using data must be established to mitigate these impacts.

In addition to errors associated with the NALS estimate, there is another important source of uncertainty related to traffic inputs for pavement design that may be even more important: the estimate of truck traffic volume and weights over time. For pavement design, it is necessary to estimate future truck traffic volume. Such estimates are subject to large variations that have major impacts on pavement performance; however, it was not within the scope of this study to evaluate these errors. This study addresses only factors affecting the reliability of axle loading data collected using WIM systems.

Error Versus Variability

It is important to understand the difference between error and variability when addressing the various sources of error. When measuring an axle load using a WIM system, a certain error may be expected, and its magnitude is associated with the accuracy of the WIM system in place. For example, for a WIM system that has accuracy in axle weight measurement within 20 percent of the true or actual value with 95 percent confidence, for an axle load of 10,000 lb, the error will be less than 2,000 lb in approximately 95 percent of all the measurements, assuming the equipment has no bias. Therefore, when counting the number of loads between 9,000 and 11,000 lb, the count may be different from the true number of counts due to axle weight measurement error associated with WIM accuracy.

However, when making WIM measurements over a given period, the number of counts within the load range may also be different because of the daily and seasonal variations in traffic. The differences in counts due to such variations cannot be attributed to measurement error but to inherent variations in traffic for that specific WIM site location. This relates to having insufficient data to provide an accurate representation of the actual NALS for that site. Variation in traffic volume, coupled with limited data availability, may result in errors in DOW, monthly, or annual traffic loading estimates.

For example, if the percentage of loads within a specific range is estimated for the month of May, but WIM measurements were taken for only 2 days in May, a difference in estimates will be found if all 31 days in May are used. Moreover, if the 2 days of measurement were taken during the weekend, a larger difference could be expected due to the potential larger variations in traffic volume or loading distribution between weekdays and weekends. Similar errors may be introduced if the number of weekdays and weekend days in the month are not properly weighted when the full month of data is unavailable. In addition, an annual spectrum represents the distribution of traffic loads during a full year, so errors from data gaps in months or partial months may also impact the final estimated load spectra. Such errors can be mitigated by increasing the sample size.

SCOPE OF SUPPORTING ANALYSES

The research team conducted a number of statistical analyses to identify and evaluate the impact of different sources of errors in axle load measurements on the calculation of NALS. The methodology for statistical analyses was as follows:

1. Define a parameter for assessing accuracy and reliability of axle load spectrum.
2. Identify different sources of errors affecting accuracy of axle load spectrum and review SPS TPF WIM precision and bias requirements.
3. Conduct statistical tests to aid in evaluation of errors associated with WIM equipment measurements, data availability, and data variability, and determine relative significance of different sources of error.
4. Use findings from data analyses to develop traffic loading data selection criteria, considering reliability of traffic load data for pavement design.

The following sections describe each step in greater detail.

STATISTICAL PARAMETER FOR ASSESSING AXLE LOAD SPECTRUM RELIABILITY—PWLE

Purpose

A major component of the proposed procedure for estimating the reliability of the traffic load data is the development of a parameter that can be used to represent the reliability of the whole axle load spectrum for pavement design. This parameter can be viewed as a representative error for load ranges of the axle load spectrum, and its magnitude is a function of the selected CL.

Definition

For this study, the research team developed a new parameter: the PWLE for the spectrum. PWLE is a single value that provides a representative estimate of expected errors in percentages of axle load counts for individual load bins in NALS for a selected CL. PWLE is designed to aid in traffic loading data selection for MEPDG design and analysis, as it takes into consideration both the relative percentage of the traffic at each load level and the impact of each load level on the MEPDG-based pavement performance predictions.

PWLE accounts for some major pavement performance and statistical factors in one parameter, including the following:

- The variability of estimated axle frequency for each load bin of the spectrum.
- The importance of each individual load bin relative to other bins in the load spectrum, represented by the frequency of axle counts (or percentage of axle loads) within the specific load range (load bin).
- The importance of the load level associated with each load bin on pavement performance, represented by the weight factor associated with each load bin and developed in this study using MEPDG runs. The approach was presented in chapter 4.

PWLE can be viewed as a representative value rather than a statistical estimate of a single probability distribution. Although some load bins in NALS may have larger or smaller errors, PWLE is representative of the whole spectrum and reflects more weight for errors associated with load bins that have higher percentage of counts, as well as those that comprise higher load magnitudes (load bins that contain heavy loads, counts, or percentages) that have a greater impact on pavement performance.

PWLE Formulation

With PWLE, an error representing the entire NALS is determined based on a selected CL. The general PWLE formula is presented in figure 12.

$$PWLE = CF(CL,n)\sqrt{\frac{\sum_{j=1}^{nt}\sum_{i=1}^{nb_i} v_{ij}^{n} \times W_{ij} \times \overline{P}_{ij}^{n} \times p_j}{\sum_{j=1}^{nt}\sum_{i=1}^{nb_i} W_{ij} \times \overline{P}_{ij}^{n} \times p_j}}$$

Figure 12. Equation. PWLE for the selected CL.

Where:

PWLE = For the selected CL; it represents the error associated with an estimate of NALS.
CF = Confidence factor; depends on the desired CL for the error assuming the error is normally distributed (see table 5). CF is a function of the sample size *n* and CL.
n = Sample size; may represent the number of days used to estimate the monthly spectrum or the number of months used to estimate the annual spectrum for an individual site.

i = Load bin number in the load spectrum.
nb = Total number of load bins in axle load spectrum for axle group type j (e.g., for single axle spectrum, nb = 39).
j = Axle group type (j = 1 for single, 2 for tandem, 3 for tridem, and 4 for quad).
nt = Number of axle group types considered in the calculation of PWLE; nt is 4 when all axle group types (single, tandem, tridem, and quad) are considered, or it can be 1 if only one axle group type is considered.
v_{ij}^{n} = Variance of the axle count percentages for load bin i and axle group type j over n days or months and is calculated from the data (P_{ijk}) used to estimate $\overline{P}_{ij}^{n}$.
W_{ij} = Weight factor (based on the importance of the load level for pavement design) for axle group type j and the load level (load bin) i (see table 4). This parameter depends only on the axle group type j and the load bin i.
$\overline{P}_{ij}^{n} = \sum_{k=1}^{n} P_{ijk} \Big/ n$ = Average percentage of axle loads for load range i and axle group type j for the number of days or number of month n considered. When PWLE is estimated for an annual NALS computed for an individual site, n is the number of months used in the NALS calculation, and P_{ijk} values represent the percentage of axle loads for load range i and axle group type j for month k. When PWLE is estimated for a monthly NALS computed for an individual site, n is the number of days and P_{ijk} values represent percentage of axle loads for load range i and axle group type j for day k.
p_j = Percentage of total axle counts that belong to axle group type j based on the total number of days or months, depending on the purpose of PWLE computation.

Table 5. CF for selected CLs for PWLE computation using a limited sample of data.*

Sample Size	CL			
	99 Percent	**95 Percent**	**90 Percent**	**75 Percent**
2	63.66	12.71	6.31	2.41
3	9.92	4.30	2.92	1.60
4	5.84	3.18	2.35	1.42
5	4.60	2.78	2.13	1.34
6	4.03	2.57	2.02	1.30
7	3.71	2.45	1.94	1.27
8	3.50	2.36	1.89	1.25
9	3.36	2.31	1.86	1.24
10	3.25	2.26	1.83	1.23
11	3.17	2.23	1.81	1.22
12	3.11	2.20	1.80	1.21
13	3.05	2.18	1.78	1.21
14	3.01	2.16	1.77	1.20
15	2.98	2.14	1.76	1.20
16	2.95	2.13	1.75	1.20
17	2.92	2.12	1.75	1.19
18	2.90	2.11	1.74	1.19
19	2.88	2.10	1.73	1.19
20	2.86	2.09	1.73	1.19
21	2.85	2.09	1.72	1.18
22	2.83	2.08	1.72	1.18
23	2.82	2.07	1.72	1.18
24	2.81	2.07	1.71	1.18
25	2.80	2.06	1.71	1.18
26	2.79	2.06	1.71	1.18
27	2.78	2.06	1.71	1.18
28	2.77	2.05	1.70	1.18
29	2.76	2.05	1.70	1.17
30	2.76	2.05	1.70	1.17
30+	2.58	1.96	1.64	1.15

*Based on Microsoft Excel® TINV compatibility function.

PWLE may also be used to estimate the pooled error for a specific vehicle class or even for a specific axle group type. The general formula is valid for both cases, and examples of these calculations are presented later in this report.

Parameters Considered in PWLE Computation

The rationale for the PWLE parameter is that it considers the expected errors and deviations for each load range of the spectrum and pools the associated variances according to the expected percentage of traffic for the specific load range and axle group type. In addition to load frequency, it considers a performance weight, W_{ij}, that is associated with the relative impact that the specific load range and axle group type has on pavement performance. Using this approach, both the impact of the load level for each axle group type and relative percentage of traffic in each load range are taken into consideration to estimate the representative error of the spectrum.

Figure 13 presents the approach for considering both frequency and importance of axle loads at different load levels in PWLE estimation. Each axle group type *j* and load bin *i* has a corresponding performance weight factor W_{ij} and percentage of loads P_{ij}. The higher the load, the higher is the performance weight factor. The relationship between load level and W_{ij} is based on pavement performance estimated using the MEPDG (see chapter 4).[4]

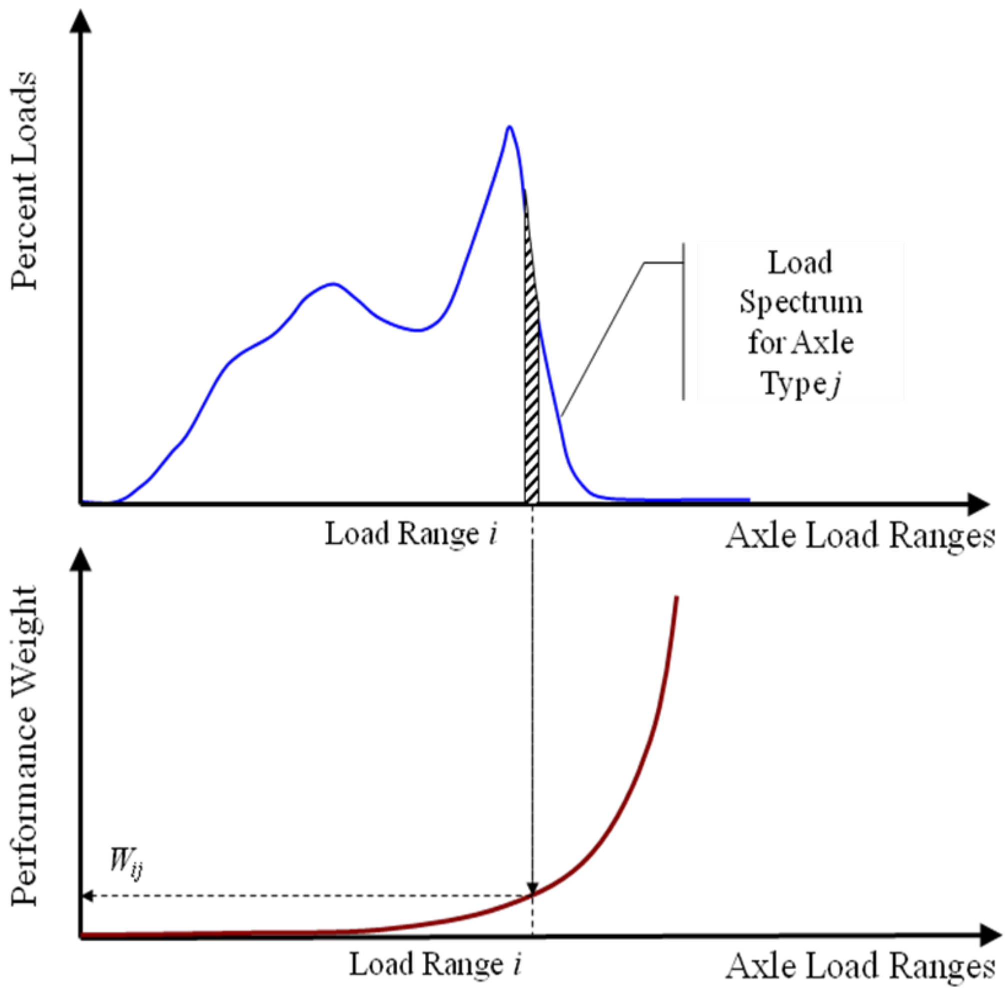

Figure 13. Graph. Estimation of parameters for PWLE.

Parameters P_{ijk} and $\overline{P}_{ij}^{n}$

P_{ijk} is the percentage of axle loads in NALS for load bin *i*, axle group type *j*, and time period (day or month) for which NALS is computed. When multiple NALS are used to estimate an average NALS (such as monthly NALS used to estimate annual NALS), the average percentage of axle loads $\overline{P}_{ij}^{n}$ is calculated for each load bin *i*, axle group type *j*, and month *k*.

Computation of P_{ikj} and $\overline{P}_{ij}^{n}$ is dependent on how PWLE is used as follows:

- PWLE to characterize errors associated with monthly NALS for a given site:
    - P_{ijk} is the percentage of axle loads for load range *i* and axle group type *j* and day *k* in daily NALS for a given site.
    - $\overline{P}_{ij}^{n}$ is the average daily percentage of axle loads for load range *i* and axle group type *j* calculated for the month using data for *n* available days in the month. In this case, $\overline{P}_{ij}^{n}$ represents the average daily percentage of axle loads for load range *i* and axle group type *j* for a typical day of the given month.
- PWLE to characterize errors associated with annual NALS for a given site:
    - P_{ijk} is the percentage of axle loads for load range *i* and axle group type *j* and month *k* in monthly NALS for a given site.
    - $\overline{P}_{ij}^{n}$ values computed for individual months are averaged to obtain a $\overline{P}_{ij}^{n}$ value. In this case, $\overline{P}_{ij}^{n}$ represents the annual average percentage of axle loads for load range *i* and axle group type *j*. NALS for 12 calendar months ($n = 12$) are recommended to compute the annual $\overline{P}_{ij}^{n}$ value.

Parameter n

Depending on the purpose of the PWLE, *n* represents the number of days. It may also represent month, number of months, or year.

Parameter v_{ij}

Variance v_{ij} is obtained by calculating the square of the differences of the P_{ijk} deviations from the average $\overline{P}_{ij}^{n}$ for each load bin. These deviations are computed for each day, each month, or each site depending on what PWLE represents. Based on the PWLE application, v_{ij} is obtained either for each month (if PWLE is based on daily traffic data for a month) or for each year (if PWLE is based on monthly traffic data for at least 1 year.)

For example, if PWLE is calculated for the year, the variance is calculated from the standard deviation of P_{ij} (for each load bin *i* and axle group type *j*) between the 12 months representing the annual traffic. Monthly NALS estimates that are used in computation of the variances for PWLE incorporate all sources of error as well as daily traffic data variation. Therefore, by using the monthly variances, the overall error associated with WIM data is being assessed.

Parameter p_j

The p_j parameter is used in PWLE to quantify the percentage of axle counts that belong to axle group type *j* in relation to total axle counts.

PWLE Applicability

PWLE was developed for this study to aid in evaluating traffic load data reliability in terms of the expected error in percentages of axles in the NALS for a given CL. This could be done for an overall axle load spectrum developed for a given site (considering all vehicle classes and axle group types) or for an individual vehicle class and axle group type.

PWLE can be used to evaluate different WIM data availability scenarios and equipment performance characteristics. The parameter allows the user to evaluate the expected error associated with the axle load spectrum that is reflective both of the relative percentage of the axle loads in each load bin and its potential impact on pavement performance based on MEPDG load-associated distress models or load equivalency factors. PWLE could be used to evaluate the following:

- Reliability of load spectrum as a function of the number of monitoring days in a given month or the number of months of available data for a given site.
- Effect of different WIM performance characteristics (precision and bias) on reliability of NALS estimates.
- Effect of different WIM site conditions and WIM technology used on reliability of NALS estimates.
- Differences in variability/reliability of NALS estimate using data before and after WIM system calibration.

Knowledge gained though these analyses could be applied to define WIM data selection criteria for the development of unbiased and reliable NALS estimates.

PROCEDURES FOR ESTIMATING RELIABILITY OF TRAFFIC LOADING DATA

Approach

During this study, the researchers developed several procedures for assessing the reliability of NALS estimates to evaluate the impact of different sources of errors on NALS estimate and to define data selection criteria for development of NALS for MEPDG use. The main component of the reliability procedures is the computation of PWLE. Computed PWLEs were used to quantify the relative importance of various sources of errors on the characterization of axle load spectra and to help define criteria for the selection of data necessary for developing MEPDG load spectrum defaults.

Method for Assessing Errors Associated with Axle Load Estimates

For some of the analyses conducted in this study, it was important to simulate different data availability and data quality scenarios. For such simulations, a Monte Carlo method was applied.

Impacts of these scenarios on errors associated with axle loading estimates were then evaluated using the PWLE parameter. Specifically, this method was used to determine how repeatability, random variation, and data availability scenarios may affect the accuracy of axle loading estimates. In addition, the research team investigated the effect of WIM precision and bias on measurement error.

The domain of inputs for the Monte Carlo simulation was axle loading data selected from the sites included in the SPS TPF study. Variances calculated from results of simulation runs were incorporated in the PWLE equation shown in the previous section to determine the importance of each source of variability and measurement error. Once the impact of different sources of error on the reliability of traffic loading estimates was quantified, this information was used to develop data selection criteria for the generation of NALS defaults.

Approach to Data Selection for Monte Carlo Simulations

Monte Carlo simulation analysis relies on typical data and variability. For this study, the research team utilized actual WIM data from the SPS TPF sites. The analysis dataset consisted of continuous WIM measurements over a specified period. In some of the analyses, such as the analysis of precision and bias, data for a whole month (e.g., 31 days) were used. For other analyses, such as evaluation of NALS reliability for a selected site, all available SPS TPF WIM data for the site were considered.

When analysis of data for all sites was cost prohibitive, a sample of sites was selected and used. In some of these cases, a site data selection process was carried out to identify data with high variability (such as DOW and seasonal variability) to test worst case scenarios. In other cases described in ensuing sections, the selection process attempted to cover the range of conditions and variability of traffic at LTPP sites. Using data for such sites, it was possible to draw conservative conclusions that can be inferred to other sites as well. In other words, modeling errors associated with sites having low variability should be smaller; therefore, if a site with high variability is tested and passes a certain reliability criterion, sites with lower variability should pass this criterion as well.

Procedure to Assess the Effect of Daily Data Availability Scenarios on Monthly Estimates

Monte Carlo simulation was used to construct axle load spectra for different data availability scenarios using the following steps. Figure 10 is a flow chart that summarizes the flow of calculations for the simulation used in this example. The following procedure describes the steps involved in a Monte Carlo simulation to check the impact of number of monitoring days per month on the monthly load spectrum estimate:

1. Select number of consecutive days of WIM data collection (2, 3, 5, 7, 10, 15, 25, or 31 days) to run the simulations. Several simulations were conducted to evaluate each number of monitored days, using the following process:

    i. Randomly select the first monitoring day from the month.

    ii. Retrieve the number of counts in each load bin from the database (vehicle classes 4 through 13 combined) for each selected day and for each axle group type.

    iii. Repeat step ii until all the load bins are exhausted.

iv. Repeat step iii until all axle group types are exhausted.

v. Repeat steps from i to viii for the next day in the month until all consecutive survey dates are exhausted.

2. Save the simulated load spectrum.

3. Calculate and save the difference in load counts between the actual and the simulated counts as percent deviation of the counts in each load bin.

4. Repeat the selection of the first monitoring day of the month and development of spectrum for 31 simulations covering all possible samples.

5. Compute the PWLE for 95 percent confidence as a function of the number of days with WIM data collected during the month. PWLE is the maximum expected error for the scenario.

6. Select a different number of days of data collection and repeat the process from steps 1 through 5.

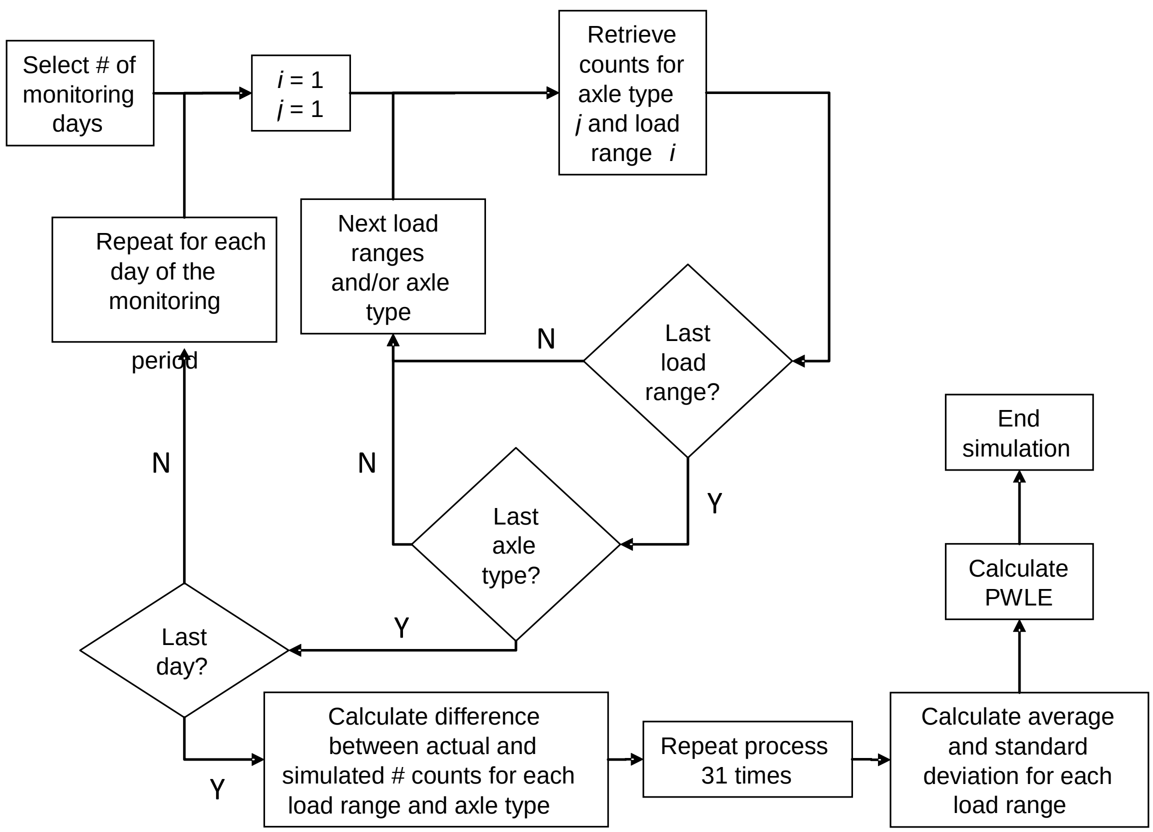

Figure 14. Flowchart. Monte Carlo simulation for analysis of data availability.

Example of Assessing the Impact of Daily Data Availability on Monthly NALS Estimates

The following example demonstrates the procedure used to evaluate PWLE associated with different data availability scenarios for a selected WIM site. Monte Carlo simulation was used to simulate different WIM data availability scenarios, expressed as number of consecutive days of data collection within a month. For this example, no precision or bias errors were simulated, and the objective was to evaluate the impact of the sample size (number of monitoring days) on the reliability of monthly axle load spectrum estimates.

To select a site for this analysis, monthly variability of tandem axle overloads was evaluated for all sites, months, and SPS TPF years. A site that had representative high monthly variability in overloads and availability of full month of daily data was selected for this example (site 20-0200 for July 2008).

Figure 15 shows the results of PWLE computation associated with different data availability scenarios simulated using 1 month of data. In this case, 31 days of data were available for the month, and the measured counts were assumed to be the actual daily counts for the site. The Monte Carlo technique was used to simulate the outcome of the load spectra when variable number of consecutive monitoring days was used. As expected, PWLE decreased as the number of monitoring days increased, and the drop in error was very significant when at least 5 monitoring days were available. In this example, it is evident that an increase in the number of available monitoring days beyond 7 DOW produced relatively low improvement in PWLE. This finding is further investigated in chapter 6 of this report.

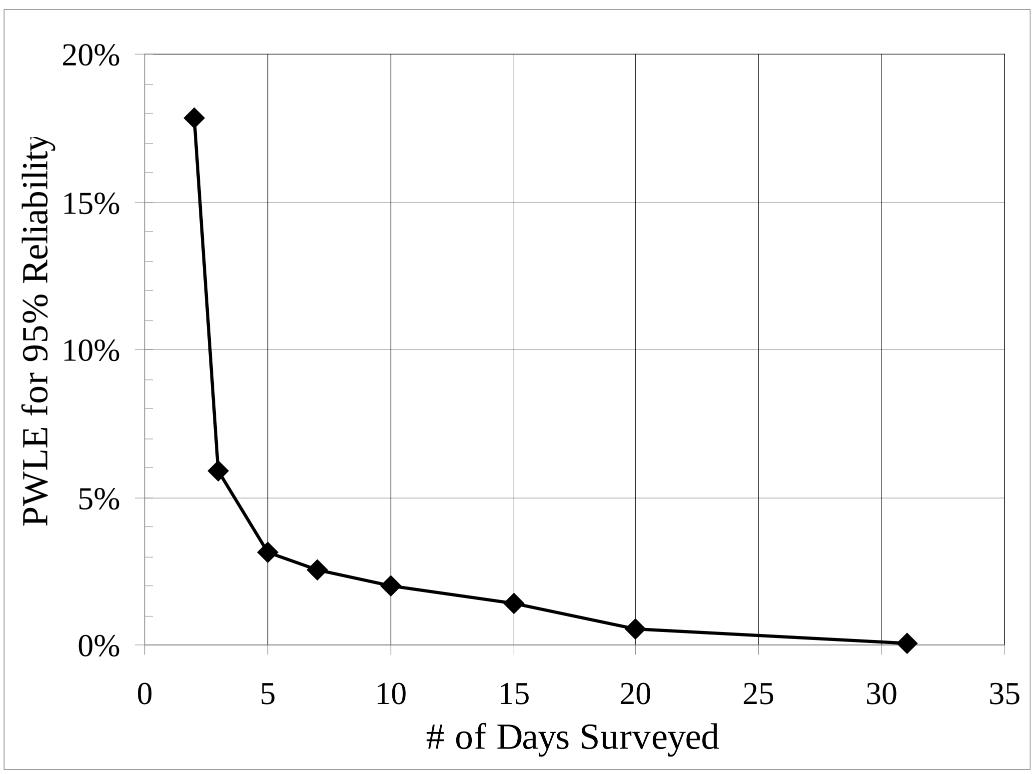

Figure 15. Graph. Impact of number of monitoring days on PWLE for site 20-0200.

Procedure to Assess the Impact of WIM Precision and Bias

The Monte Carlo simulation steps used in the analysis is a variation of that described in the previous example. Figure 12 is a flowchart that summarizes the flow of calculations for the simulation used in this example. The following procedure shows the steps involved in the Monte Carlo simulation:

1. Select number of consecutive days of data collection (7 or 31 days) to run the simulation.

   i. Randomly select the first monitoring day from the month.

   ii. Retrieve the number of counts in each load bin from the database for each selected day for each axle group type.

   iii. Randomly generate a load for every count in the load bin based on a uniform distribution between the minimum and maximum loads that define a given load bin.

   iv. Adjust the load value from step iii for equipment precision and bias.

      a. Generate a random load magnitude to simulate precision error based on a normal distribution with the mean equal to the above random load and a random error based on the user-defined limit error for the axle group type (the following limits were obtained from SPS TPF data analysis: 8.9 percent for single axles and 7.7 percent for other axle group types with a 95 percent level of confidence).

      b. Multiply the load obtained in step iii to simulate bias error by 1 ±0.039 for positive/negative bias of single axles or 1 ±0.035 for positive bias of tandem, tridem, and quad axles (these values were obtained from SPS TPF data analysis; different values could be used to simulate different bias).

   v. Assign the randomly generated load to the corresponding load bin.

   vi. Repeat steps iii to v until each count in the load bin has been simulated.

   vii. Repeat steps ii to vi until all the load bins are exhausted.

   viii. Repeat ii to vii until all axle group types are exhausted.

   ix. Repeat steps from i to viii for the next day in the month until all consecutive survey dates are exhausted.

2. Save the simulated load spectrum.

3. Calculate and save the difference in load counts between the actual and the simulated counts as percent error of the counts in each load bin.

4. Repeat the selection of the first monitoring day of the month and development of spectrum based on precision and bias for 1,000 simulations. Although the simulation involves selection of the same day for multiple runs, each of these runs will be different due to the error associated with WIM precision and bias.

5. Compute the PWLE for 95 percent confidence as function of the number of monitoring days during the month. PWLE is the maximum expected error for the scenario.

6. Select a different number of days of data collection and repeat the process from steps 1 through 5.

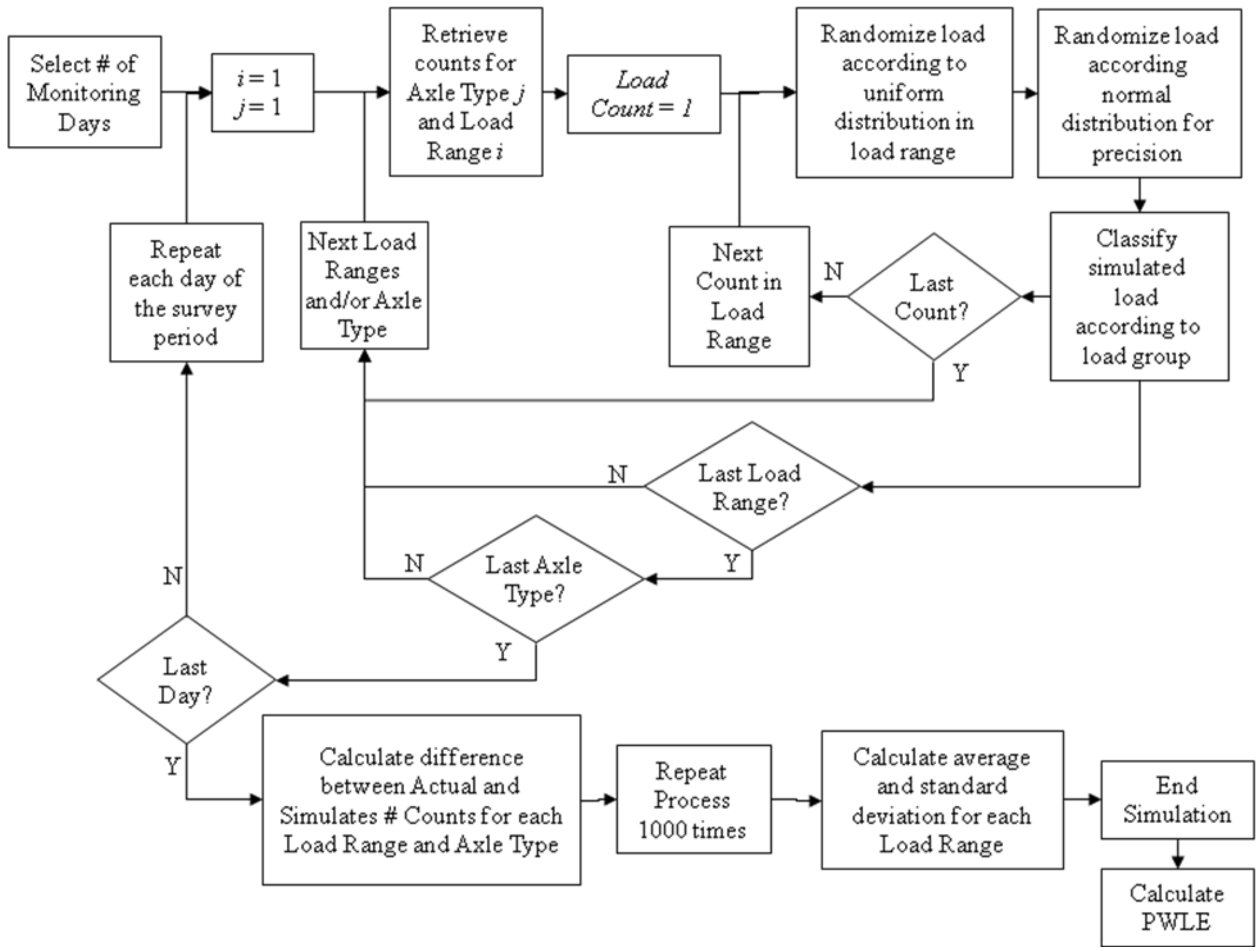

Figure 16. Flowchart. Monte Carlo simulation for analysis of precision and bias.

Procedure to Assess Reliability of Annual NALS Estimates

The procedure to calculate PWLE associated with representative annual normalized axle load spectra (RANALS) for an individual site takes into account the process used to compute annual NALS. The computation requires a minimum of 12 months of WIM data (each calendar month, January through December) for which at least 7 days of data (each DOW, Monday through Sunday) are available for each month to mitigate potential seasonal and DOW biases.

The load spectra computed for each of the 12 months of the year (all vehicle classes combined) are used to calculate the average percentage of axle loads in the annual NALS ($\overline{P}_{ij}^{12months}$) by averaging monthly axle load percentages P_{ij} for load bin i and axle group type j. In addition to the average value for each load bin, the variance is calculated based on the 12 monthly values for each load bin, and both parameters are used to calculate PWLE for the site. Assuming the deviations in percent axle loads for a given load bin in the spectrum have a normal distribution, the range of error can be estimated for a desired CL. In this case, the PWLE formula takes the following form in figure 17.

$$PWLE = CF(CL)\sqrt{\frac{\sum_{j=1}^{4}\sum_{i=1}^{nb_i} v_{ij}^{12} \times W_{ij} \times \overline{P}_{ij}^{12} \times p_j}{\sum_{j=1}^{4}\sum_{i=1}^{nb_i} W_{ij} \times \overline{P}_{ij}^{12} \times p_j}}$$

Figure 17. Equation. PWLE representing the whole axle load spectrum.

Where:

$PWLE$ = Represents the whole axle load spectrum (all vehicle classes and axle group types combined) of an individual site.
W_{ij} = Weight (RPPIF) for load bin i and axle group type j developed in this study based on MEPDG sensitivity analysis (see table 4).
CF = Depends on the desired CL for the error, assuming the error is normally distributed; for 95 percent CL, CF is equal to 1.96 (see table 6).
i = Load bin.
j = Axle group type.
nb_i = Number of load bins for axle group type i.
p_j = Percentage of total axles corresponding to axle group type j computed using data for the 12 months.
$\overline{P}_{ij}^{12}$ = Average percentage of axle loads in the annual normalized axle load spectrum computed by averaging 12 monthly axle load percentages P_{ij} for load bin i and axle group type j.
v_{ij}^{12} = Variance of axle load percentages P_{ij} in the annual normalized axle load spectrum for load bin i and axle group type j computed using 12 monthly axle load percentages P_{ij} for load bin i and axle group type j.

Table 6. CF for PWLE calculation for site-specific annual NALS.

	CL			
	99 Percent	**95 Percent**	**90 Percent**	**75 Percent**
CF	2.58	1.96	1.65	1.15

It should be noted that CF presented in table 6 represents population values rather than student *t*-value factors for a sample used in table 5. This is a simplification, since all 12 months of data are used to estimate the annual load spectrum. Also, the values in table 6 should be used to calculate PWLE for a given month if axle load data are available for the whole month. For any other case, table 5 values should be used in the PWLE formula, particularly when calculating PWLE for default spectra based on a certain sample of *n* sites.

The variance v_{ij}^{12} for a given load bin i and axle group type j is calculated based on the percentages of axle counts in that load bin for the 12 individual monthly estimates. For example, if the percentage of tandem axle loads between 30,000 and 31,999 lb are 4, 6, 7, 6, 5, 3, 7, 4, 5, 6, 6, and 3 percent (corresponding to the months from January to December), the variance (computed as the average of the squared differences from the mean value) is 2 percent.

The following steps should be used to calculate PWLE:

1. Select WIM site for analysis that satisfies minimum data availability requirements (12 calendar months with at least 7 DOW of data per month).

2. Compute NALS (all classes combined) for each axle group type, for each of the 12 months for the selected site. This will provide percentage of axle counts P_{ij} for each load bin i and axle group type j.

3. Compute total annual number and percentage of axles (p_j) for each axle group type.

4. Compute average $\overline{P}_{ij}^{12}$ and associated variance v_{ij}^{12} for each load bin i and axle group type j. This is done based on the percentages of axle counts P_{ij} in each load bin i using data from the 12 individual monthly estimates.

5. Select desired CL.

6. Obtain CF based on selected CL from table 6.

7. Obtain W_{ij} factors from table 4 for each axle group type.

8. Compute PWLE using the formula presented above.

The calculation of PWLE associated with representative annual NALS estimate for individual sites is based on the monthly variance (of percent counts obtained for load bins). It can be argued that this monthly variance arises primarily from seasonal or monthly effects rather than WIM system errors. However, the monthly estimates from WIM data used in computation of variance for PWLE incorporate all sources of error as well as daily traffic data variation. Therefore, by using the monthly variances, the overall error associated with WIM data is assessed. One exception is WIM system bias. If a WIM system has a consistent bias that is not mitigated/changed between calibration visits, this bias is not accounted for in PWLE estimation for individual sites.

Example of Assessing Reliability of Annual NALS Estimates

An example PWLE calculation associated with annual NALS estimate for an individual site is presented in this section. Data for site 51-0100 were used in this example. Table 7 presents the distribution of axle counts by axle group type based on 30 months of data for this site.

Table 7. Percentage of total loads by axle group type for site 51-0100.

Axle Group Type	Percent Count
Single	57.0
Tandem	42.6
Tridem	0.3
Quad	0.1

Figure 18 presents the RANALS by axle group type for the site.

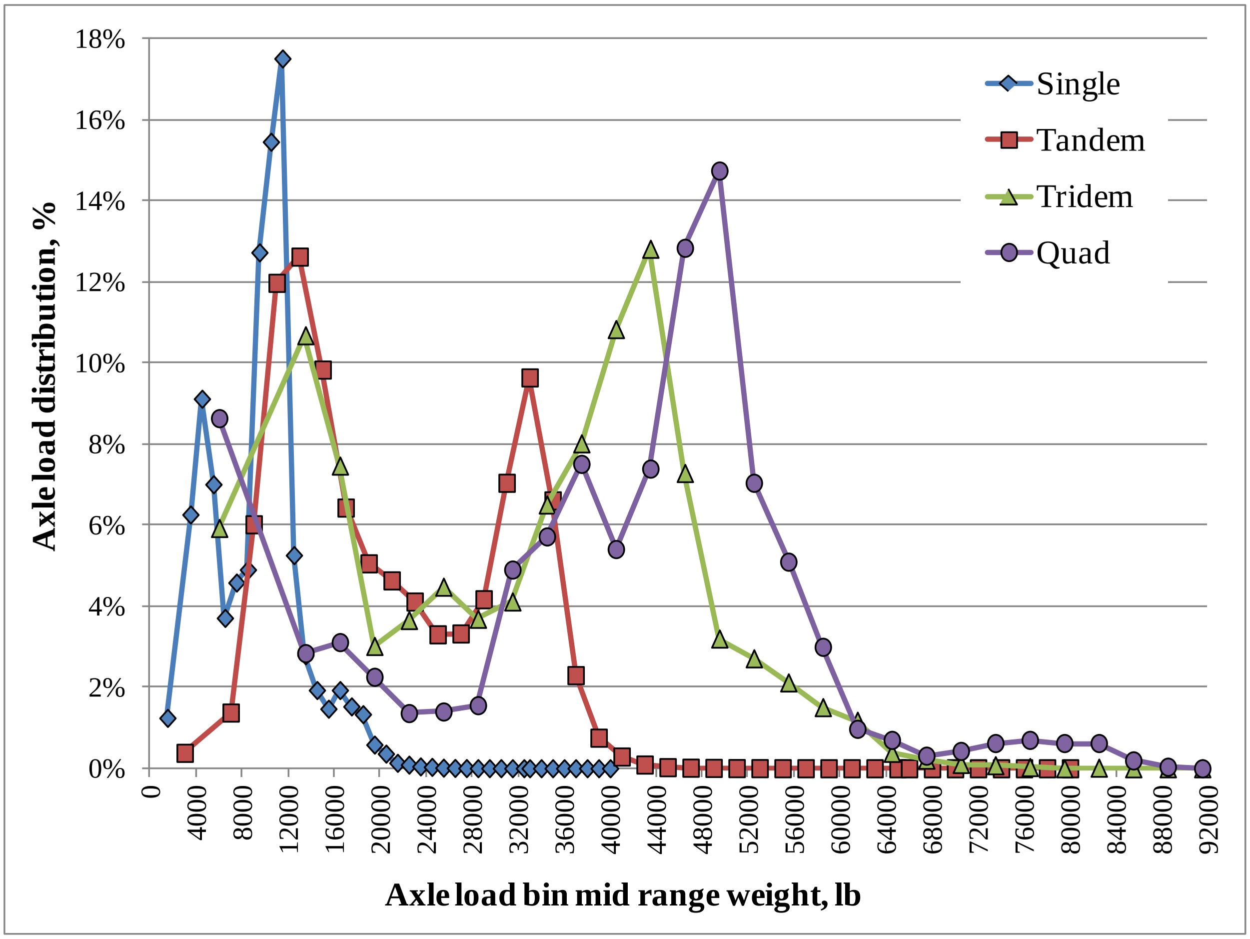

Figure 18. Graph. RANALS by axle group type.

RANALS were computed using the 12 monthly spectra estimates (one for each calendar month) and axle group type. If data for more than 1 year were available for a given calendar month, the average monthly percentages based on multiple years for each load bin were computed to characterize the spectrum for that month.

Averages $\overline{P}_{ij}^{12}$ and variances v_{ij}^{12} of the percentages for each load bin *i* and axle group type *j* were computed based on the percentages of axle counts P_{ij} in each load bin using data from the 12 representative monthly estimates.

Weight factors (see table 4) were used as multipliers to account for the relative importance of the load bin in relation to pavement performance.

Using the averages and variances for each load bin and axle group type over 12 months, PWLE for a desired CL was estimated based on monthly variability of axle load spectra, using the equation presented earlier. CF is obtained from table 6 (e.g., for 95 percent confidence, CF is 1.96).

For the example presented here, PWLE for the 95 percent confidence was found to be 1.27 percent—a small value reflecting a site with small monthly variations in load spectra. This means that the representative error associated with percentages of axles reported in load bins comprising the annual NALS for the site is within ±1.27 percent for 95 percent of the observations.

It is important to note that it was assumed that WIM calibration procedures conducted for this site resulted in unbiased load measurements. Analysis of WIM calibration data for this site indicated that average bias for the monitoring period included in this analysis was -0.63 percent for the single axles, +1.83 percent for tandem axles, and +1.2 percent for GVW, as measured by calibration trucks. However, measurements obtained during calibration visits provide only a snapshot of equipment performance and reflect measurements associated with calibration trucks only. As such, these values cannot be used directly in the assessment of data reliability. Indirectly, drifts and changes associated with WIM bias are accounted for in computation of monthly axle load spectra and associated variance used in PWLE computation.

APPLICABILITY AND USABILITY OF RELIABILITY PROCEDURES DEVELOPED IN THIS STUDY

Applicability of Reliability Procedures

The statistical analysis approach to evaluate reliability of axle load spectra estimates presented in this chapter can be used to aid in the development of the data selection criteria for generating NALS defaults. It could be used to quantify the relative importance of various sources of errors in the characterization of axle load spectra. The main component of the proposed analysis is the computation of PWLE, a parameter that can be used to represent the reliability of the axle load spectrum for pavement design.

In addition to this study, States may choose to use the PWLE statistic and analytical approaches presented in this chapter to evaluate the reliability of their axle loading data and use this information for selecting their WIM data for development of MEPDG traffic inputs, including traffic loading defaults.

Other uses of PWLE include the following:

- Evaluation of load spectra reliability as a function of the number of monitoring days in a given month or the number of months of available data for a given site.
- Evaluation of the effect of different WIM performance characteristics (precision and bias) on reliability of NALS estimates.

- Evaluation of the effect of different WIM site conditions and WIM technology used on reliability of NALS estimates.

- Evaluation of the differences in variability/reliability of NALS estimates using data before and after WIM system calibration.

The procedure to assess the reliability of axle load spectrum estimates using PWLE may be used for other applications as well. For example, it can be used to assess the representative error when a different number of sites with WIM data are used to estimate the load spectrum for a roadway section in the same region.

Recommended Future Development and Use of PWLE

PWLE is a new parameter introduced in this study, and additional studies may be required to determine acceptable PWLE levels for different pavement design and analysis applications, as well as different MEPDG input levels (levels 1–3). These acceptable PWLE levels should be determined based on changes in pavement performance predictions or pavement design estimates to answer the question, how close is close enough? Higher accuracy levels of traffic inputs may be required for design of pavements of higher volume roads (i.e., roads of higher significance).

CHAPTER 6—ANALYSIS OF AXLE LOAD SPECTRA VARIABILITY USING SPS TPF WIM DATA

OBJECTIVE AND SCOPE

The objective of the analyses presented in this chapter was to evaluate the effect of different data availability and data quality scenarios on load spectra reliability using LTPP SPS TPF data.[2] The findings from these analyses are useful to support the definition of data quality (precision and bias) and availability criteria, as well as the procedures to minimize errors when determining the NALS for MEPDG use.

LTPP has developed and implemented procedures to mitigate some types of errors affecting WIM data reliability, such as WIM system performance requirements and minimum number of monitoring days. However, it is not possible to avoid some gaps in data coverage when equipment malfunctions and some days of the month have missing data. The following types of statistical analyses were conducted to help evaluate the impact of different sources of error on reliability of axle load spectra estimates:

- Evaluation of errors due to WIM equipment precision and bias.
- Evaluation of errors associated with different data availability scenarios.
- Evaluation of temporal consistency and reasonableness in traffic loading data.

EVALUATION OF ERRORS ASSOCIATED WITH WIM EQUIPMENT PRECISION AND BIAS

Consideration of WIM Precision and Bias for Pavement Design

SPS TPF WIM data must conform to the ASTM E1318-02 specification for type I WIM system accuracy detailed in table 2.[12] Accuracy in axle weight measurements is evaluated by errors associated with WIM measurement precision and bias.

In the context of this study, WIM bias is the difference between the expected axle load value (average of all measurements) measured by the WIM equipment and the true axle load value (measured by static scale). Bias is determined as deviation of the mean axle weight error from zero. The WIM calibration process seeks to minimize bias in axle weight measurements. ASTM E1318-02 requires bias in all weight measurements to be approximately zero.[12]

Precision refers to the WIM equipment's ability to reproduce an axle load measurement consistently. Precision is defined by a maximum axle weight error expected for a specified CL. For a type I WIM system, the maximum allowable axle weight error is up to ±20 percent of the true value for single axles over 12,000 lb and up to ±15 percent for tandem, tridem, and quad axles over 25,000 lb for 95 percent conformance. WIM equipment precision is a function of WIM technology, maintenance, sensor array, and site conditions.

Precision or bias errors may have a potential impact on resulting axle load spectrum. However, the effects of bias and precision on the estimated load spectrum are different as follows:

- The accuracy level can theoretically cause a shift in the spectrum; however, the expected shift is relatively small if there is no bias because of the compensation of precision-related errors once different loads are combined in a single load bin. Some loads are measured higher, while some are measured lower than the true value. On average (i.e., when thousands of axle load applications collected over the year are combined), they are measured correctly if there is no bias. This is the principle behind the central limit theorem: the loads are measured with some error however the central tendency leads to correct average values, particularly when traffic volume is high. When the annualized NALS are built, the average number of axles in multiple load bin categories is used.

- Bias may result from calibration drift and equipment undercalibration (underestimation of weights) or overcalibration (overestimation of weights). If a WIM system has a significant calibration drift (over 5 percent error in heavy axle loads due to bias alone), the resulting load spectrum will be shifted and may have a significant impact on pavement performance predictions, as will be demonstrated in the ensuing sections.

Both precision and bias represent deviations from the true axle load value, and for the analyses conducted in this study, these differences are represented as percentage differences from the true static weight. For this study, a 95 percent CL was used to compute the representative bias and precision values based on data obtained from field validation and calibration reports for each SPS TPF site. This CL indicates that 95 percent of all observed precision and bias values were lower than the representative values selected for the analyses. Therefore, these values represent a conservative estimate of precision and bias. The reason for selecting the conservative estimate is to make sure that the conclusion obtained using these values would apply to a majority of observations based on LTPP WIM calibration data.

Analysis Purpose

Among the sources of variability of axle load spectra, WIM precision and bias have the potential to cause errors relative to the true distribution of axle loads for a highway section. In this study, researchers investigated the impact of precision and bias on MEPDG estimates to check if WIM measurements based on existing LTPP field calibration criteria may negatively influence predictions of pavement performance.

The starting point for the analyses was to define representative levels of precision and bias of WIM equipment using historical data from field calibrations for the 26 LTPP SPS TPF WIM sites.

Data Used

To estimate the representative values of WIM system precision and bias values and to investigate the effect of WIM system precision and bias associated with axle weight measurements, WIM data collected during routine WIM field calibrations for 26 LTPP SPS TPF WIM sites were obtained and analyzed. This included both pre- and post-calibration data collected during each field validation visit. Only periods (years and months) that had sufficient WIM data for developing MEPDG load spectra (based on data availability and data reasonableness criteria presented later in this report) were considered in this analysis. No pre-calibration data from the initial WIM installation were included in the analysis. The number of calibration visits for each site varied from two to eight.

During each calibration session, axle weight data from 40 passes of the calibration trucks (20 runs by each of 2 calibration trucks, primarily class 9 trucks) were collected as part of pre- and post-calibration axle weight measurement accuracy assessment.

Representative Bias

Historical WIM calibration data were used to calculate the differences between actual and measured axle loads and GVW for each calibration truck. These values were used to estimate the bias of WIM measurements for the 26 sites for each field calibration visit. In addition, changes in bias values between calibration visits were evaluated, and average bias values were computed for each site and each period between calibration visits. The distribution of average WIM system biases observed between calibration cycles among all SPS TPF sites is shown in figure 19. All distributions are centered close to zero and do not show any strong skewness.

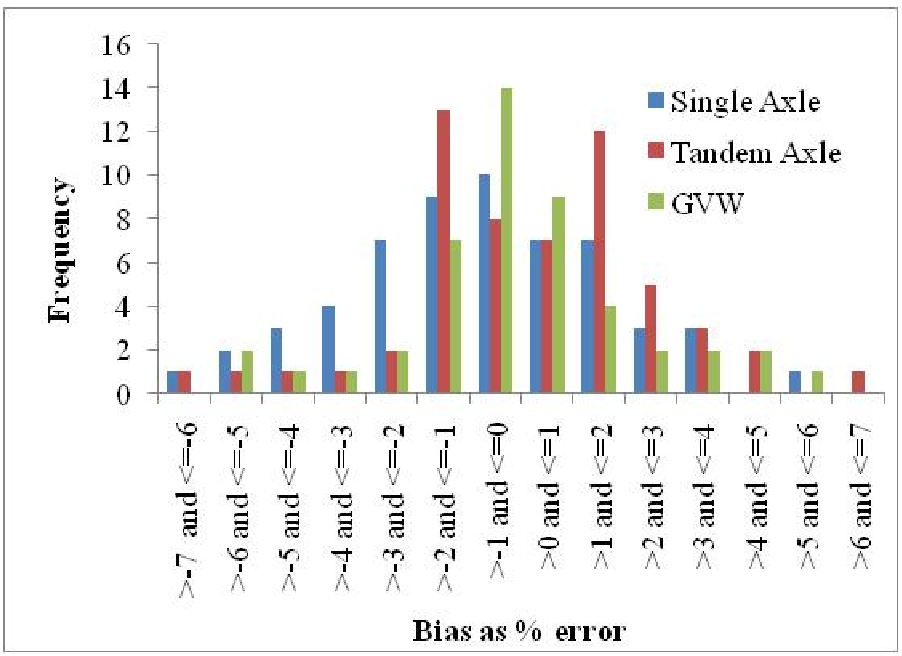

Figure 19. Graph. Distribution of average WIM system biases observed between calibration cycles among all SPS TPF sites.

The percentile differences between the actual and measured loads were averaged to estimate the bias for each site between two consecutive calibration visits. These values were then averaged over all calibrations for the site to estimate the average bias. Average bias values were computed separately for single and tandem axles for each site.

The probability distributions (characterized by the standard deviation and the average) of bias values for single and tandem axles computed for each site were used to estimate representative bias values with 95 percent confidence. The representative bias values computed for tandem axles also were used in the later analyses to represent bias of other multi-axle groups, like tridem and quads.

Once the average and standard deviation of bias for the 26 sites were established, a hypothesis test was performed to check if the overall bias was zero, considering all 26 WIM sites. This hypothesis was accepted. Assuming the overall bias representing all sites is zero, the 95 percent confidence interval was calculated, and the limits provided a conservative value for bias to use in Monte Carlo simulations and MEPDG analysis. The results indicate that, for 95 percent of all observations, the bias did not exceed approximately ±3.9 percent for single axle load measurements and ±3.5 percent for tandem axle load measurements.

Representative Precision

Precision is normally described as the largest error expected with a certain level of confidence, usually 95 percent. To estimate this value, it is necessary to use the standard deviation or variance associated with the measurement errors. The following procedure describes how the variances of the percentile differences between actual and measured axle loads obtained during WIM calibration sessions were used to estimate representative WIM precision values observed at SPS TPF sites.

The standard deviation for the percent differences between actual and measured axle loads obtained during each calibration session provided an estimate of precision achieved for the site. For an individual site, two values of standard deviations (one before and one after calibration) were computed based on 40 calibration truck measurements. Each of these values was squared to estimate the precision variances. Next, the pooled variance using all the variances obtained during individual calibration sessions was calculated to represent the typical precision variance for each site (based on two to eight variance values obtained from multiple calibration sessions), as follows:

$$\sigma_p = \frac{\sum_{i=1}^{n} \sigma_i}{n}$$

Figure 20. Equation. Pooled variance for a site.

Where:

σ_p = Pooled variance for a site.
σ_i = Precision variance obtained for each sample (in this case, for each pre- or post-calibration set of 40 test truck measurements).
n = Number of variance estimates used in the calculation (total number of pre- and post-calibration datasets for a given site, n varies from two to eight for different sites).

With 26 variance estimates (one for each site) the overall pooled variance was calculated using the same formula, with n representing the total number of sites (n = 26) and σ_i representing the precision variance calculated for each site. The overall pooled variance (16.2 for single axle and 12.1 for multiple axles) was calculated from a sample of WIM site calibrations, and it represents the sample variance.

To infer a representative variance for precision error, a CF was applied to the sample variance to ensure that in 95 percent of the cases, the population variance was below the assumed value based on the sample. To estimate the population variance with 95 percent confidence, it was assumed that the sample variance followed a chi-square probability distribution. With the sample size of 113 variance estimates, considering all pre- and post-calibration estimates for all sites used in this analysis, a chi-square test was conducted to estimate the one-sided 95 percent confidence interval for the variance. This limit (20.5 for a single axle and 15.3 for multiple axles) was assumed to represent a conservative value for the precision variance representing the 26 sites analyzed. Table 8 provides a summary of representative precision variance and bias values computed for individual SPS TPF sites.

Table 8. Summary of representative precision variance and bias values for SPS TPF sites.

Site	Number of Calibrations (Pre- and Post-Calibration)	Percent Single Axle Load		Percent Tandem Axle Load	
		Bias	Precision Variance	Bias	Precision Variance
40100	4	-0.6	15	1	17.7
40200	4	1.7	12.8	-0.5	17.9
50200	4	-0.6	11.4	2.3	10.9
60200	2	1.7	3.7	2.5	2.9
80200	6	-3.9	11.9	0	9.8
100100	4	0	19.8	-1.6	28.6
170600	8	-3	21.9	1.4	6.2
180600	2	-0.1	9.1	-0.9	5.1
200200	6	-0.9	23.2	-0.2	11.4
220100	2	-2.9	4.9	-2.7	8.6
230500	3	2.8	15.6	2.4	7
240500	6	0.5	23.2	1.7	13.8
260100	6	-1	16.4	-2.9	12.4
270500	6	-2.6	13.9	-1.3	10.2
350100	2	-2.1	3.5	0.2	15.2
350500	2	-1.5	11.9	-0.6	12.5
390100	2	-1.5	5.5	1.2	9.7
390200	2	-5.4	10.3	1.2	12.9
420600	4	-0.4	39.6	-1.6	9.4
470600	4	-0.7	12.5	-1.4	7.9
480100	7	-2.6	8.8	1.2	13.4
510100	6	-0.6	12.7	1.8	13.8
530200	6	1.4	33.5	2.6	16.5
550100	4	1.4	8.9	0.9	9.1
120100	4	0.9	41.9	-1	19
120500	7	-0.4	29.9	-3.2	13.2

The population variance with 95 percent confidence based on 26 sites was used to estimate the maximum precision error. To estimate this value, the standard deviation was computed as being the square root of the population variance and then multiplied by the standard deviate for 95 percent confidence.

Table 9 presents a summary of maximum percentile axle load errors associated with conservative estimates of SPS TPF WIM precision and bias. The expected maximum error due to precision alone is 8.9 percent for single axles and 7.7 percent for tandem axles. The expected total maximum error is obtained by summing both the precision and bias errors, each with 95 percent confidence. These values represent conservative values for precision and bias, as more than 95 percent of all observations are expected to be lower than these values. These values are 12.8 percent for single axles and 11.2 percent for tandem axles—well below the LTPP accuracy criteria of 20 and 15 percent for single and tandem axles, respectively.

Table 9. Percent axle load error for representative WIM precision and bias.

Parameter	Single Axle	Tandem Axle
Standard deviation of precision error (percent axle load)	4.5	3.9
Maximum precision error with 95 percent confidence	8.9	7.7
Maximum site bias error with 95 percent confidence	3.9	3.5
Maximum error (precision + bias)	12.8	11.2
LTPP criteria (percent axle load error, 95 percent confidence)	20	15

Effect of WIM Precision and Bias on Load Spectra Accuracy

Data Selection

The effect of WIM precision and bias on reliability of monthly NALS estimates was evaluated for selected SPS WIM sites that exhibit different levels of data variability to investigate the significance of this effect. To cover the range of observed daily variability in percentages of heavy axles, a set of sites was selected for the analysis that correspond to 50th, 75th, 95th, and 99th percentiles of all other observations with respect to observed variability in daily percentages of heavy tandem axles. For example, 50 percent of all the observed variations in daily percentages of heavy tandem axle counts are lower than the variation observed at site 8-0200 for the month of April 2009. A summary of the selected sites is shown in table 10. These sites cover a range of geographical locations as well as daily volumes and axle load spectra distributions.

Table 10. Variability of heavy tandem axle loads for selected WIM sites.

Site ID	Year	Month	Daily Volume of Tandem Axles	Standard Deviation of Daily Percentage of Heavy Tandem Axles	Percentage of All Other Observations with Variability Less than Selected Site
8-0200	2009	4	1,475	4.2	50
26-0100	2008	3	953	5.7	75
24-0500	2006	12	482	10.7	95
4-0100	2008	7	92	13.8	99

Analysis Process

To check the impact of precision and bias on the reliability of monthly NALS, the research team conducted a Monte Carlo simulation analysis using a sample of 31 days (1 month) of continuous WIM data for four different LTPP sites. The following three scenarios were evaluated:

- Precision and no bias.
- Precision and positive bias.
- Precision and negative bias.

The precision and bias levels used in this analysis are shown in table 8. These are conservative estimates based on SPS TPF sites. It was expected that more than 95 percent of all sites would have maximum axle weight errors due to WIM equipment precision and bias less than the percentages shown in table 8.

In addition, the researchers tested two data availability scenarios: 7 and 31 days. The reason for testing different data availability scenarios in combination with precision and bias is that the combined error is likely to increase due to permutation of individual errors.

The Monte Carlo simulation was used to simulate different data availability and precision and bias scenarios using procedures described in chapter 5. The results of analysis are summarized in table 11.

Table 11. Summary of errors (PWLE for 95 percent reliability) computed considering WIM precision and bias.

Site	Number of Monitored Days per Month	Precision and No Bias (Percent)	Precision and Negative Bias (Percent)	Precision and Positive Bias (Percent)
4-0100	7	2.2	3.4	3.4
	31	0.7	2.9	2.9
8-0200	7	3.7	6.9	5.1
	31	3.4	6.9	5.1
24-0500	7	1.5	2.5	2.2
	31	1.0	2.2	2.0
26-0100	7	1.8	2.2	2.7
	31	1.0	2.0	1.7

Analysis Findings

Using table 11, the effect of precision alone can be evaluated using the unbiased scenario for data available for all days of the month. It is noted that errors associated with both precision and bias can be more important than the number of days surveyed, if data for at least 7 days are available. The difference in PWLE between 7 and 31 days provides the basis for this conclusion because the levels of precision and bias are similar in both cases.

To evaluate the amount of error caused by WIM equipment precision and bias alone, the results for monthly data availability scenarios where all 31 days of data were available were used. It can be noted that when bias is introduced, PWLE increases no matter if the bias is positive or negative. Based on the results presented in table 11, the following conclusions can be made:

- As expected, PWLE decreased as the number of days surveyed increased. In general, a decrease lower than 1.5 percent in the total error was achieved when comparing 7 days surveyed to the full month. The small error difference between the full month and 7 days confirms that data collected during 1 week is representative of the spectrum for the month.

- The impact of precision can only be assessed by observing PWLE estimated for the case of no bias and 31 days of data available in a month. PWLE for the four sites investigated ranged from 0.7 to 3.4 percent, which is considered small. The precision values used in the analysis were representative of the upper end of all precision errors calculated from calibration reports for SPS TPF sites. Therefore, this conclusion could be considered representative for the precision levels observed in SPS TPF data. Because precision-related errors tend to compensate each other when all the available data are considered in calculation of representative annual axle load spectrum, the impact of these errors on estimated pavement performance is low.

- The impact of bias on PWLE ranged from 1.0 to 3.5 percent and is considered low for the typical bias values found in the LTPP sites (see table 8). The impact of bias alone can be evaluated by comparing the results for the 31 days surveyed. Because bias can cause greater differences in pavement performance estimates using the MEPDG, the impact of bias was further investigated in this study using the MEPDG analysis presented later in this chapter.

- The impact of negative and positive bias was similar among different sites; however, the values vary slightly due to differences in the NALS.

- PWLE proved to be useful to quantify the effect and relative importance of precision, bias, and sample size. The impact of these three effects would be very difficult to assess without a parameter like PWLE because it accounts for the load distribution as a whole, the performance weights for each load level, and the errors associated with the percentage for each load bin in the spectrum.

It is important to note that this analysis was conducted using conservative estimates of axle weight errors due to WIM equipment precision and bias values applied to LTPP sites. This was done to investigate the effect of precision and bias for sites with different data variability and different axle load spectra.

Effect of WIM Precision and Bias on MEPDG Outcomes

The research team investigated the effect of precision and bias on the NALS estimates and associated MEPDG outcomes. The goal of the analysis was to evaluate whether typical precision and bias values observed at LTPP SPS TPF WIM sites were likely to produce significant differences in MEPDG outcomes. The results of the analysis could be used to confirm current WIM accuracy requirements or to provide information for refinement.

Development of NALS for MEPDG Analysis

NALS obtained as the average of all SPS TPF sites (global default) was selected as the baseline (unbiased) load spectra for the analysis. Monte Carlo simulation was used to generate the load spectra for positive and negative bias. To do that, positive and negative bias percentages provided in table 9 (3.9 percent error due to bias for single axles and 3.5 percent error due to bias for multiple axles) were applied to each load bin value. In addition to bias, errors resulting from limited precision of WIM devices were also accounted for (8.9 percent precision error for single axle weight measurements and 7.7 percent error for multiple axle weight measurements). Examples of resulting single and tandem axle load spectra for class 9 vehicles are shown in figure 21 and figure 22. Similar adjustments were made to load spectra for all other vehicle classes and axle group types used in the analysis.

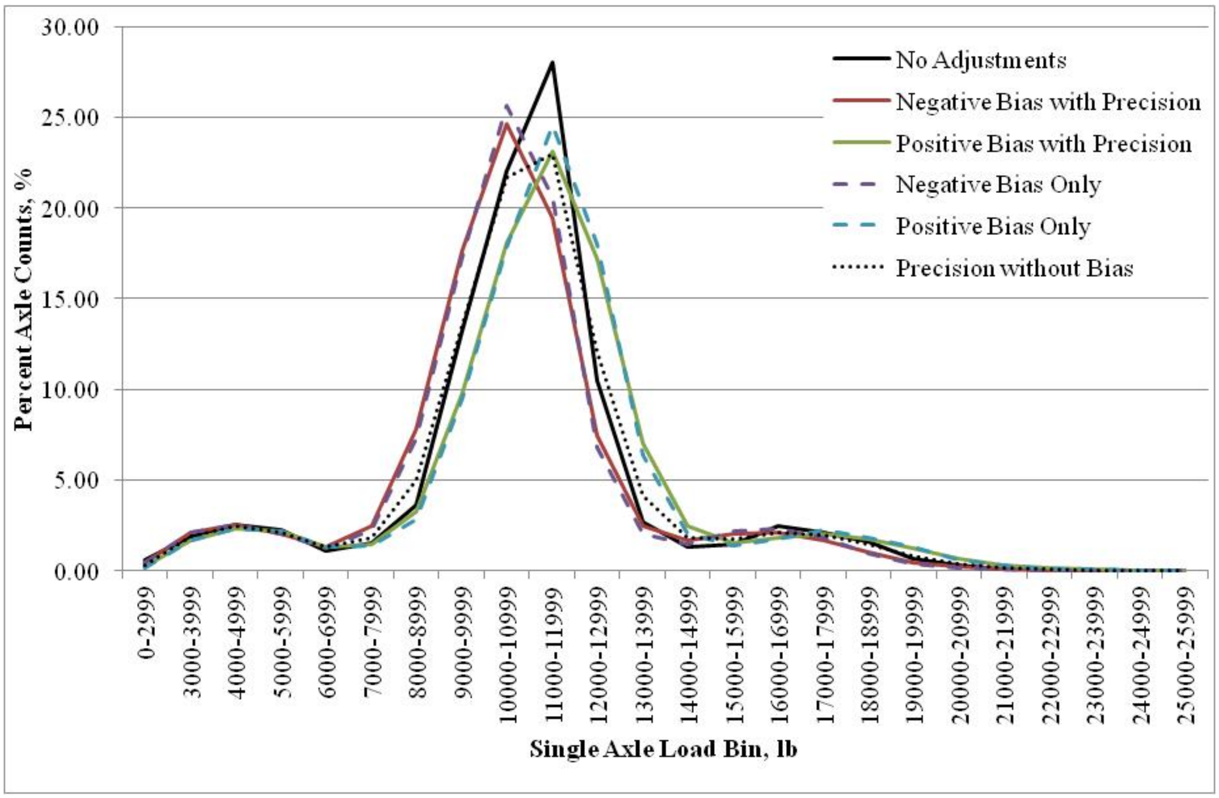

Figure 21. Graph. Example of biased single axle load spectra for class 9 vehicles.

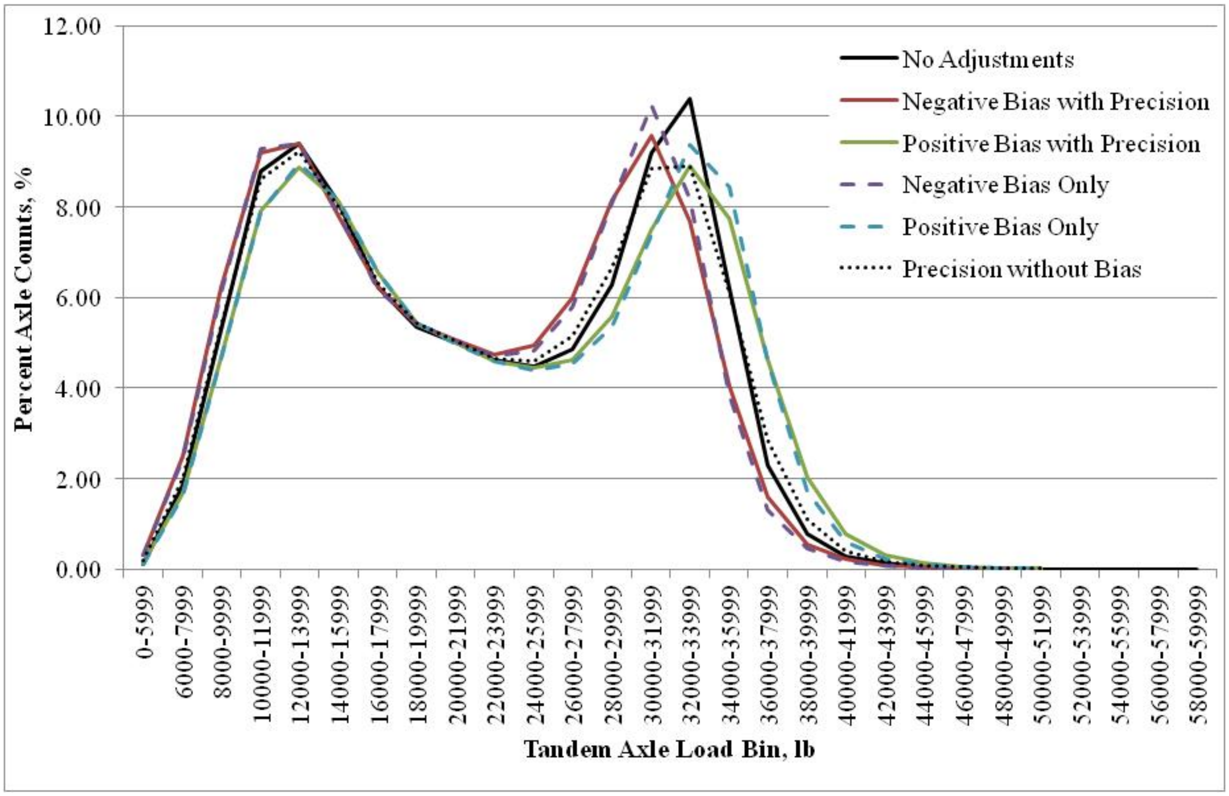

Figure 22. Graph. Example of biased tandem axle load spectra for class 9 vehicles.

MEPDG Designs

The research team developed a set of representative rigid and flexible pavement designs and analyzed the predicted pavement performance. Table 12 presents a summary of the pavement design structures used for this analysis. VCDs and AADTT values characteristic to RI and ROPA roads were used for the analyses and represent typical values observed in LTPP database for rigid and flexible pavements.

Table 12. Pavement design inputs used in MEPDG analysis of WIM precision and bias.

Scenario	MEPDG Inputs
Flexible RI—top-down cracking	• AADTT: 2,000 • TTC: 1 • Climatic file: Wet-freeze (Wisconsin) • Binder grade: 76-22 • Binder content: 10 percent • Air voids: 5 percent • Base type/thickness: Crushed stone/12 inches • Modulus: 32,000 psi • Soil type: A-1-b • Modulus: 26,500 psi

Scenario	MEPDG Inputs
Flexible RI—rutting	• AADTT: 2000 • TTC: 1 • Climatic file: Wet-freeze (Wisconsin) • Binder grade: 64-22 • Binder content: 10 percent • Air voids: 5 percent • Base type/thickness: Crushed stone/12 inches • Modulus: 30,000 psi • Soil type: A-7-6 • Modulus: 8,300 psi
Flexible RI—bottom-up cracking	• AADTT: 2,000 • TTC: 1 • Climatic file: Wet-freeze (Wisconsin) • AC layer 1 thickness: 2 inches • Binder grade: 76-22 • Binder content: 11 percent • Air voids: 5.5 percent • AC layer 2 thickness: Variable • Binder grade: 64-22 • Binder content: 8 percent • Air voids: 8 percent • Base type/thickness: Crushed stone/12 inches • Modulus: 32,000 psi • Soil type: A-1-b • Resilient modulus: 26,500 psi
Flexible ROPA—bottom-up cracking	• AADTT: 500 • TTC: 6 • Climatic file: Dry-freeze (Arkansas) • AC layer 1 thickness: 2 inches • Binder grade: 76-22 • Binder content: 11 percent • Air voids: 5.5 percent • AC layer 2 thickness: Variable • Binder grade: 64-22 • Binder content: 8 percent • Air voids: 8 percent • Base type/thickness: Crushed Stone/8 inches • Modulus: 26,000 psi • Soil type: A-1-b • Resilient modulus: 26,500 psi
Flexible ROPA—top-down cracking	• AADTT: 500 • TTC: 6 • Climatic file: Wet-no freeze (Alabama)

Scenario	MEPDG Inputs
	• Binder grade: 70-22 • Binder content: 10 percent • Air voids: 5 percent • Base type/thickness: Crushed stone/8 inches • Modulus: 33,600 psi • Soil type: A-1-b • Modulus: 26,500 psi
Rigid RI—cracking	• AADTT: 2,000 • TTC: 1 • Climatic file: Wet-no-freeze (Alabama) • 28-day PCC modulus of rupture: 650 psi Dowels: Yes • Erodibility Index: Very erosion resistant (2) • Base type/thickness: Soil cement/6 inches • Modulus: 100,000 psi • Soil type: A-6 • Modulus: 14,000 psi
Rigid ROPA—faulting	• AADTT: 700 • TTC: 2 • Climatic file: Dry-no freeze (Arizona) • 28-day PCC modulus of rupture: 650 psi Dowels: Yes • Erodibility Index: Fairly erodible (4) • Base type/thickness: Soil cement/6 inches • Modulus: 500,000 psi • Soil type: A-6 • Modulus: 14,000 psi
Rigid ROPA—cracking	• AADTT: 700 • TTC: 2 • Climatic file: Wet-freeze (Wisconsin) • 28-day PCC modulus of rupture: 650 psi Dowels: Yes • Erodibility Index: Very erosion resistant (2) • Base type/thickness: Soil cement/6 inches • Modulus: 100,000 psi • Soil type: A-6 • Modulus: 12,000 psi

Note: Top-down cracking was used in the analysis. However, there is extensive debate in the pavement engineering community on the applicability of the mechanism included in the MEPDG for top-down cracking predictions. The *Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice,* suggests using top-down cracking predictions for information purposes and not to make changes to the designs.[1]

In the sensitivity analysis, a pavement was first designed using NALS without adjusting for precision and bias and then analyzed again using load spectra adjusted for negative and positive bias, as well as with and without precision adjustment to see the differences in pavement design life predictions. To analyze the difference in pavement thickness resulting from different load spectra, changes were made to the top structural layer (AC or PCC) only. For this analysis, MEPDG results computed for 90 percent design reliability and pavement performance criteria specified in the MEPDG version 1.1 software were used.

MEPDG Analysis Findings

To evaluate the results of the analysis, the following criteria were used: results were considered significantly different if pavement life was reduced by at least 20 percent (3 years for flexible pavements and 4 years for rigid pavements) or if the thickness difference in the AC or PCC structural (top) layer was more than 0.5 inch. Table 13 and table 14 show the results of MEPDG sensitivity analysis for the design life and layer thickness scenarios, respectively.

Table 13. Difference in pavement life using different WIM precision and bias scenarios.

Pavement Type and Functional Class	Critical Distress	Pavement Life (Years)							
						Difference			
		N	P	NBP	PBP	N − NBP	PBP − N	PBP − NBP	P − N
Flexible—RI	Bottom-up cracking	15.8	15.7	15.8	14.1	0.1	1.7	1.8	0.1
	Top-down cracking	15	14.8	16.8	13.8	1.8	1.2	3	0.2
	Rutting	15.7	15.6	15.8	13.8	0.1	1.9	2	0.1
Flexible—ROPA	Bottom-up cracking	15.7	15.6	15.8	13.7	0.1	2.0	2.1	0.1
	Top-down cracking	15.5	14.9	16.8	13.7	1.3	1.8	3.1	0.6
Rigid—RI	Slab cracking	19.6	19.5	21.7	17.5	2.1	2.1	4.2	0.1
Rigid—ROPA	Faulting	20.3	20.3	20.3	19.4	0	0.9	0.9	0
	Slab cracking	21	20.8	22	18.8	1	2.2	3.2	0.2

N = No adjustment.
P = Precision only.
NBP = Negative bias + precision.
PBP = Positive bias + precision.

Table 14. Difference in top layer thickness using different WIM precision and bias scenarios.

Pavement Type and Functional Class	Critical Distress	Pavement Thickness (Inches)							
						Difference			
		N	P	NBP	PBP	N − NBP	PBP − N	PBP − NBP	P − N
Flexible—RI	Bottom-up cracking	6.8	6.8	6.7	7	0.1	0.2	0.3	0
Flexible—RI	Top-down cracking	8.2	8.2	8.1	8.3	0.1	0.1	0.2	0
Flexible—RI	Rutting	8.2	8.2	8	8.7	0.2	0.5	0.7	0
Flexible—ROPA	Bottom-up cracking	5.3	5.3	5.3	5.5	0	0.2	0.2	0
Flexible—ROPA	Top-down cracking	7.2	7.3	7.1	7.5	0.1	0.3	0.4	0.1
Rigid—RI	Slab cracking	10.4	10.4	10.3	10.5	0.1	0.1	0.2	0
Rigid—ROPA	Faulting	10.1	10.1	10.1	10.3	0	0.2	0.2	0
Rigid—ROPA	Slab cracking	8.8	8.8	8.8	8.9	0	0.1	0.1	0

The results show that when either negative or positive bias was introduced to axle load spectra, the resulting differences in pavement life were close but not over the selected threshold criterion of 20 percent difference in pavement design life, compared to results using axle load spectra with no bias. When pavement life predictions were compared for the cases with positive versus negative bias, half of design cases showed difference in pavement design life over the 20 percent criterion.

With respect to observed differences in pavement thickness, only one design case (rutting for flexible RI) showed significant difference when the no bias design case was compared with the positive bias design case. When pavement thickness predictions were compared for the cases with positive versus negative bias, again only the rutting case showed a difference in AC thickness over the 0.5-inch criterion. This was primarily due to rutting in unbound layers and subgrade, and this type of rutting is not expected to be mitigated by adjusting the thickness of the surface layer. It has been found that the MEPDG overpredicts the amount of rutting in the unbound layers and subgrade. Local calibration factors less than unity have been recommended to reduce the amount of rutting in those layers.

With respect to WIM measurement precision evaluation for the precision values tested, no MEPDG results indicated differences in pavement life or thickness that would be considered significant from a practical point of view.

Additional MEPDG Analysis of 5 Percent WIM Bias

Since bias potentially contributes to significantly different MEPDG outcomes, a decision was made to increase bias values to 5 percent to see if this would result in significantly different MEPDG outcomes. Bias values of 5 percent or more were observed in a few instances at SPS TPF sites before WIM calibration was conducted, indicating changes in axle weigh measurement accuracies between calibration visits. Table 15 and table 16 show a summary of MEPDG results considering 5 percent bias.

Table 15. Difference in pavement life considering 5 percent WIM bias.

Pavement Type and Functional Class	Critical Distress	Pavement Life (Years)					
		No	NB	PB	Difference		
					NB− No	No − PB	NB − PB
Flexible—RI	Bottom-up cracking	15.8	18.5	13.8	2.8	2.0	4.8
	Top-down cracking	15	17.7	13.7	2.7	1.3	4
	Rutting	15.7	17.8	13.8	2.1	1.9	4
Flexible—ROPA	Bottom-up cracking	15.7	17.8	13.2	2.2	2.5	4.7
	Top-down cracking	15.5	17.7	13	2.2	2.5	4.7
Rigid—RI	Slab cracking	19.6	22.7	16.8	3.1	2.8	5.9
Rigid—ROPA	Faulting	20.3	21.2	19.1	0.9	1.2	2.1
	Slab cracking	21	24.2	18.3	3.2	2.7	5.9

No = No bias.
NB = Negative bias.
PB = Positive bias.

Table 16. Difference in AC/PCC thickness considering 5 percent WIM bias.

Pavement Type and Functional Class	Critical Distress	Pavement Life (Years)					
		No	NB	PB	Difference		
					NB − No	No − PB	NB − PB
Flexible—RI	Bottom-up cracking	6.8	6.5	7.1	0.3	0.3	0.6
	Top-down cracking	8.2	8.1	8.5	0.1	0.3	0.4
	Rutting	8.2	7.5	8.8	0.7	0.6	1.3
Flexible—ROPA	Bottom-up cracking	5.3	5.1	5.5	0.2	0.2	0.4
	Top-down cracking	7.2	6.9	7.5	0.3	0.3	0.6
Rigid—RI	Slab cracking	10.4	10.2	10.5	0.2	0.1	0.3
Rigid—ROPA	Faulting	10.1	10	10.3	0.1	0.2	0.3
	Slab cracking	8.8	8.6	9	0.2	0.2	0.4

The results from this analysis show that when a negative or positive bias of 5 percent is introduced to the axle load spectra, the resulting differences in estimated pavement life for all cases were different but not over the selected threshold criterion of 20 percent difference in pavement design life compared to results using axle load spectra with no bias. When pavement life predictions were compared for cases with positive and negative bias, all but one design case (joint faulting for rigid ROPA) showed a significant difference in pavement design life over the 20 percent criterion.

With respect to observed differences in pavement thickness, only one design case (rutting for flexible RI) showed a significant difference when the no-bias design case was compared with the positive and negative bias design cases. When pavement thickness predictions were compared for the cases with positive versus negative bias, three of five flexible pavement design cases showed a difference in AC thickness over the 0.5-inch criterion, while no rigid designs showed differences at or above 0.5 inch.

Conclusions from Analysis of WIM Precision and Bias

SPS TPF WIM data were assessed, and it was determined through statistical analysis that for 95 percent of the data, the average error in axle weight measurements due to WIM bias observed between calibration visits was 3.9 percent or less for single axles and 3.5 percent or less for tandem axles. The expected maximum error due to precision was found to be 8.9 percent for single axles and 7.7 percent for tandem axles using 95 percent confidence. These observations are based on the historical data collected during field calibration visits under the SPS TPF study (from 2003 to 2011).

These conservative estimates of expected errors due to WIM precision and bias were used to estimate PWLE for selected LTPP sites representing different axle load spectra. The observed errors in monthly axle load spectra estimates varied based on axle load spectra shapes and daily data variability. None of the estimates exceeded 7 percent in PWLE. MEPDG analysis of selected pavement designs did not show significant differences in MEPDG outcomes for these levels of error. Based on these findings, it is possible to infer that, using current ASTM and LTPP SPS TPF calibration procedures, the level of errors caused by WIM equipment precision and bias is likely to be insignificant for MEPDG applications.[12]

However, the statistical analysis and MEPDG sensitivity analyses presented in this section indicate that it is beneficial to develop and enforce acceptance criteria for maximum allowable weight measurement bias for individual axles to ensure that good quality data are used to define the load spectrum for MEPDG applications. MEPDG analysis indicates that bias exceeding 5 percent of mean error could lead to significant differences in MEPDG design outcomes. It is recommended that mean error in axle weight measurements of calibration trucks should stay below 5 percent to ensure good quality data for pavement design.

Through MEPDG analysis, it was also determined that different MEPDG outcomes could be observed for under- versus over-calibrated WIM systems. This case represents real-life situations when an under-calibrated WIM system is over-calibrated in subsequent visits. However, when load spectra from multiple calibration cycles are combined, the errors in the over- or under-calibrated load spectra will likely compensate each other.

Based on the analysis of data from WIM site calibration reports, it is evident that bias values change between calibration visits. LTPP recognizes this and mitigates it through cyclic annual calibrations. However, because it is cost prohibitive to calibrate more than once a year, some level of bias in the data is inevitable between calibrations. To mitigate the effect of bias in development of axle load spectra for MEPDG applications, it is beneficial to have the data collected for the period covering multiple calibration cycles. This way, the effect of the bias is minimized by averaging data from the months that had different biases within the year and between years.

EVALUATION OF ERRORS ASSOCIATED WITH DATA AVAILABILITY

Analysis Purpose

The extent of data coverage (number of days per year/month/DOW) and procedures used to derive axle loading estimates from the available data affect the reliability of NALS estimates. A considerable amount of work has been done in this area through previous studies that analyzed the effects of various traffic data collection scenarios on the accuracy of traffic estimates.[6,13] For this study, a number of analyses were conducted to evaluate the impact of data availability on the expected error (represented by PWLE) in NALS estimates using SPS TPF WIM data. The purpose of the analysis was to obtain information that could be used to define data availability criteria and computational procedures for developing default NALS estimates.

Effect of Daily Data Availability on Monthly NALS Estimates

Data Used

The researchers developed a dataset to aid in the analysis of the impact of daily data availability on computed monthly NALS values. Specifically, the analysis focused on scenarios with high variability in heavy axle percentages in NALS, as accuracy in these values matters most for pavement design applications. The analysis focused on tandem axles, as these axles carry the majority of heavy axle loads observed at SPS TPF sites.

To select a representative dataset for analysis, variability in daily percentages of heavy tandem axle loads was evaluated for the 26 SPS TPF sites for all months and all years. All the months of data for all SPS TPF sites that had daily counts for every day of the month were included in this evaluation.

Heavy axle load percentages were computed using NALS by summing percentages of axles in load bins that represent heavy loads. Two different definitions of heavy loads were considered: one that includes all load bins at or above the legal load limit value for a given axle group type and one that includes all load bins above 75 percent of legal load limit value for a given axle group type. The initial analysis was based on an evaluation of consequences of variability in daily percentages of overloaded axles on monthly NALS estimates. However, the limitation of this analysis approach was a very low percentage of tandem axles with overloads typically observed at SPS TPF sites. Therefore, it was decided to expand the definition of heavy loads from legal limit to 75 percent or more of the legal limit in further analyses.

Analysis of Heavy Axle Loads Variability

Variability in daily percentages of heavy axle loads was evaluated by comparing standard deviations in daily percentages of heavy axles computed for each month for each SPS TPF site. The distribution of standard deviations in daily percentages of heavy axles with respect to daily axle counts is shown in figure 23.

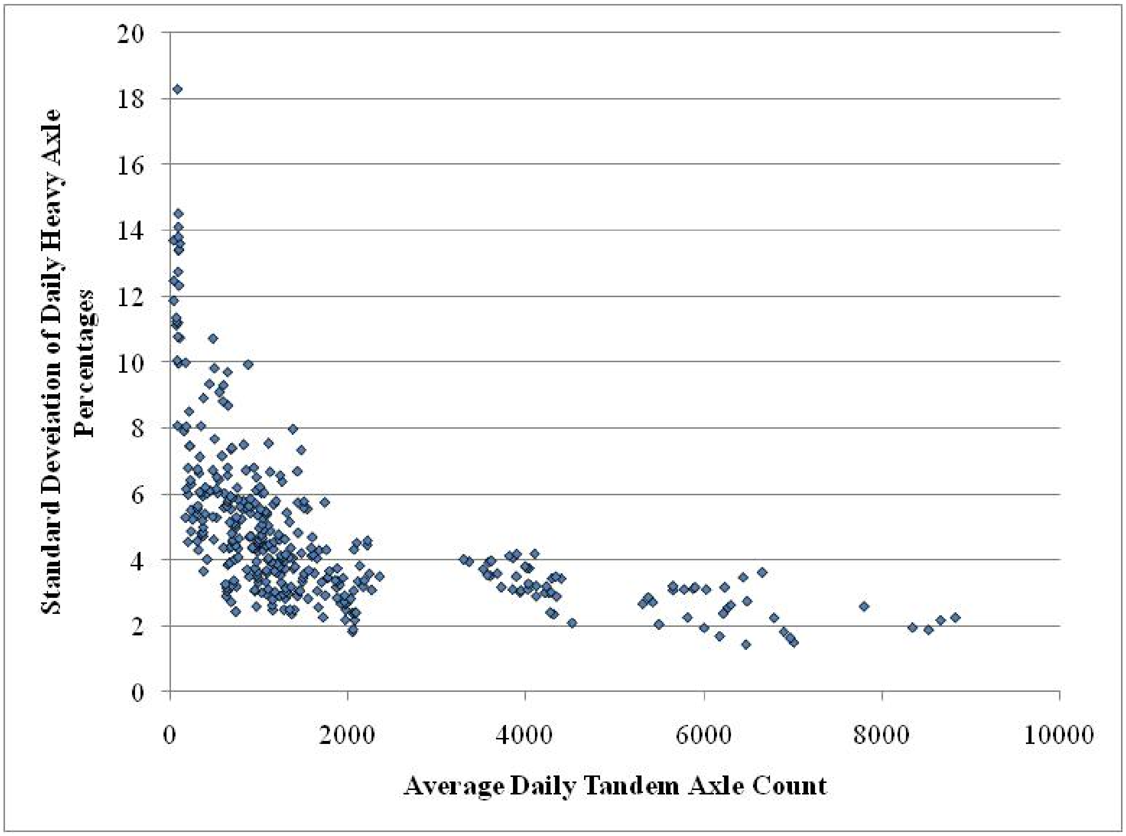

Figure 23. Graph. Distribution of standard deviations of daily heavy tandem axle percentages.

Based on analysis of SPS TPF data, it was found that sites with low daily axle counts generally had much higher variability in daily percentages of heavy axle counts. Two of the SPS TPF sites with consistently highest variability also had the lowest overall volume of tandem axle loads—sites 4-0100 and 12-0500.

Selection of Representative Sites for Analysis

To cover the range of observed daily variability in percentages of heavy axles, a set of sites was selected for a detailed analysis of different data availability scenarios. The selected sites and months of data correspond to 50th, 75th, 95th, and 99th percentiles of all other observations with respect to observed variability in daily percentages of heavy tandem axles. For example, 50 percent of all the observed variations in daily percentages of heavy tandem axle counts were less than variation observed at site 8-0200 for the month of April 2009. Table 17 summarizes the selected sites, which cover a wide spectrum of geographical locations and daily volumes.

Table 17. Sites selected and observed variability of heavy tandem axle loads.

Site ID	Year	Month	Daily Volume of Tandem Axles	Standard Deviation of Daily Percentages of Heavy Tandem Axles	Percentage of All Other Observations with Variability Less than Selected Site
8-0200	2009	4	1,475	4.2	50
26-0100	2008	3	953	5.7	75
24-0500	2006	12	482	10.7	95
4-0100	2008	7	92	13.8	99

For each of the four selected data samples, different data availability scenarios (from 2 to 31 days per month) were simulated using the Monte Carlo method and the procedure described in figure 14. Using the simulation results, PWLE values were computed for different data availability scenarios. A reliability level of 95 percent for PWLE was used in this analysis. In other words, the representative error was expected to be within ±PWLE in 95 percent of the cases. This analysis did not account for errors associated with precision and bias of WIM equipment.

Analysis Results

Results from the Monte Carlo simulations for different data availability scenarios are shown in table 18. As can be seen, the PWLE value decreased as the number of monitoring days increased. The decrease in PWLE was small for data availability over 7 days.

Table 18. PWLE computed for different data availability scenarios.

Number of Monitored Days per Month	PWLE for Selected LTPP Sites (Percent)			
	Site 4-0100	Site 8-0200	Site 24-0500	Site 26-0100
2	25.2	13.5	14.3	14.1
5	2.7	1.6	1.3	2.2
7	1.1	0.6	0.7	1.8
15	0.8	0.6	0.5	1.1
25	0.4	0.3	0.2	0.4
31	0.0	0.00	0.0	0.0

Conclusions

For all the cases evaluated, there was a significant drop in the error of monthly NALS estimate when 7 or more consecutive days of WIM data were available for each month. This trend is observed whether the variability of heavy loads was higher or lower. Therefore, availability of data for 7 days in a month was found to be a good conservative criterion to ensure the errors associated with daily data availability were small when estimating monthly axle load spectra.

Another conclusion is that the PWLE parameter is helpful to assess the variability associated with the whole load spectrum (all axle load levels and axle group types considered). For site 26-0100, PWLE for 7 days availability scenario was higher compared to the other sites despite the fact that for this site, the variability of heavy tandem axle loads was not the highest. This is the result of the combined effect of the full range of loads and axle group types on the PWLE value.

Effect of Seven Consecutive Versus Non-Consecutive DOW on Monthly NALS Estimates

Another analysis was carried out to evaluate the impact of using data from 7 consecutive or non-consecutive DOW. In this analysis, each DOW was randomly selected from the full month of data using Monte Carlo simulation until every DOW (Sunday through Saturday) was represented at least once in the 7-day sample. PWLE errors were computed separately for the consecutive and random 7 DOW samples.

The results of this analysis indicate that while the use of consecutive days resulted in slightly lower errors in NALS estimates, the differences in PWLE were relatively small and had little practical impact on the accuracy of monthly NALS estimates. For example, for site 27-500 that exhibited daily data variability typical for SPS TPF sites, the difference in PWLE error between consecutive and non-consecutive 7 DOW was less than 1 percent, as shown in figure 24.

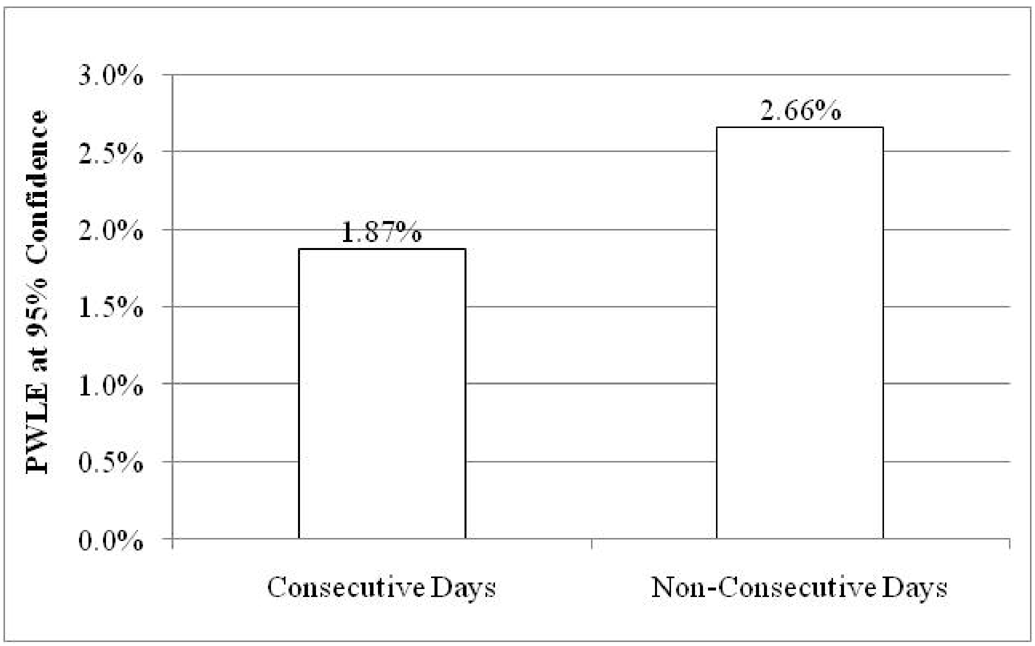

Figure 24. Graph. PWLE at 95 percent confidence for 7 consecutive and non-consecutive DOW for site 27-0500.

Effect of Monthly Data Availability on Annual NALS Estimates

Twelve Consecutive Versus Non-Consecutive Months

Despite the availability of SPS TPF WIM data over several years, there are some gaps in monthly data coverage, either due to equipment malfunction during certain periods or because data were filtered out during the data QC review process. Sometimes, a given month could be missing for 1 year but available for the next year. Therefore, it was necessary to evaluate the impact of using non-continuous monthly data in the development of RANALS (i.e., estimate of

NALS based on all years and all months with available high quality SPS TPF WIM data). The data are averaged in several steps: first to develop a DOW estimate for each month, then to develop an estimate for each month, and finally to develop a representative annual estimate considering all available years and months.

In this case, the analysis was conducted using data from site 51-0100 as seed data for the simulation. This site was selected as an example based on the availability of 30 continuous months of data (one of the longest continuous monitored periods without gaps in monthly data summaries) and higher data variability due to relatively low truck volume.

Two types of simulation were performed to estimate the annual NALS based on data from 12 of the 30 months of data. In the first scenario, data for one January, one February, and so on were picked up at random from the 30 months until the data included each of the months in a year regardless if they were from the same year or not. This scenario was called “any random month.” For the second scenario, the first month of data was randomized, and data for the 11 consecutive months from the starting month were used to estimate the load spectrum. This scenario was called “continuous months.” The PWLE results for 95 percent confidence for both scenarios were comparable, and both PWLEs were lower than 0.8 percent, indicating that for practical purposes, the difference between having consecutive and non-consecutive months in a period of 2.5 years can be considered very low.

Traffic loading patterns may differ from year to year due to changes in national and local economic conditions. Therefore, for each site, it is beneficial to use all available years of data to develop RANALS to account for potential year-to-year variability. However, if multiple years of data are unavailable or if only several partial years are available, data still could be used for NALS generation if, as a minimum, representative loading estimates can be obtained for 12 calendar months from available acceptable quality data and any potential outliers are identified and removed based on temporal analysis of monthly NALS (see procedures provided later in this chapter).

These conclusions are based on the analysis of data collected over a period of 30 months. It is not possible to say for certain if these conclusions will hold for data collected many years ago due to the fact that traffic loading patterns may change over time.

Multiple Years Versus 12 Monthly Values

The benefit of using multiple years of data versus a sample of 12 months was evaluated using statistical analysis techniques. No site-specific data were used for this analysis because the goal was only to evaluate the trend in PWLE as the amount of available data increased. The scenario assumed a generic site having a PWLE value of 3 percent if data for more than 60 months were available to compute this parameter and low variability in monthly NALS estimates that typically is observed among SPS TPF WIM sites.

In this case, PWLE based on different monthly data availability scenarios can be estimated using the following equation in figure 25:

$$PWLE_n = t_{n-1,p} \times PWLE_{act}$$

Figure 25. Equation. Actual PWLE for the site.

Where:

$PWLE_n$ = Value estimated for n months of data.
$t_{n-1,p}$ = Student t-value for a sample size of $n-1$ degrees of freedom and CL p.
$PWLE_{act}$ = Actual PWLE for the site.

The results of the analysis for 95 percent confidence are shown in figure 26. It demonstrates that the error range for a selected level of confidence decreases when more months of data are available for the PWLE estimate. Assuming the actual PWLE with 95 percent for a site is 3 percent, after 12 months of data, the difference from the true PWLE is very small. Moreover, using at least 12 months of data will take into consideration any seasonality in the traffic pattern. Based on the trend shown in figure 26, use of less than 12 months is possible provided there is compelling evidence supporting an assumption of the low month-to-month variation in NALS; however, use of less than 4 months will lead to high PWLE values due to the small sample size.

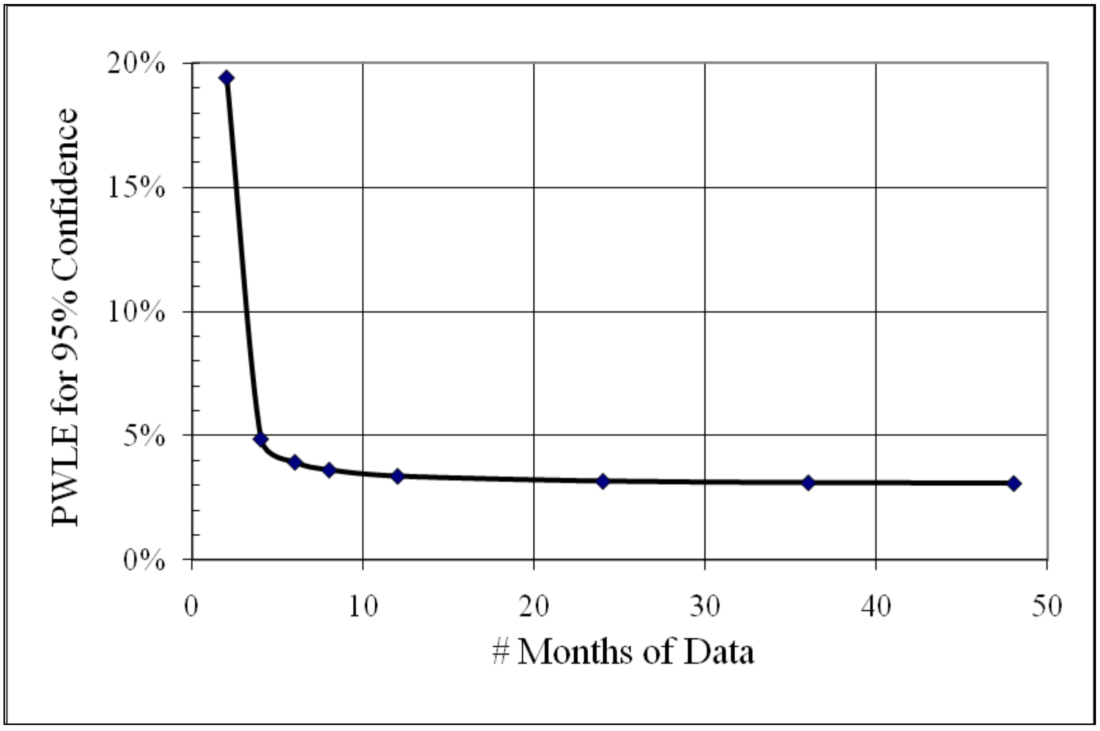

Figure 26. Graph. PWLE trend with data availability (in months of data).

Conclusions from Analysis of WIM Data Availability

The analysis of different data availability scenarios indicates that the following data availability criteria will minimize error due to limited data availability and assure high accuracy of monthly and annual NALS estimates based on SPS TPF WIM data:

- Availability of at least 1 of each 7 DOW per month to avoid potential DOW bias. Days do not need to be consecutive.

- Availability of at least 1 of each 12 calendar months to avoid potential seasonal bias. Months do not need to be consecutive or from the same calendar year. (Use of data collected more than 4 years apart was not investigated and is not recommended at this time.)

These criteria apply to the development of site-specific monthly and annual NALS estimates for individual sites and based on analysis of errors associated with the total axle load spectrum that considers all truck classes (FHWA classes 4 through 13) and all axle group types (single, tandem, tridem, and quad). However, for the individual vehicle classes and axle group types that have low percentages in a given VCD (such as vehicle classes 7, 11, 12, and 13), the errors in NALS may be higher than for well-represented classes and axles due to higher variability of axle loads and lower data availability.

These criteria may be considered too conservative for roads that do not exhibit high seasonality or high DOW variability in normalized axle load distributions. For such roads, analysis of temporal consistency could be used to determine lesser minimum data availability requirements on a case-by-case basis.

EVALUATION OF TEMPORAL CONSISTENCY AND REASONABLENESS IN TRAFFIC LOADING DATA

Analysis Purpose

The purpose of the analysis was to identify data that may represent accurate WIM counts but atypical loading condition for a given site. In addition, this analysis provided means of carrying out verification checks for the WIM data that already passed LTPP QC checks.

The analysis focused on evaluating the stability in monthly NALS over time for individual sites and identifying load distributions that differ significantly from other monthly load distributions for each site. Identified outliers were further investigated to identify potential reasons for atypical trends. The results were reported to LTPP using feedback reports. The researchers performed limited analysis of daily data for the cases where biases in monthly data summaries were found.

Analysis Scope

This analysis focused primarily on evaluating the differences in single and tandem monthly NALS for class 9 vehicles, which were found to be the dominant heavy vehicle class for all SPS TPF sites. The decision to use NALS for class 9 vehicles was based on the following reasons:

- Most of the heavy loads used in pavement design of interstate and principal arterial roads (road types associated with SPS TPF sites) come from class 9 vehicles.
- Characteristics of load distribution for class 9 vehicles, including peak loads and legal load limits, are well known, allowing for the development of QA checks to identify anomalies.
- Class 9 vehicles are used to calibrate WIM sites, so WIM sensors that are performing well should be able to capture class 9 loads accurately.

Single and tandem class 9 NALS were analyzed separately. Monthly NALS was considered an outlier if the spectrum was significantly different from other monthly NALS available for a given site. After outliers were identified using single and tandem class 9 load spectra, load spectra for all classes combined were additionally reviewed for single, tandem, tridem, and quad axle groups, and any additional anomalies were documented.

Analysis of outliers was performed in a two-step approach. First, several statistical parameters were computed and used to screen the data and flag potential outlier NALS using methods described in the next section. This step was automated. Second, a data analyst reviewed flagged load spectra using a systematic procedure to determine if the data represented true outliers. Based on the manual review, a decision was made to remove or to keep flagged load spectra from development of the defaults. If the load spectrum was removed, statistical parameters used in the outlier identification were then recomputed using the updated set of available monthly NALS, and the outlier identification process was repeated until no more outliers were identified.

Two automated procedures were used to flag potential outlier NALS based on the analysis of monthly NALS for class 9 single and tandem axles:

- Analysis of cumulative absolute differences between individual monthly and average monthly NALS.
- Analysis of shift in individual monthly peak loads compared to average monthly peak.

Outliers based on the whole NALS distribution and outliers specific to distribution of heavy loads (over 75 percent of the legal limit) were identified and analyzed for each site. The following sections describe the procedures used to flag potential outliers.

Procedure to Analyze of Cumulative Absolute Difference between Individual and Average Monthly NALS

Cumulative absolute difference between individual and average monthly NALS is a statistic that allows for the identification of differences in monthly NALS distribution shapes. To compute this statistic, first, an average monthly NALS was computed by averaging all available monthly NALS for a given site, vehicle class, and axle group type. Then, the cumulative absolute difference between a given monthly NALS and the average monthly NALS was computed by summing the absolute differences computed for each load bin between a given month and the average monthly load frequencies. These cumulative absolute differences were computed for each month, separately for single and tandem class 9 NALS.

$$\sum_{i}^{n} Abs.Diff_m = \sum_{i}^{n} |Pct\ Loads_{im} - Avg\ Pct\ Loads_{im}|$$

Figure 27. Equation. Cumulative absolute differences for month, *m*.

Where:

$\sum_{i}^{n} Abs.Diff_m$ = Cumulative absolute differences for month *m*.

$PctLoads_{im}$ = Load frequency for month *m* for bin *i*.
$AvgPctLoads_{im}$ = Average load frequency for bin *i*.
i = Bin *i*.
m = Month.
n = Total number of bins in NALS.

Next, cumulative absolute differences computed for each month were used to compute the average and standard deviation of the cumulative absolute differences. This computation was carried out separately for single and tandem axle class 9 monthly NALS for each site.

Monthly NALS that had cumulative absolute differences that exceeded the value of the average cumulative NALS difference plus two standard deviations of cumulative absolute differences were flagged as potential outliers. Figure 28 presents this testing criterion mathematically.

$$\sum_{i}^{n} Abs.Diff_m > \left(Average\left(\sum_{i}^{n} Abs.Diff_m \right) + 2\ StDev\left(\sum_{i}^{n} Abs.Diff_m \right) \right)$$

Figure 28. Equation. Cumulative absolute differences for *m*.

Where *StDev* = Standard deviation. All other variables have been previously defined.

This process was repeated iteratively by removing flagged months from the calculation of mean and standard deviation of the absolute cumulative differences, recomputing mean and standard deviation values, and identifying additional months that had absolute cumulative differences exceeding the recomputed mean plus two standard deviations. A data analyst reviewed the flagged months to make final outlier determination using a procedure described later in this chapter. An example of flagged outlier load spectra based on this procedure is shown in figure 29. In this example, NALS for October and December 2008 were flagged as outliers based on automated checks.

It should be noted that flagged data does not imply “bad” data. The default NALS should represent typical loading characteristics and not localized anomalies that occur for whatever reason. Thus, any outliers within the dataset should be removed. Potential outliers were not removed under NCHRP Project 1-37A, which probably caused some of the long tails in the NALS.[(3)] Removal of the outliers is considered an improvement in simulating typical loading conditions at the regional or global levels.

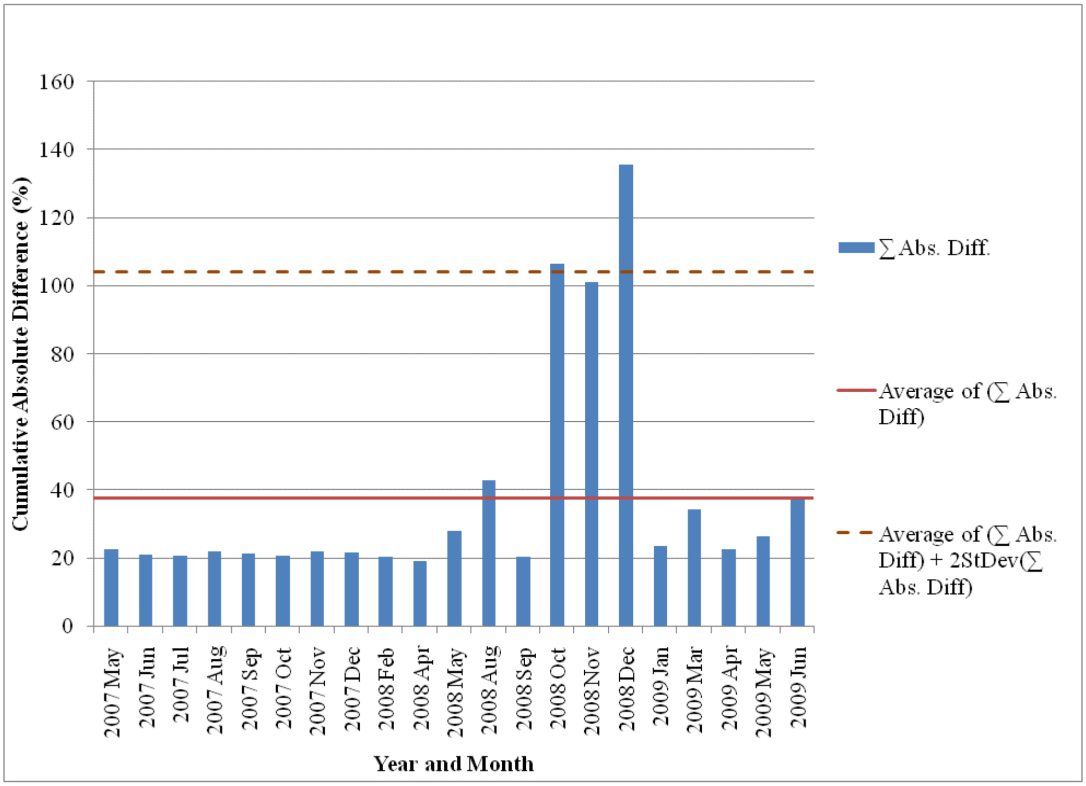

Figure 29. Graph. Comparison of absolute cumulative differences between average and monthly single axle NALS for site 05-0200 in Arkansas.

In addition to evaluating cumulative differences associated with the whole load spectrum, the same test was repeated using only the heavy loaded portion of the load spectrum. Heavy loads were defined as those that are 75 percent or more of the legal load limit for a given axle group type.

Analysis of Shift Between Individual Monthly and Average Peak Load

Peak load was identified separately for single and tandem axle group types for each monthly class 9 NALS for each site. Peak load corresponds to the load bin in which maximum load frequency is observed in the NALS. For consistency, the low value of the NALS load bin was used to identify the load bin. For example for a single axle load, if peak load was observed in a load bin defined as 11,000 to 11,999 lb, a value of 11,000 lb was used as the peak value. After peak load was computed for each month, the average peak load value was computed based on all available months.

Monthly NALS were flagged as a potential outlier if a peak load for a given month was outside of the range bound by the average peak load plus/minus two load bins. In LTPP tables, the load bin for single axle NALS is set to 1,000 lb, and the load bin for tandem axle NALS is set to 2,000 lb. An example of flagged outlier load spectra based on this procedure is shown in figure 30. Circled peak values represent outliers, as their values are below the average peak load minus two load bins (for November and December 2008).

Through analysis of peak load values for class 9 vehicles considering all SPS TPF sites, it was found that for single NALS, peak load corresponds to steering axle load for all SPS TPF sites, with an average value (rounded to the nearest 1,000 lb) of 11,000 lb. For tandem NALS, only loaded peaks were considered in the analysis, with an average value of 30,000 lb (corresponding to the beginning of the 2,000-lb load bin interval. Thus 30,000-lb value represents load bin from 30,000 to 32,000 lb).

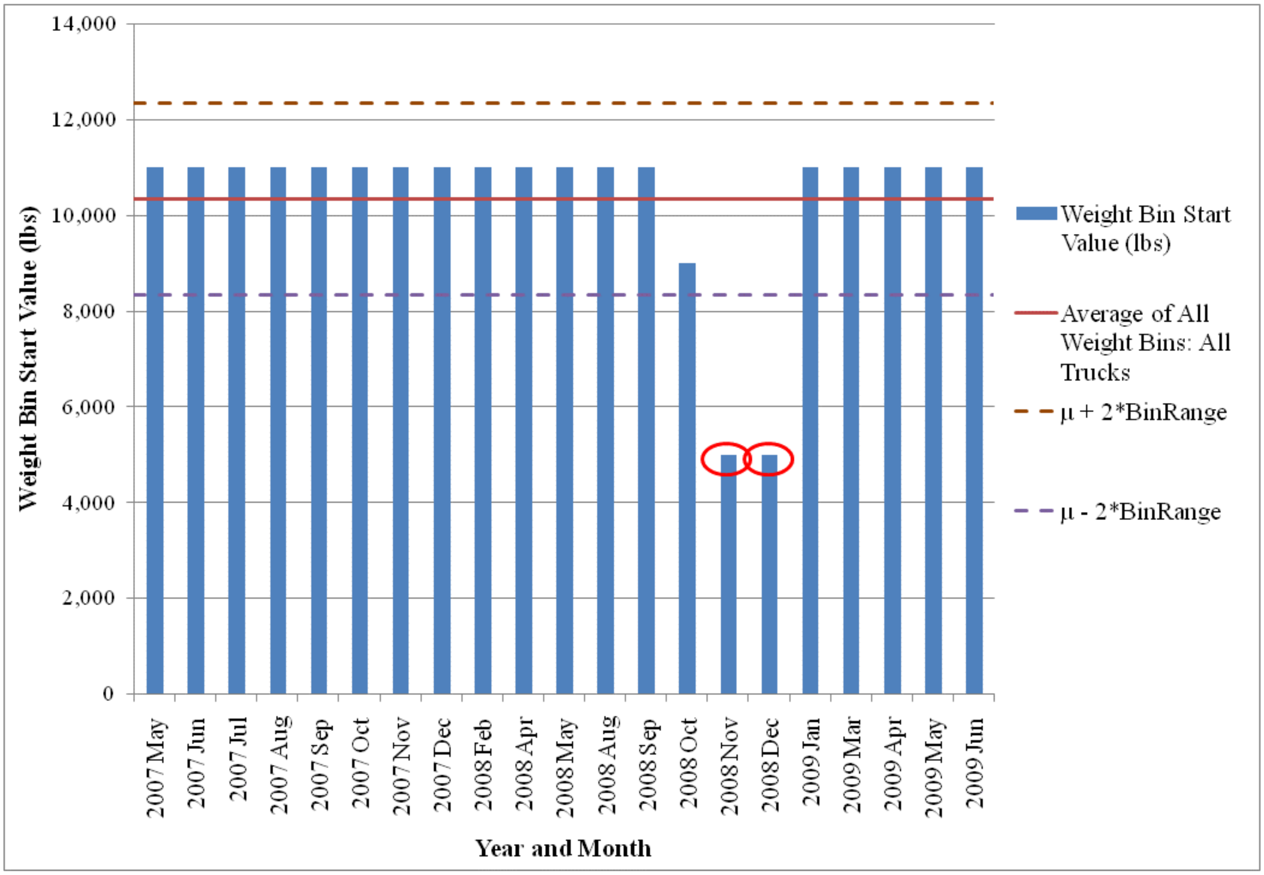

Figure 30. Graph. Comparison of monthly peak loads for single axles for site 05-0200 in Arkansas for class 9 vehicles.

Procedure for Manual Checks of Monthly NALS

The research team developed several manual checks to guide the data analyst in manual review of the potential monthly NALS outliers flagged through automated statistical outlier screening, as described in the following paragraphs.

Class 9 Single Axle NALS Manual Check

The class 9 single axle NALS manual check is as follows:

1. The peak load bin for the flagged months should be within the range defined by the peaks for all other months (excluding flagged months) for the same site. If peak loads for all available months cover a range of several bins, flagged spectra should have the peak within this range.

In addition, sites that have monthly single axle load peaks range greater than four load bins should be flagged as sites with inconsistent single axle NALS. An example of outlier load spectra is shown in figure 31.

2. The peak load bin should be within a range bound by 11,000 lb ±2,000 lb. This range was established based on analysis of peak loads for all 26 SPS TPF sites. An example of typical peak range is shown in figure 31.

3. Cumulative percentage of overloaded axles (over 20,000 lb) should be within a range bound by the mean ±3 standard deviations of cumulative percentage of overloaded axles computed using data for all the months for a given site.

4. Cumulative percentage of overloaded single axles for class 9 should be below 1 percent, typically observed for SPS TPF sites class 9 single axles. This value was established based on analysis of class 9 single axle overloads for all 26 SPS TPF sites and is equal to the mean percentage of overloads plus two standard deviations computed based on 26 SPS TPF sites. If a high percentage of overloads is observed, the number of single and tandem axles per truck should be checked to see if the high number of single axles per class 9 trucks indicates the presence of split-tandem axles classified as singles.

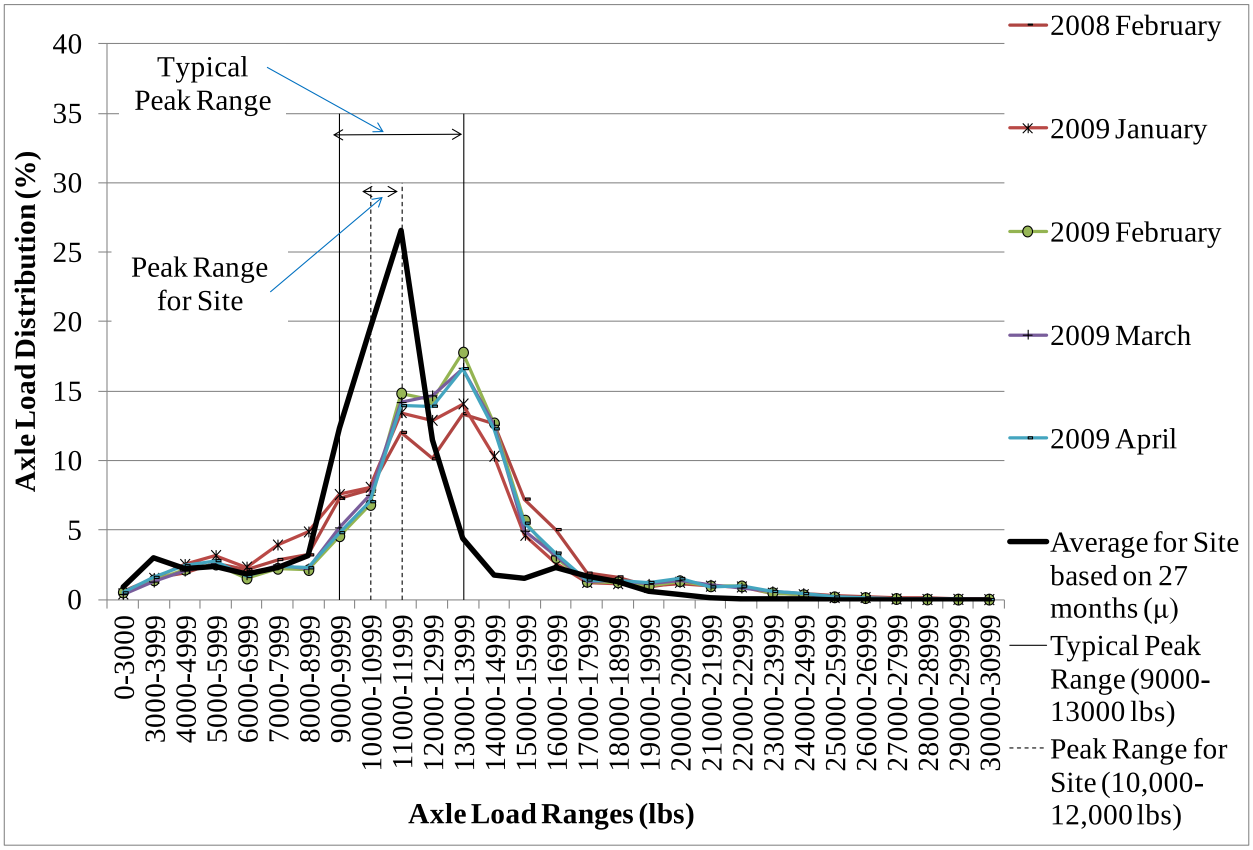

Figure 31. Graph. Monthly NALS for single axles for SPS site 26-0100 class 9 trucks.

Class 9 Tandem Axle NALS Manual Check

The class 9 tandem axle NALS manual check is as follows:

1. For a site with no defined seasonality in axle load distributions, load bins corresponding to the loaded peak should have a similar monthly value. For a site with seasonal variation in axle load distributions, peak loads for all available months cover a range of several bins; all spectra should have the peak within this range (spectra flagged during automated outlier screening are excluded from computation of the range). If a peak for flagged spectrum is outside of loaded peak bin or range of bins, it is considered an outlier. An example of outlier load spectra for several months in 2009 is shown in figure 32.

2. Sites that have a range of monthly loaded peaks greater than four load bins should be flagged as sites with inconsistent tandem axle NALS, unless they have a repeatable seasonal pattern for different loaded peak bins.

3. The peak load bin should be within a range bound by 30,000 lb ±4,000 lb. An example of outlier load spectra is shown in figure 32. This example demonstrates that for a period from January through April 2009, the majority of fully loaded class 9 tandem axles shifted into the illegal overloads category, which represents a very different load distribution compared to the 27 distributions available for the other months with data for this site. This is a possible but highly unlikely scenario. A more plausible explanation is WIM system malfunction. Analysis of single axle load spectra for this site presented in figure 31 indicated similar shifts in single axle load peak loads, supporting the conclusion regarding WIM system malfunction or calibration drift (since steering axle loads for class 9 vehicles are not likely to become heavier during 4 out of 27 monitoring months). The fact that both unloaded and loaded peaks in the tandem axle distribution shifted also is indicative of a likely calibration shift.

4. Cumulative percentage of overloaded axles should be within a range bound by mean ±3 standard deviations of cumulative percentage of overloaded axles computed using data for all the months for a given site.

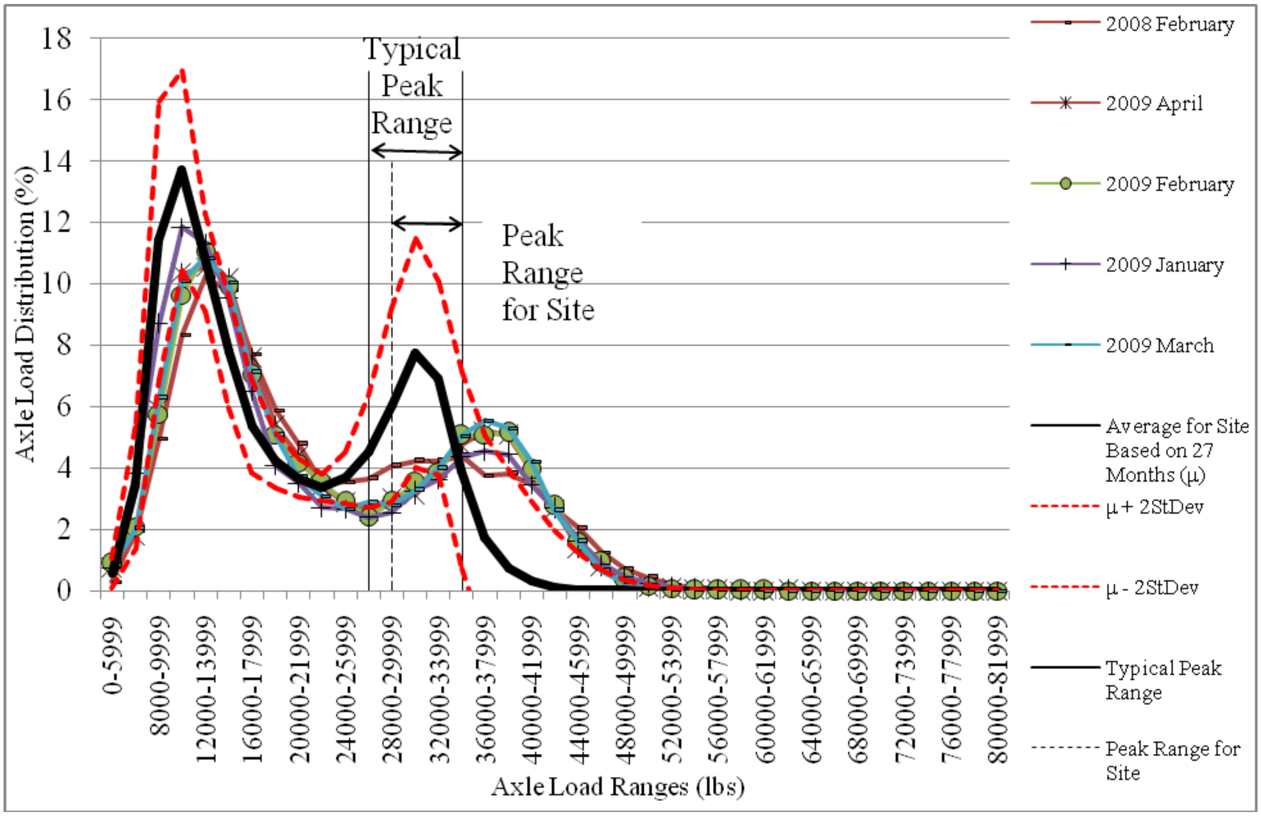

Figure 32. Graph. Monthly NALS for tandem axles for site 26-0100 class 9 trucks.

Additional Manual Checks for All Classes Combined

In addition to class 9 single and tandem checks of monthly NALS, the following checks were conducted:

1. Review combined (classes 4 through 13) axle load distribution plots for each axle group (single, tandem, tridem, quad) and visually identify monthly NALS that have shape different from the other months and from the average NALS shape computed based on all the months. Note these atypical distributions in the outlier report table.

2. Review axle load distribution plots for each axle group and identify monthly NALS that have higher percentages of very low weight loads (the first two load bins in each distribution). Note these atypical distributions in the outlier report table.

3. For sites where class 9 is not a dominant truck class, review consistency in load spectra for the dominant heavy vehicle classes (classes 4 and 6 through 13).

Results of Traffic Loading Data Temporal Consistency and Outlier Analysis

Data available in LTPP SDR 24 LTAS database table MM_AX were used to construct monthly NALS and used in temporal consistency and outlier analysis. Detailed results of traffic loading data temporal consistency and outlier analysis outcomes are presented in appendix A for the automated and manual checks described in the preceding sections. Table 19 provides a summary of types of outliers observed and the amount of data flagged as a result of outlier analysis. As can be inferred, most outliers were identified as distributions that have excessive cumulative absolute difference in NALS (i.e., different shape of load distribution) and addition had load peaks (single and/or tandem class 9) outside typical range for a given site.

Table 19. Summary of monthly NALS outlier analysis.

Reason for Exclusion	Number of Months	Percent of all Months
Excessive cumulative absolute difference in NALS (auto)	70	9
Significant shift in monthly peak loads for class 9 single and tandem axles (auto)	22	3
Load peaks outside typical range for the site (manual)	81	11
Load peaks outside typical range for class 9 (manual)	35	5
Load peaks spread > four load bins (manual)	28	4
Cumulative percent of overloads > typical upper range for a site (manual)	0	0
Cumulative percent of overloads > typical upper range for single axle class 9 (manual)	6	2

As a result of the outlier analysis, 12 percent of all months with WIM data included in the SDR 24 dataset for SPS TPF sites were removed from further data analysis. Sites that had large number of outliers include the following:

- **OH 39-0100**: Excluded 8 of 30 months, all 2004 (27 percent).
- **FL 12-0500**: Excluded 21 months of 53 months, all 2005 and 2006 (40 percent).
- **MI 26-0100**: Excluded 8 months of 35 months (23 percent).

Table 20 summarizes sites that have unusually high percentages of light loads for classes 4 and 6 through 13. Class 5 was excluded from this evaluation, as low loads were expected for this class. None of the class 9 vehicles had high percentages of light loads. Evaluating the high percentage of light loads can reveal vehicle classification problems whereby passenger vehicles or passenger vehicles pulling trailers are classified as trucks.

Table 20. Sites with significant percentage of light loads in first load bin.

Station	Single Axle 0–2,999 lb (Percent)					Tandem Axle 0–5,999 lb (Percent)			Tridem Axle 0–11,999 lb (Percent)				Quad Axles 0–11,999 lb (Percent)
	C6	C7	C8	C10	C13	C7	C8	C13	C4	C10	C12	C13	C13
4-0100			22				44						
4-0200			15		26								
5-0200			10										
8-0200			10										
17-0600			12										
18-0600								14					
23-0500										34			
25-0500										44			
26-0100												14	
35-0100			11										
35-0500			18				14						
39-0100			15			19			100			20	50
39-0200	17	43	24	20	56	23		15					
47-0600			11										
53-0200			12			34					18		

Note: Blank cells indicate that no instances were recognized.

Procedures to Evaluate Axle Group Type and Number of Axles per Truck Reasonableness

Accurate axle group type and number of axles per truck are important input parameters for computing the total number of axle load applications for MEPDG analysis. These two parameters, in combination with vehicle class volumes and growth rates, are used to transform NALS into total axle loading input used in the MEPDG. The following sections describe reasonableness checks for these two parameters.

Axle Group Type Checks

Axle group types reported for individual vehicle classes were reviewed to identify atypical axle group types for each class using the LTPP vehicle classification scheme. Axle group type QC checks by class included the following:

- **Class 4**: Should have either two single axles or a single and a tandem axle.
- **Class 5**: Majority of class 5 vehicles should have two single axles, with the exception of lightweight single unit trucks pulling a trailer (note that the *Traffic Monitoring Guide* does not allow trailers on class 5, while the LTPP scheme does).[14]
- **Class 6**: Should have a single and a tandem axle.
- **Class 7**: Should have a single and a tridem or a quad axle. Tandems are possible per the LTPP classification scheme but atypical based on vehicles' physical configuration.

Also, future data may have five or more axles per the updated 2012 LTPP classification scheme.

- **Class 8**: Should have single and tandem axles. Tridems are possible per the LTPP classification scheme but atypical based on vehicles' physical configuration.
- **Class 9**: Should have one single and two tandem axles, three single axles and one tandem axle, or two single and one tridem axle. Quads are possible per the LTPP classification scheme but atypical based on vehicles' physical configuration.
- **Class 10**: Could have single, tandem, tridem, and quad axles.
- **Class 11**: Should have single axles. Tandems are possible per the LTPP classification scheme but atypical based on vehicles' physical configuration.
- **Class 12**: Should have single and tandem axles.
- **Class 13**: Should have single, tandem, and can have triple and quad axles.

Atypical axle group types identified as a result of this review were reported to FHWA using feedback reports. A summary of the evaluation is presented in appendix B.

Number of Axles per Truck Checks

APC coefficients were computed for each site, vehicle class, and axle group type. These values depend on the vehicle classification algorithm, as well truck traffic composition at each site. Average number of axles per class computed based on the 26 SPS TPF sites (shown in table 21) were used as a basis for comparison with individual site values.

Table 21. Typical APC coefficients based on SPS TPF sites.

Vehicle Class	Single	Tandem	Tridem	Quad
4	1.43	0.57	0.00	0.00
5	2.16	0.02	0.00	0.00
6	1.02	0.99	0.00	0.00
7	1.26	0.20	0.63	0.15
8	2.62	0.49	0.00	0.00
9	1.27	1.86	0.00	0.00
10	1.09	1.15	0.79	0.05
11	4.99	0.00	0.00	0.00
12	3.99	1.00	0.00	0.00
13	1.59	1.26	0.69	0.31

Summary of Results

The results of this evaluation are summarized as follows:

- Most unexpected APC values were observed for class 7 trucks (8 of 26 sites) due to higher-than-expected single and tandem values. However, there is some evidence that this is becoming a typical configuration for dump trucks transporting excavated material and gravel in many States. Therefore, these values were not flagged as atypical.

- About 50 percent of all APC flags were for SPS TPF sites in Ohio (39-0100 and 39-0200) and Washington (53-0200). This could be explained by the differences between the LTPP classification scheme and schemes utilized in the WIM systems installed by these States. In addition to unexpected APC values, these same States have the highest occurrences of very light axle weights for truck classes. This leads to a conclusion that these States implement the LTPP vehicle classification scheme with adjustments in the algorithm that allow different types of vehicles (mostly lightweight vehicles) to be classified as trucks.

- Site 39-0100 in Ohio is the only SPS TPF site with tridems reported for buses. This may be a case of misclassification, possibly because of aluminum dump trucks in Ohio having long axle spacing between the first and the second axles.

CHAPTER 7—DATA SELECTION CRITERIA FOR DEVELOPMENT OF MEPDG AXLE LOADING DEFAULTS AND RESULTS OF DATA ASSESSMENT

This chapter contains the following information:

- A review of the data selection criteria used for generation of the NCHRP 1-37A MEPDG traffic defaults.[3]
- A recommended approach for developing new data selection criteria.
- A summary of the new proposed data selection criteria.
- An assessment of the extent of SPS TPF data available in LTPP SDR 24 that satisfy data selection criteria for development of the updated MEPDG traffic loading defaults.

REVIEW OF DATA SELECTION CRITERIA USED FOR ORIGINAL DEFAULTS

The requirements for sufficient traffic data used by the NCHRP 1-37A research team were based on criteria summarized in the earlier FHWA LTPP data analysis report.[15] These criteria took into consideration findings presented in an internal working paper of the LTPP Traffic ETG in July 1997. The criteria for sufficient data availability were defined as follows:

- The availability of at least 210 days of vehicle classification data (to develop vehicle classification and truck volume based defaults).
- The availability of at least 1 weekday and 1 weekend of WIM data per quarter, preferably 1 week per quarter as a minimum (to develop traffic loading defaults).
- Availability of these data items for at least 2 years in a 5-year period.

In addition, the NCHRP 1-37A team developed WIM and AVC data collection guidelines to achieve several user-specified levels of data reliability (or maximum expected error) based on selected levels of confidence.[3] These guidelines were based on observed error in traffic estimates based on data availability for selected LTPP GPS sites and did not take into account errors associated with data quality.

When these criteria were developed in the late 1990s, very limited research had been done on the quality of LTPP WIM data. The logic behind the 210 days per year and the weekday/weekend availability per quarter was to make sure that researchers included the effects of seasonality since there was minimal knowledge at the time of what those seasonal effects actually were. As a result, the criteria represent a conservative approach that assumes that such variation exists when, in fact, in many cases there are no seasonal effects.

Another limitation of these criteria is the focus on data availability and lack of documented criteria to address data quality (such as WIM equipment precision and bias requirements).

APPROACH FOR DEVELOPMENT OF NEW DATA SELECTION CRITERIA

Focus on WIM-Based Traffic Loading Defaults

The scope of this study was to use SPS TPF WIM data to improve existing MEPDG traffic loading defaults, such as NALS and number of axles per class and axle group type. As such, data selection criteria for developing MEPDG loading defaults focused on identifying WIM data quality and availability requirements to develop unbiased and accurate NALS estimates.

Maximize Use of Available Quality WIM Data

To take full advantage of the available SPS TPF WIM study, the data selection criteria focused on maximizing the use of available data from SPS TPF WIM sites without compromising the quality of NALS estimates. WIM data selection criteria identified for this study address the following three data selection categories:

- **Data availability**: Maximized use of available data that satisfy data quality criterion.
- **Data quality**: Identification and utilization of reliable, high-quality axle loading data.
- **Data reasonableness**: Identification of data that are not only accurate but also represent typical/expected conditions for a given site or a group of sites that have similar traffic loading patterns.

The third category addresses cases when data may be valid but are atypical due to a special short-term non-repeatable event (typically lasting less than 6 months) that took place at a site, when the loading pattern observed at a site is significantly different from other sites due to unique truck traffic generators in the vicinity of the site or adjustments made to vehicle classification algorithm, or when truck volumes for a particular vehicle class are so low, given a specific truck class distribution at the site, that data are not sufficient to produce a representative axle load spectrum for that class.

For analysis of traffic patterns observed at the individual SPS TPF sites, *atypical* is defined as a traffic trend that occurs during a short period of the pavement life, typically less than 6 months (but possibly longer), such as during a construction event occurring near the site. Traffic is correctly measured during that period, but it is not representative of the long-term traffic conditions for the site. These data would be useful for site-specific MEPDG analysis but should not be used to generate global defaults.

The following sections provide detailed requirements that were developed for the three data selection criteria based on analyses presented in chapter 6.

AXLE LOADING DATA AVAILABILITY CRITERIA

MEPDG NALS defaults are built based on data from annualized NALS rather than monthly NALS and represent percentile distribution of axle counts by axle weight categories for a typical day of the year. The reason is that monthly fluctuations in percentages of heavy or light axle loads are likely to be driven by local conditions and are not applicable on the national default level. As such, site-specific annual NALS selected for generation of defaults should be representative of annual axle loading conditions for each site included in computation of defaults. Therefore, minimum data availability criteria should be set to assure that site-specific axle load spectra developed based on the selected data will be representative of loading conditions for a typical day of the year for each site.

To define the criteria, it is important to understand how RANALS are computed for each site. Annual NALS estimates are based on averaging of monthly NALS estimates, and monthly NALS estimates are based on averaging of DOW estimates. DOW spectra are based on averaging of load spectra for the same DOW within a month. Based on the computational procedure and intended use of NALS, is it important to use procedures that would avoid introducing bias in the computation process. More details on computational procedure for RANALS development are provided in chapter 8.

Since NALS are subject to DOW and monthly variation, a number of statistical analyses to evaluate the potential for DOW and monthly errors in annual NALS computations were conducted in this study. Based on the statistical analyses presented in previous chapters, the following conservative minimum data availability criteria were identified to remove any potential DOW and monthly bias from the computation of RANALS for individual WIM sites:

- Availability of at least 1 of each 7 DOW per month to avoid potential DOW bias. Days do not need to be consecutive.

- Availability of at least 1 of each 12 calendar months to avoid potential seasonal bias. Months do not need to be consecutive or from the same calendar year (use of data from a dataset longer than 4 consecutive years was not tested in this study).

These criteria account for temporal axle load data variability and limit bias due to the computation process, thus facilitating the development of representative annual axle load spectra for individual WIM sites.

When more than 7 DOW per month or more than 12 calendar months of acceptable quality data are available, all available data should be used in the computation of site-specific RANALS.

AXLE LOADING DATA QUALITY CRITERIA

WIM data selected for the development of traffic loading defaults should accurately represent axle loading conditions observed at each site selected for the generation of defaults. To achieve this objective, the data should be of a known acceptable quality. The following acceptable data quality criteria were identified for this study based on a review of documentation from the SPS TPF study, results of the statistical and MEPDG analyses presented in the previous chapter, and recommendations from the LTPP Traffic ETG:

- Data should be from a WIM site conforming to the ASTM E1318-02 specification for type I WIM system accuracy and performance requirements specified in the LTPP Program’s internal field operations guide for SPS WIM sites, as evidenced by documented WIM installation reports, and annual or semiannual validation/calibration reports.[6,12]

- Selected data must pass a quality review using LTPP QC procedures for the SPS TPF study and be identified as level E data in the LTPP SDR database.

Analysis of NALS that had been adjusted based on representative precision and bias values obtained from SPS TPF data indicated that these values are not likely to produce significant differences in MEPDG outcomes compared to the true axle weight values.

Based on these criteria, maintaining current LTPP requirements for WIM accuracy is an important measure to have reliable data for studies in this area. Current requirements could be further enhanced by limiting the maximum acceptable bias in axle weight measurements to less than 5 percent. Potential calibration drift between field calibration sessions should be checked periodically (by comparing current NALS against NALS computed using 2 weeks of data after calibration), and calibration activities should be scheduled or data flagged if data analysis indicates likely bias over 5 percent.

AXLE LOADING DATA REASONABLENESS CRITERIA

Temporal Consistency

In addition to data quality and availability criteria, another set of data checks was developed in this study called "data reasonableness criteria." The purpose of these checks was to assure that RANALS computed for each WIM site were not biased by short-term events that could take place at the site. These events could include calibration drifts, equipment malfunction, or local business events affecting axle load distribution over some period of time.

Data reasonableness checks focused on evaluating the temporal consistency in monthly NALS distributions, primarily for class 9 vehicles, and included the following:

- Excessive cumulative absolute difference in monthly NALS check.
- Significant shift in monthly peak loads for class 9 single and tandem axles check.
- Load peaks outside typical range for the site check.
- Load peaks outside typical range for class 9 check.
- Load peaks spread over four load bins check.
- Cumulative percentage of overloads is over typical upper range for a site check.
- Cumulative percentage of overloads is over typical upper range for single axle class 9 check.

In addition, monthly NALS for all vehicle classes were checked to identify possible vehicle misclassification cases based on the following:

- High percentages of light loads in the first load bin.
- Axle group type and APC values checks.

Detailed descriptions of these checks and outcomes of data reasonableness assessment were provided in the previous chapter. Data that were flagged based on data reasonableness checks were excluded from computation of defaults.

Representativeness

Data reasonableness criteria also address the evaluation of whether a spectrum computed for a site can be considered representative of a specific loading condition and, therefore, used for development of the defaults. NALS with unusual loading distributions were flagged and investigated further to determine the reasons for such distributions. NALS based on valid and sufficient data were then identified as special cases and were not included in the computation of typical axle loading conditions. Invalid data were removed from further use.

Where very few axles were observed in a specific load spectra over the course of a year, the load spectra at that site was considered unstable and was not included in the computation of defaults. For example, there may be 3 years of data collected at a WIM site that has low volumes of class 7 vehicles. These data are valid and correctly represent loading condition observed at a site, with valid zero volumes for some days of the month. But the amount of data may be too low to develop NALS with well-defined loading distribution representative of a typical loading condition associated with a given vehicle class and axle group type, and these data should not be used as inputs for developing national default NALS for that vehicle class.

To be included in the computation of the default axle load spectra, a site had to produce at least 100 axles of that axle configuration for that vehicle class to ensure that the shape of the normalized load spectra was not unduly affected by a single random axle.

DATA ASSESSMENT SUMMARY

Data selection criteria were used to assess the extent of SPS TPF WIM data included in LTPP SDR 24 that satisfied these criteria. Table 22 shows axle loading data availability by the number of occurrence of different calendar months for each SPS TPF site. This table includes only the months that pass all data selection criteria (quality, availability, and reasonableness) for a given site.

Table 22. SPS TPF loading data availability by the number of months with data.

State Name	State Code	SHRP ID	Total No. of Months	Number of Months with Sufficient Data											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AZ	4	0100	21	1	2	2	2	3	3	2	2	1	1	1	1
	4	0200	21	1	1	2	2	3	3	2	2	1	1	2	1
AR	5	0200	15	1	1	1	2	3	2	1	1	2	1	1	1
CA	6	0200	19	1	2	2	2	2	2	2	2	1	1	1	1
CO	8	0200	29	2	2	2	2	3	3	3	4	2	2	2	2
DE	10	0100	24	2	2	2	2	2	2	2	2	2	2	2	2
FL	12	0100	52	4	4	5	5	4	4	4	4	4	5	4	5
	12	0500	27	3	2	2	3	2	2	2	2	2	2	2	3
IL	17	0600	48	4	4	4	4	4	4	4	4	4	4	4	4
IN	18	0600	13	1	1	1	1	1	1	2	1	1	1	1	1
KS	20	0200	33	3	3	3	2	2	3	3	2	3	3	3	3
LA	22	0100	17	1	2	2	2	2	2	1	1	1	1	1	1
ME	23	0500	23	1	2	2	2	2	2	3	2	2	2	2	1
MD	24	0500	40	3	3	4	4	4	3	4	3	3	3	3	3
MI	26	0100	27	3	2	3	2	3	3	3	1	1	2	2	2
MN	27	0500	27	3	2	2	2	2	2	3	2	2	2	2	3
NM	35	0100	12	1	1	1	1	1	1	1	1	1	1	1	1
	35	0500	15	1	1	2	2	2	1	1	1	1	1	1	1
OH	39	0100	22	2	2	2	1	2	2	2	2	1	2	2	2
	39	0200	12	1	1	1	1	1	1	1	1	1	1	1	1
PA	42	0600	26	2	2	2	2	2	3	3	2	2	2	2	2
TN	47	0600	25	2	2	2	2	2	3	2	2	2	2	2	2
TX	48	0100	27	1	2	1	3	2	2	2	3	4	3	3	1
VA	51	0100	30	3	3	3	3	3	3	2	2	2	2	2	2
WA	53	0200	30	3	3	3	3	3	2	2	2	2	2	2	3
WI	55	0100	19	2	2	2	1	2	2	2	1	1	1	2	1

SHRP = Strategic Highway Research Program.

Data availability was assessed using data for all truck classes (FHWA classes 4 through 13) combined. Each site in table 22 has at least 1 of each 12 calendar months with at least 7 DOW of axle loading data to facilitate development of the site-specific RANALS and APC coefficients and the updated MEPDG traffic loading defaults. For example, for class 9 vehicles, all 26 SPS TPF sites have sufficient data to compute the defaults. However, based on the specific VCDs observed at each of the SPS TPF WIM sites, not all vehicle classes and axles type have the same data availability. For some sites, underrepresented vehicle classes (such as classes 7, 11, 12, and 13) and axle group types (such as, tridems and quads) may have less than 12 calendar months of non-zero data with less than one week of non-zero axle counts per month due to low volumes observed for these vehicle classes.

CHAPTER 8—METHODOLOGY FOR DEVELOPMENT OF MEPDG TRAFFIC LOADING DEFAULTS USING LTPP SPS TPF DATA

OVERVIEW

This chapter provides a description of the methods used in this study to compute axle loading defaults.

Scope of Defaults

The focus of this study was to develop alternate MEPDG traffic loading defaults based on the LTPP SPS TPF WIM data. The main traffic loading default is NALS. Other defaults that are based on WIM data are APC, axle spacing, and wheelbase.

NALS defaults are used when site-specific NALS are not available or are of limited quality. Two types of situations may be encountered for the pavement design project location: no knowledge of the loading conditions or limited knowledge of traffic loading conditions at the project site. The default NALS developed in this study were designed to provide traffic loading alternatives for these situations.

NALS developed in this study are grouped in the following two tiers:

- **Tier 1**: Global defaults based on all applicable SPS TPF data.
- **Tier 2**: Supplemental defaults based on subsets of SPS TPF data representing a specific loading condition.

Tier 1 NALS defaults are useful for sites that have no information regarding expected traffic loading. These defaults represent an average traffic loading condition observed at the 26 SPS TPF sites.

The benefit of tier 2 defaults is that they provide users with multiple choices for selecting traffic loading conditions for different truck classes and axle group types. This allows pavement designers to simulate different loading scenarios and select scenarios that best describe the expected traffic loading conditions at the design site. This tier 2 approach for specifying defaults is a significant improvement over the scope of defaults currently available in the MEPDG software; however, use of these defaults requires some knowledge about the traffic loading condition expected at the pavement design site. This knowledge may be obtained through short-term truck surveys, portable WIM measurements, interviews with personnel involved in freight and commodity analyses, and discussions with law enforcement personnel engaged in monitoring truck weight violations.

Approach for Development of NALS Defaults

The development of MEPDG traffic loading defaults started with the selection of WIM sites that satisfied data selection criteria and development of representative NALS for each of these sites. Then, NALS from selected individual sites (or all the sites, in the case of global defaults) were averaged to compute defaults. Based on this approach, the methodology for development of the MEPDG traffic loading defaults includes the following tasks:

1. Development of MEPDG traffic loading parameters for each of the 26 SPS TPF sites.

2. Development of one global set of global traffic loading defaults using all 26 SPS TPF sites (tier 1).

3. Development of supplemental sets of NALS using subsets of data from 26 SPS TPF sites (tier 2).

Specific methods to accomplish these tasks are described in the following sections.

DEVELOPMENT OF REPRESENTATIVE ANNUAL NALS FOR INDIVIDUAL SITES

MEPDG NALS inputs represent the expected axle load frequency distributions by vehicle class and axle group type for a typical day of a month. Since seasonal changes in axle load frequency distributions are not uniform across different States and are likely to be observed only on the roads that carry a large percentage of seasonal loads, default values are developed to represent axle load frequency distributions for a typical day of the year. If truck loads change seasonally due to truck volume changes, monthly adjustment coefficients are used to adjust truck volumes between different months. Therefore, before defaults NALS could be developed, RANALS for individual sites must be computed.

Approach for Development of RANALS

The purpose of RANALS is to accurately represent RANALS for a given site. These RANALS should not only accurately characterize axle loading condition observed at a given site but be representative for development of the default axle loading conditions (i.e., spectra based on low axle counts may be accurate for the site but insufficient for development of a well-defined axle load spectrum for computation of the default).

Several approaches for computing RANALS were considered, and the advantages and disadvantages of each were analyzed. In the end, the approach for computing RANALS based on representative monthly NALS considering all available years was selected. This approach resembles the approach for computing AASHTO monthly average daily traffic and is designed to minimize DOW and monthly bias when data for less than 365 days per year are available. Computed monthly NALS values are averaged across all available years for each calendar month to remove potential bias in estimates toward partial years.

The challenge with this approach is that for classes that typically have low volumes, the NALS for individual months may not have the representative normalized shape that would have been computed based on cumulative annual axle load counts. In other words, certain load bins in monthly NALS would have zero values, and non-zero bins may have disproportionately high percentile values in individual monthly NALS. To mitigate this, a criterion of minimum cumulative number of 100 axles was used.

Procedure for Development of RANALS Estimates for SPS TPF Sites

The following procedure shows the steps involved in computing RANALS using daily axle loading distributions from the LTAS DD_AX series of tables included in LTPP SDR24 (figure 33 is a flowchart that summarizes the flow of calculations):

1. Extract daily axle load spectra, expressed as daily axle load counts by weight bin, from LTPP LTAS DD_AX tables for all SPS TPF sites for years and months that satisfy the data selection criteria of at least 7 DOW for each calendar month and at least 12 calendar moths per site that pass LTPP SPS TPF QC checks for data and WIM equipment and passed data reasonableness checks developed in this study (see chapter 6).

2. For each site, compute axle load spectra representing a typical day of the month for each month, by year, axle group type, and vehicle class (classes 4 through 13). Daily axle load spectra should be averaged first by DOW and then across DOW to produce unbiased monthly axle load spectra (as representative loading for a day of the month for a given year) for each vehicle class, axle group type, month, and year.

3. For each site, year, month, axle group type, and vehicle class (classes 4 through 13), normalize axle load spectra representing a typical day of the month to obtain monthly NALS.

4. For each site, axle group type, vehicle class (classes 4 through 13), and calendar month (January through December), compute average monthly NALS (as representative loading for a day of the month) by averaging data across all available years. This will result in 12 representative monthly NALS for each calendar month, axle group type, and vehicle class (classes 4 through 13) for each site.

5. For each site, axle group type, and vehicle class (classes 4 through 13), average the monthly NALS over 12 calendar months. This will result in one RANALS value representing a typical day of the year for each axle group type, vehicle class (classes 4 through 13), and for each site.

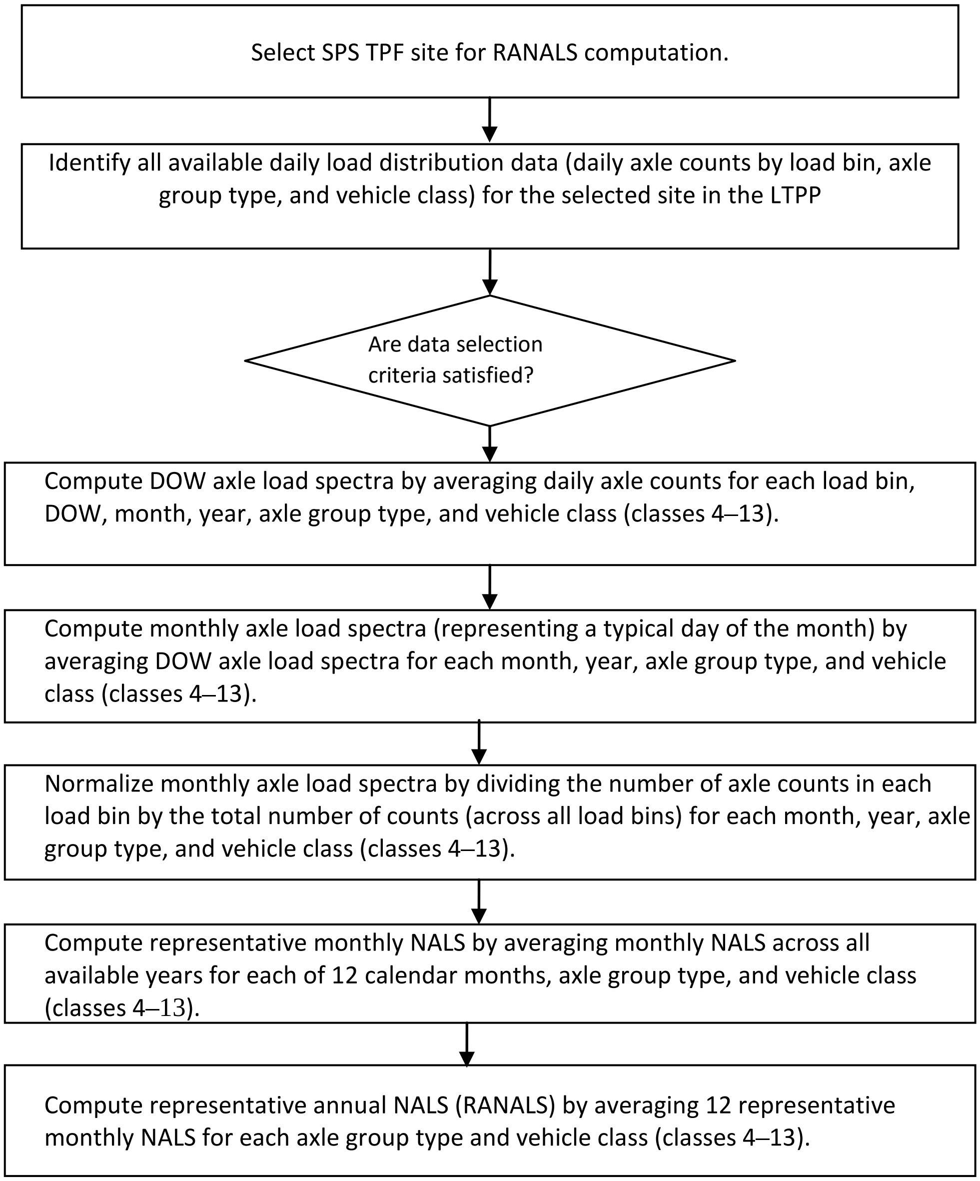

Figure 33. Flowchart. RANALS computation.

Using this procedure, one set of RANALS was computed for each of the 26 SPS TPF sites. Each set of RANALS includes NALS for each vehicle class (classes 4 through 13) and each axle group type (single, tandem, tridem, and quad as applicable) representing expected axle loading distribution for a typical day of the year for a given site. Appendix D contains a CD with RANALS results for 26 SPS TPF sites.

DEVELOPMENT OF GLOBAL NALS DEFAULTS USING SPS TPF SITES (TIER 1)

Overview

The purpose of the global NALS defaults is to serve as an input to the MEPDG when little or no information about existing or expected future traffic loading patterns is available for a design site. Global NALS defaults were computed to follow the exact format of the original MEPDG defaults. In this way, any significant difference in default values can be implemented easily by MEPDG users.

Procedure for Development of Global NALS Defaults (Tier 1)

This procedure is based on averaging RANALS from the SPS TPF sites that have sufficient data. The following procedure shows the steps involved in computing global NALS defaults (figure 34 is a flowchart that summarizes the flow of calculations):

1. Obtain RANALS for all SPS TPF sites that satisfy the data selection criteria presented in the previous chapter.

2. For each vehicle class and axle group type, exclude from further computations:

    - RANALS that are based on very low axle counts (less than 100 axles and/or axles per class less than 0.01).

    - RANALS representing highly unusual or unique loading conditions that are not likely to be encountered on road classes where global defaults will be used.

3. For each vehicle class and axle group type, average available RANALS.

4. Save results in a table format compatible with NCHRP 1-37A and DARWin-ME^{TM} NALS inputs.[3]

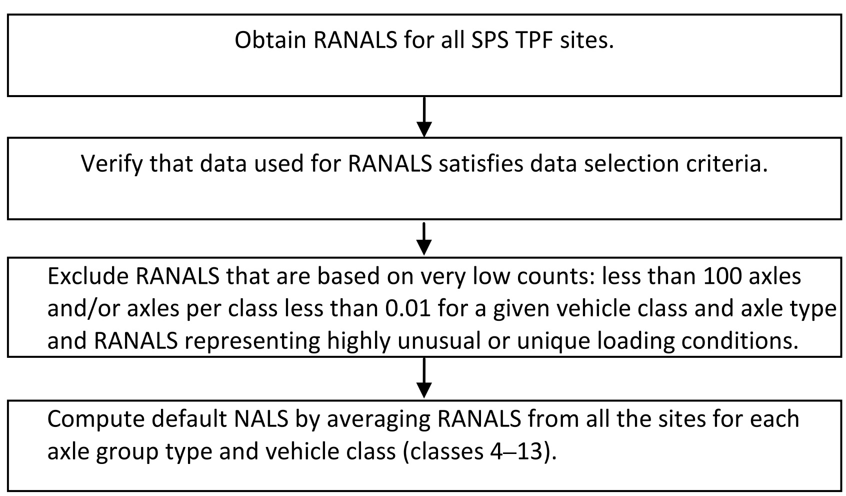

Figure 34. Flowchart. Global default NALS computation.

DEVELOPMENT OF SUPPLEMENTAL NALS DEFAULTS REPRESENTING ALTERNATIVE AXLE LOADING CONDITIONS (TIER 2)

A supplemental set of NALS was developed to represent different loading conditions observed for different vehicle classes and axle group types among SPS TPF sites. These additional NALS were developed to provide flexibility to MEPDG users in the selection of axle loading defaults that best describe their local loading conditions. These NALS could be used to specify different truck loading conditions by class and axle group type. For example, a pavement designer may select a heavy axle load spectra for class 9 vehicles but a light load spectra for class 6 vehicles because those loading conditions are appropriate for the truck traffic using the roadway they are designing. These supplemental NALS expand traffic loading options for local calibrations of MEPDG models and for load sensitivity analyses.

Developing RPPIF—A Single Statistic to Characterize Load Spectra

To produce these supplemental NALS, specific attention was placed on identifying different axle loading conditions within each vehicle class and axle group type that are likely to produce significantly different MEPDG outcomes. The research team searched for a quantifiable approach that would take into account both the pavement damage potential of different axle load weights and the frequency of the application of those loads (i.e., the fraction of loads of a given magnitude in the axle load spectra) to compute a single statistic associated with each load spectra.

The approach selected was to convert load spectra into a single statistic that could be associated with pavement damaging potential per axle for each type of axle for each vehicle class (FHWA classes 4 through 13). The selected statistic RPPIF per axle was computed by multiplying the W_{ij} factors (see table 4) by the fraction of axles (of type j) in the normalized axle load spectrum within the same load bin i. That value was then summed across all load bins i included in that normalized axle load spectrum, computing a single RPPIF per axle for each axle group type j and each truck class. Using this method, each RANALS was converted to a single number for each type of axle by class of truck. Because W_{ij} factors were developed based on outcomes from many different distress modes, these factors are not tied to any specific pavement distress but rather represent relative damaging potential across all types of distresses.

The intent of the RPPIF is to allow for simple summary comparisons of the size of different loading conditions. They are not intended for direct use as inputs to pavement analysis.

Methodology for Grouping TPF Sites with Similar Loading Conditions

Using the RPPIF statistic, RANALS for individual SPS TPF sites were grouped for each vehicle class and axle group type so that each resulting group represented a loading condition with a high potential to cause a significant change in expected pavement life or design when that class of truck was heavily represented on a roadway compared to the other groups of sites representing different loading conditions for a given vehicle class and axle group type. These groupings were done separately for each class and axle group type.

The hierarchical clustering technique in the SPSS software package was used to group load spectra with similar damaging potential as defined by their RPPIF values. No specific number of clusters was preselected when performing this clustering process. Instead, the cluster process was run until just prior to the point where the mean RPPIF for two clusters was going to be larger than the RPPIF determined to be the minimum observed to cause a change in pavement depth of more than 0.5 inch. (Thus, if combining two current clusters to form one new cluster makes the maximum difference between the mean RPPIF for any two nearest neighbor clusters greater than the value shown in table 23, that new cluster is not formed and the cluster process stops.)

Table 23. Maximum difference between mean RPPIF in cluster groups.

Class	Frequency of Truck Occurrence (Percent of Total Truck Volume)	Truck Type by Weight	Axle Group Type			
			Single	Tandem	Tridem	Quad
7, 10, 13	Infrequent (< 35 percent)	Heavy	> 0.55	0.41	0.49	0.8
6, 8, 11, 12	Moderate to infrequent (< 50 percent)	Moderate	0.25	0.23	N/A	N/A
9, 4	Frequent to moderate (> 50 percent)	Heavy	> 0.13	0.09	N/A	N/A
5	Frequent (> 75 percent)	Light	> 0.09	N/A	N/A	N/A

N/A = Not applicable.

These minimum RPPIF differences were determined from the MEPDG analyses presented in chapter 9 for vehicle classification scenarios representing the highest percentage of each class of vehicles found in the LTPP database. The values used to differentiate clusters are shown in table 23. By selecting the maximum observed percentage of each class of vehicles in the LTPP database, holding the other truck percentages and loads constant, it was possible to test the sensitivity of pavement design to changing loads of each class of vehicles.

If an agency were to develop its own State-specific load spectra clusters, it would have the option of using the values in table 23 to define when to stop the cluster process. However, an agency also could develop a State-specific version of table 23 by conducting the analyses similar to the ones described in chapter 9 using State-specific datasets. If this is done, the maximum observed percentage of any one class of truck or type of axle will change. The load spectra used to test MEPDG sensitivity will change as well, as only data from that State will be used. Because these key inputs change, State-specific break points between clusters will be different than in table 23. The outcome (the size in terms of allowable difference in mean RPPIF between clusters) will indicate which specific classes of vehicle and types of axles are important for pavement design in that State.

At the global level, this approach allowed for the adoption of fairly conservative values that account for the fact that some trucks are fairly uncommon and/or very light, and thus, nationwide, are less important to pavement design than other vehicle classes that are both heavy and numerous. This latter category of trucks (such as class 9 trucks) generally controls the design of the pavement. It is, therefore, important to more accurately estimate their axle loads. For truck classes that are rare (small in number relative to other truck types) or particularly light, it is less important to accurately estimate their axle loads, since even large errors in these estimates when multiplied by a small number of axles will have little impact on the final pavement design.

For the key vehicle classes that both have heavy axles and can be observed in large numbers (e.g., class 9 trucks), modest errors in estimated load/axle can result in significant errors in the pavement design. Thus, clusters for more important types of trucks (heavier trucks are more important because they cause more pavement damage) and classes of axle require clusters with small differences in mean RPPIF between the nearest neighbor clusters. At the same time, less common truck classes (e.g., class 12) and axle group types (e.g., class 7 quad axles) are allowed to have larger differences between nearest neighbor clusters, because these vehicle classes and/or axle group types contribute only a small percentage of the total load on specific pavements, and therefore even modestly large errors in their NALS are unlikely to result in significant errors in pavement design or expected pavement life.

Consequently, as can be seen in table 23, class 9 tandems, which are both common and are frequently heavy, must have clusters where the mean RPPIF of the resulting clusters are not more than 0.09 apart. Conversely, because tandem axles on class 13 trucks are generally not the type of axle which drives pavement design, neighboring clusters can be as much as much as 0.41 RPPIF different before clustering of class 13 tandems is halted.

Once clusters have been formed and default NALS computed for each load cluster, it is necessary to give users a means by which they can select between these different cluster groups. (Note: these default tables should only be used when better State- or site-specific load spectra are not available to the user.) These procedures are presented in chapter 10 of this report.

Procedure for Development of NALS Defaults Representing Different Loading Conditions

To develop default NALS representing different loading conditions, the following steps should be used (figure 35 is a flow chart that summarizes the flow of calculations):

1. Ensure that the WIM data come from accurately calibrated WIM scales and pass the data selection criteria described in the previous chapter.

2. Develop RANALS for each site using the procedures described earlier in this chapter.

3. Using each RANALS in combination with the appropriate W_{ij} factors (see table 4), compute a mean RPPIF for each vehicle class and axle group type.

4. Determine the importance of each vehicle class and axle group type based on the frequency with which specific classes of vehicles are observed and the characteristics of those vehicles.

5. Determine the sensitivity of the MEPDG to the variation inherent in the truck fleets observed by the agency, given the pavement design philosophy of the agency, by analyzing MEPDG outcomes over a range of NALS for different vehicle classes and axle group types.

6. Perform a cluster analysis of the RPPIFs (by vehicle class and type of axle) using the MEPDG outputs to different load spectra as a guide for determining when to stop the clustering process.

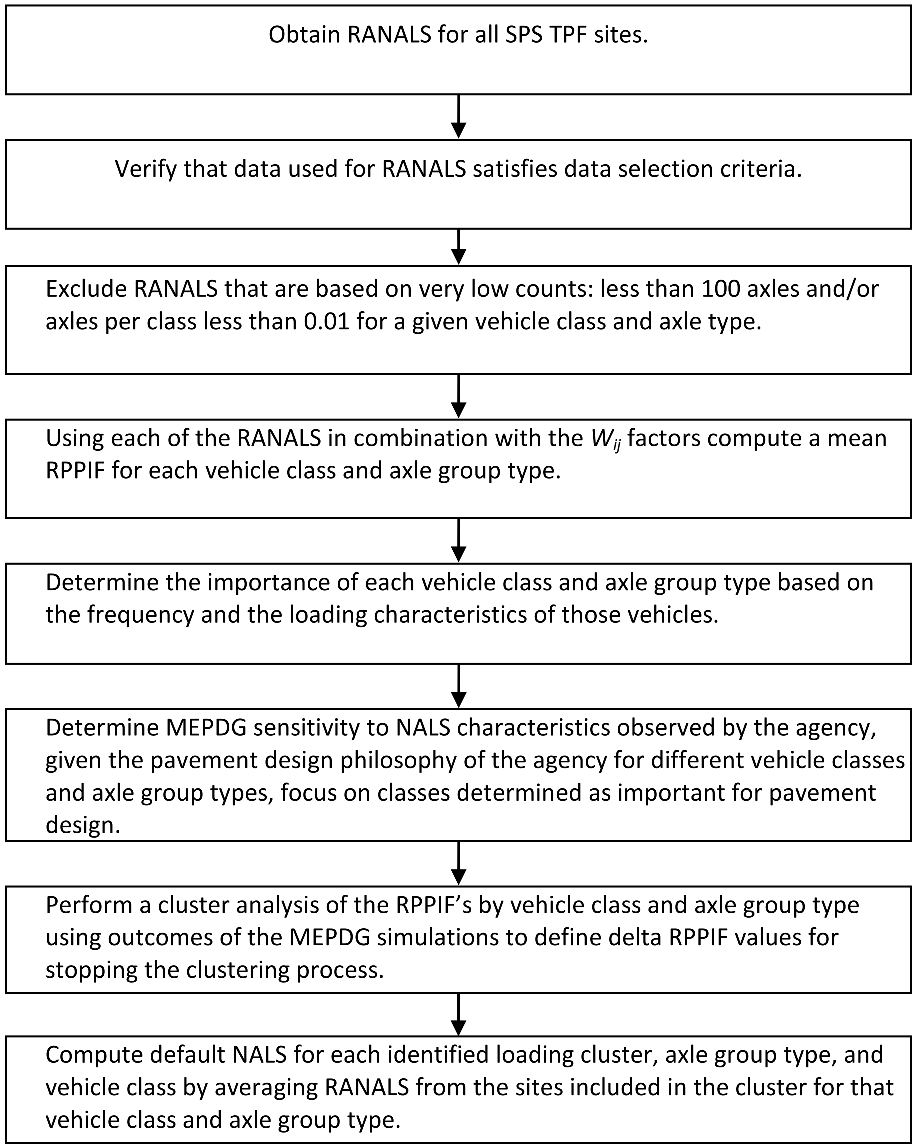

Figure 35. Flowchart. Supplemental default NALS computation.

Each of these steps is described in the following subsections.

Step 1: Use Only Accurately Calibrated WIM Data

Calibrating WIM systems is a difficult, costly, and time consuming task. However, considerable LTPP research has shown that unless WIM calibration is performed carefully and routinely, the accuracy of WIM data tends to degrade quickly as a result of changes in WIM system performance caused by changes in roadway roughness and environmental conditions that affect performance of in-road sensors.(16) Poor calibration of WIM systems, combined with the effects of dynamic truck motion on the forces applied by truck axles on WIM scales or in-road sensors, can easily result in substantial error in the weights reported for truck axles. Calibration errors consequently result in very poor estimates of the number of heavy and very heavy axle loads being experienced by a pavement. These estimates result in poor traffic loading estimates.

Consequently, it is vitally important that an agency developing its own set of default load spectra only use data that have been collected by well-calibrated, accurately operating WIM scales. In addition, to assure that collected data reflect loading trends observed throughout the year, this computation requires a minimum of 12 months (each calendar month) of WIM data for which at least 7 days (each DOW) of load counts are available for each month to mitigate potential seasonal and DOW biases in loading estimates.

Step 2: Develop RANALS for Each Site

Computing NALS requires that each site being used in the computation have at least 24 h of valid data for each DOW for each month of a year. Procedures to compute RANALS were presented earlier in this section. These normalized load spectra can be used directly within the MEPDG and DARWin-ME™ procedures. They can also be grouped to create additional default or surrogate loading conditions. The best approach for grouping more than one site together is to convert each load spectra into an RPPIF statistic and then perform a cluster analysis based on similarities in RPPIF or other similar statistic.

Step 3: Compute RPPIF Statistics Using RANALS

To compute the RPPIF statistics needed to cluster the various load spectra, start with the RANALS (by class of vehicle and type of axle) from the previous step. Multiply load frequency corresponding to each load bin in those load spectra by the corresponding W_{ij} factor from table 4. Sum these values across all load bins (i = 1 to n) for that load spectra as follows:

$$RPPIF_{jk} = \sum_{i=1}^{n} (F_{ijk} \times W_{ij})$$

Figure 36. Equation. RPPIF statistic for vehicle class and axle type.

Where:

F_{ijk} = Fraction of axles in load range i, for axle group type j, and vehicle class k.

Step 4: Determine the Importance of Specific Vehicle Classes and Axle Group Types

The next two steps are necessary if an agency wishes to cluster their site-specific NALS into groups and if they wish to incorporate into that grouping process State-specific truck travel attributes and pavement design considerations. These issues are discussed in considerable detail in the next chapter of this report.

The primary outcome of this task is to find traffic conditions (VCD and truck volume) that maximize the impact of each vehicle class on pavement design. That is, under what truck volume and VCD conditions does a given vehicle class represent the largest percentage of the total truck load on roads found in the State? Identified maximum truck volume conditions (relative to other truck volumes) can then be used to determine how sensitive the MEPDG outcomes are to the possible changes in load observed in that class.

These truck volume scenarios should be identified for each heavy truck type, resulting in up to 10 truck volume-by-class scenarios (for classes 4 through 13). These values are then used in the MEPDG sensitivity tests.

Step 5: Determine MEPDG Sensitivity to NALS

This task takes the data obtained in the previous steps and uses it to test the sensitivity of the MEPDG to the loading conditions present for each vehicle class scenario identified in the previous step. By holding all other loading conditions constant, except for the NALS for the selected vehicle class scenario, and then looking at the amount of pavement distress occurring due to the maximum volume of each truck type under different NALS loading conditions found in that State, it is possible to determine when specific loading conditions are important to the design process.

For example, class 5 trucks can be numerous. However, by looking at the loading conditions of class 5 trucks observed at SPS TPF sites, it is normally found that class 5 trucks always have light axles. As a result, regardless of which class 5 load spectra is used, even large numbers of class 5 trucks have little effect on pavement damage. As a result of these kinds of tests, it can be determined that it is not necessary to create multiple load spectra for class 5 trucks, as the selection between any rational group is unlikely to affect the MEPDG outcome. Consequently, only one group of loads is required for class 5.

Similarly, in a State where class 7 trucks are infrequently used (heavy natural resources may be carried in class 10 trucks in that State), the low volume of trucks (rather than the light weight of the truck) may mean that little benefit is gained from spending a large amount of resources on estimating class 7 weights. In such a case, only a very limited number of load spectra (e.g., moderate and heavy) may be warranted as defaults. Conversely, in a State where class 7 trucks are common and can be a moderately high percentage of the trucks on a roadway, the agency may find it necessary to create multiple class 7 loading groups to more accurately predict the effects of class 7 loads on pavement performance.

In addition to the observations described above, the sensitivity tests described in chapter 9 provide the quantitative outputs such as those shown in table 23 that are used in the cluster identification process. The outputs from the MEPDG are used to determine when two RANALS for a given vehicle class produce significantly different pavement analysis results. For example, a change in AC or PCC thickness of 0.5 inch could be used as one measure of significantly different. The difference in the RPPIF values between those two RANALS is used to establish criteria for determining when two RANALS should be kept as part of two different tier 2 NALS clusters. That is, if two RANALS produce significantly different pavement analysis outcomes, they are not similar, and they should not be combined into the same group for computation of default NALS. The difference in their RPPIF values then becomes a measure that can be used to determine the size of required boundaries between tier 2 NALS clusters, as shown in table 23.

Step 6: Perform Cluster Analysis

The final step in the development of default load spectra is the clustering of similar load spectra into a limited number of groups. This is best done with a statistical program such as SPSS®, SAS®, or similar programs. The cluster process used for this study was SPSS's hierarchical clustering option.

The clustering of RPPIFs computed in step 3 is controlled by the sensitivity of the pavement design process to traffic loadings (i.e., RPPIF differences identified in step 5). If State-specific sensitivity tests have been performed, use those results to control the clustering process. If no State-specific tests have been performed, use the values in table 23.

In the clustering process, the mean RPPIF between two nearest neighbor cluster should not exceed the values in table 23. Thus, the cluster process should be stopped one step prior to the step when that distance is exceeded.

Step 7: Compute NALS for Each Identified Loading Cluster

Once all clusters are identified, RANALS for the sites that belong to the same cluster should be averaged to compute default NALS representing that cluster group. This should be done for each vehicle class and axle type. For each computed average NALS, RPPIF and percent heavy statistics should be computed. Based on these statistics, a name and/or code should be assigned to the NALS cluster, similar to the names/codes included in the first column of Table 24.

Table 24. Summary of axle loading categories by weight for different axle group types.

Axle Category by Weight	Average RPPIF per Cluster	Percent of Single Axles ≥ 15 kip	Percent of Tandem Axles ≥ 26 kip	Percent of Tridem Axles ≥ 39 kip	Percent of Quad Axles ≥ 54 kip
Very light (VL)	< 0.05	< 3	0	N/A	N/A
Light (L)	0.05–0.15	< 10	< 10	N/A	N/A
Moderate (M)	0.15–0.30	10–30	10–30	N/A	N/A
Heavy (H)	0.30–0.50	> 30	30–50	< 50	< 30
Very heavy (VH)	> 0.50	N/A	> 50	> 50	> 30

N/A = Not applicable.

If more than one cluster is identified for the same loading category, then sequential codes should be assigned to these NALS. For example, if two NALS cluster for class 9 tandems fall within the H loading category, cluster codes H1 and H2 should be used (H1 for the lighter of the two NALS and H2 for the heavier). A cluster that has a majority of sites for a given vehicle class and axle type should be selected as the default or typical cluster, and the letter code (T) should be added to the cluster code (e.g., H1(T)). All computed NALS should be saved to the database.

DEVELOPMENT OF REPRESENTATIVE SITE-SPECIFIC AND DEFAULT APC COEFFICIENTS

Overview

The MEPDG requires users to specify the number of axles per truck type as a part of traffic inputs for pavement design and analysis. These numbers are also called APC coefficients. These are used in the MEPDG procedure as a multiplier in the process of converting NALS to projected axle load spectra for pavement design.

APC coefficients are required for each vehicle class and axle group type. If a specific axle group type is not used for a given vehicle class, then a zero value is entered as the coefficient for that axle group type. One set of coefficients is used per pavement design, representing the typical number of axles observed per truck for each axle group type for vehicle classes 4 through 13.

APC statistics are computed for each vehicle class and axle group type by dividing the count of the number of axle load by type of axle by the count of vehicles of that class as collected for the same periods of time. Since the MEPDG requires only one set of APC coefficients per design, these values are computed based on the annual axle count and vehicle volume estimates.

Computational Approach

The research team evaluated several approaches for developing the default APC based on WIM data collected for SPS TPF sites. While development of APC for classes and axle group types that are well represented was not affected by different approaches, axles per class for less represented truck and axle group types were found to be sensitive to different computation routines. A reason for that observation is that certain axle group types had occurrences only for some but not all days in a year. For these situations, estimated average APC were different based on assumption whether zero values should be used for the days where no axle group type occurrence was detected or these days should be excluded from the averaging process.

Averaging APC using only non-zero axle count days led to overestimation of the axle load application for underrepresented vehicle classes and axle group types because all the days with valid zero volume were excluded from computation of the average. Including days with zero axle counts led to very small values of APC coefficients for certain underrepresented axle group types. However, this latter approach was found to more accurately represent actual field conditions over the long design period. As a result, all the days with non-zero truck volume for a given vehicle class were included in computations. If no axles of a certain type were recorded for a given vehicle class and day but daily vehicle volume for this class was non-zero, then an APC coefficient of zero was computed for this axle group type and vehicle class.

Procedure for Development of Site-Specific and Default APC Coefficients

The approach selected to compute default APC based on SPS TPF sites is as follows:

1. Extract daily vehicle and axle count summaries from the LTPP LTAS DD_AX and DD_WT_CT tables for all SPS TPF sites for years and months that satisfy the data selection

criteria of at least 7 DOW for each calendar month and at least 12 calendar moths per site that pass LTPP SPS TPF QC checks for data and WIM equipment.

2. Compute site-specific APC for each individual SPS TPF site (MEPDG level 1 inputs):

    a. Develop a list of all matching dates in the DD_AX and DD_WT_CT tables.

    b. For all matching dates, compute total daily axle counts by class and axle group type by summing axle counts reported in individual load bins. If no axle counts are found for a given axle group type, vehicle class, year, month, and day while non-zero volume is computed for the matching vehicle class, year, month, and day, enter "0" for the total axle counts for this axle group type, vehicle class, month, and year.

    c. For all matching dates in the DD_AX and DD_WT_CT tables, compute total daily vehicle volumes by vehicle class for each month and year.

    d. For each day, month, and year that had non-zero total vehicle class volume, divide total axle counts by total vehicle volumes for each axle group type and vehicle class. This step will result in APC for each axle group type and vehicle class by day, month, and year.

    e. For each axle group type and vehicle class, average computed daily APC over all available days. This step will result in site-specific APC for each axle group type and vehicle class for a given SPS TPF site (MEPDG level 1 inputs for individual SPS TPF sites).

3. To compute default APC based on all SPS TPF sites, average site-specific APC over all SPS TPF sites for each axle group type and vehicle class. This step will result in global default APC for each axle group type and vehicle class (MEPDG level 3 input).

DEVELOPMENT OF DEFAULT AXLE SPACING AND WHEELBASE VALUES

Average Axle Spacing and Wheelbase for JPCP Model

Average axle spacing or wheelbase information is used for MEPDG applications involving top-down slab cracking failure mode in JPCP. For this failure mode, the critical loading is caused by a combination of axles that place axle loads close to both ends of the same slab (in the direction of travel) at the same time. For JPCP designs with 15-foot-long slabs, axle spacing between 12 and 15 ft would result in axle loading positions most critical to development of top-down slab cracking. For JPCP with 20-ft joint spacing, the most critical joint spacing would be between 17 and 20 ft.

The current MEPDG top-down slab cracking model assumes that the majority of axle spacing that could induce top-down slab cracking is attributed to the wheelbase of the tractor unit in tractor-semitrailer combination trucks (FHWA classes 8 through 13). To account for such axle spacing, the MEPDG directly considers wheelbase of the tractor unit in the form of three inputs: percentages of tractor units with short, medium, and long wheelbase. The MEPDG indicates that the percentages of trucks in short, medium and long categories should be based on the axle spacing distribution (or wheelbase) of truck tractors in class 8 and higher. The MEPDG recommends the following three axle spacing or tractor wheelbase categories for analysis:

- **Short**: 12 ft (typically observed on trucks used for short hauls).
- **Medium**: 15 ft (typically used for long hauls).
- **Long**: 18 ft (typically observed on trucks used for long hauls).

By default, the MEPDG software assumes an even distribution of short, medium, and long axle spacing occurrences (33, 33, and 34 percent, respectively).

In addition, the MEPDG states that if other vehicles in the traffic stream also have the axle spacing in the range of the short, medium, and long spacing defined above, the frequency of those vehicles could be added to the axle spacing distribution of truck tractors.[(1)] For example, if 10 percent of truck traffic is from multiple trailers (class 11 and higher) that have the trailer-to-trailer axle spacing in the short range, 10 percent should be added to the percent truck tractors for short axles. Thus, the sum of percent trucks in the short, medium, and long categories can be greater than 100.

Data Used

A sample of axle spacing data from SPS TPF WIM sites was used to estimate percentages of axle spacing that fall in different length categories. The results of axle spacing distribution analysis could provide additional insights into what vehicle classes are likely to have axle spacing that could contribute to development of top-down cracking in JPCP.

The analysis was based on a sample of per-vehicle records for 1 month of individual vehicle records for each of SPS PFS WIM. The 1 month limit was used to manage millions of records. This sample size was determined to be a representative based on evaluation of the consistency of the axle spacing measurements through the year using analysis of the axle spacing for tandem axle groups (axles 2 and 3) of the two most common truck classes. For the majority of the sites, the month picked for a sample was June 2009. Where the measurements were not consistent, a different year was picked (2008), and data were evaluated for consistency. Where the volumes were low or data were not available, a different month was used. A total of 4.7 million records of axle spacing were analyzed.

Procedure to Compute Average Axle Spacing and Wheelbase

The procedure to compute average axle spacing and wheelbase is as follows:

1. Extract axle spacing values from PVR records by vehicle class for all the sites.
2. Filter records corresponding to the first axle spacing for classes 8 and higher.
3. Determine ranges for short, medium, and long axle spacing relative to JPCP joint spacing values used by the agency or use the MEPDG values of 12, 15, and 18 ft.

4. Compute percentages of the first axle spacing for classes 8 and above for each of the three categories.

In addition, MEPDG states that if other vehicles in the traffic stream also have axle spacing in the range of the short, medium, and long spacing defined above, the frequency of those vehicles could be added to the axle-spacing distribution of truck tractors.[(1)] For example, if 10 percent of truck traffic is from multiple trailers (class 11 and higher) that have the trailer-to-trailer axle spacing in the short range, 10 percent should be added to the percent truck tractors for short axles. Thus, the sum of percent trucks in the short, medium, and long categories can be greater than 100. Short spacing should not include multi-axle groups like tandem, tridem, and quad in computation.

Procedure to Compute Average Axle Spacing for Multi-Axle Groups

Axle spacing for multi-axle groups is the distance between the two consecutive axles of a tandem, tridem, or quad axle configuration (currently, the DARWin-ME™ software does not accept load spectra for axle group types with five or more axles for routine pavement design). Default axle spacing values can be computed based on averaging the values extracted from PVR records for all the sites using the following procedure:

1. Extract axle spacing values from PVR records for all the sites.

2. Filter records that have axle spacing less than 8 ft for vehicle classes 4–13.

3. Review filtered records and identify multi-axle groups as following:

    a. Mark two consecutive spacing of less than 8 ft each per record as tridems.

    b. Mark three consecutive spacing less than 8 ft each per record as quads.

    c. If there is only one spacing less than 8 ft in sequence per record, mark it as tandem.

4. Compute average axle spacing values among axles marked as tandem, tridem, and quad. For tridem and quads, compute average axle-to-axle spacing.

CHAPTER 9—MEPDG SENSITIVITY TO DIFFERENT AXLE LOAD SPECTRA CLUSTERS

BACKGROUND

Causes of Differences in Axle Load Spectra

Analysis of WIM data from the LTPP Program indicates that axle loading distributions vary between different axle group types, truck types (vehicle classes), and roadways. Differences in axle load spectra between different axle group types are attributed to the differences in axle configuration and different axle load limits that apply to single, tandem, tridem, and quad axles. Differences in the axle load spectra for the same axle group type between different truck types (vehicle classes) are attributed to differences in truck body structure and vehicle length (single unit versus multiple unit trucks) and the purpose of the axle (i.e., steering or load-carrying axle).

In addition, the commodities typically carried by different truck types affect axle weights (tandem axle weight on log hauler versus class 8 truck with short trailer). Bulky but lightly weighted commodities result in lighter axle loads than heavier commodities for the same type of axle and vehicle class (e.g., cereal boxes versus soda cans).

Even for the same vehicle class and axle group type, axle weights vary based on local conditions, such as the following:

- The differences in truck size and weight laws between States can result in different truck body/configurations for the same FHWA truck class.
- The presence and effectiveness of weight enforcement activities in the State and the percentage of through trucks versus local delivery trucks.
- The number of roadway lanes (outer lanes typically are heavier loaded than inner lanes on multilane roads).

It is also observed that these site conditions are more likely to have a significant effect on load spectra for locations that have a high percentage of intrastate traffic and a low percentage of interstate traffic.

Load Spectra Clusters

To test the sensitivity of the MEPDG outputs to traffic load, the project team developed a series of different NALS for use as inputs to the MEPDG program. These inputs were developed using axle weight collected at the 26 SPS TPF WIM sites.

The 26 sets of SPS TPF load spectra (i.e., load spectra for each class of vehicle and type of axle) were summarized into a limited number of NALS groups based on the similarities in their expected damaging effect on pavement deterioration. Expected damaging effect was determined using the RPPIF statistic discussed in chapter 8. Essentially, these groups represented different axle loading conditions (by type of axle and class of vehicle) that could be considered light to heavy within a given vehicle class and axle type, where light and heavy were determined based on the observed differences in RPPIF for each of the SPS TPF sites. The grouping (clustering) process used to create these NALS was similar to that described in chapter 8, except that the maximum allowed distance between mean RPPIF for nearest neighbor clusters (i.e., the break points between clusters) was determined using different criteria than for the spectra developed as new NALS defaults.

The initial criterion that the project team used was to make up to five clusters for each type of axle and class of vehicles while allowing for some flexibility in that number. To decide how to create the groups and how many groups to create, first a mean RPPIF was computed for each load spectra. The mean RPPIF was then used to find load bin for which the mean RPPIF and *W* factor were equal. If the difference between two mean RPPIF values for nearest neighbor load spectra groups was less than the difference between two consecutive *W* factor values, the load spectra groups were combined, even if this meant there were less than five groups. Similarly, for some heavy axle group types, if the mean RPPIF of individual sites was more than 1.0 RPPIF different than any group, these sites were left as independent groups even if that meant retaining more than five groups.

The end result was a diverse set of NALS groups from light to heavy which allowed a detailed analysis of sensitivity of the MEPDG to different traffic loading conditions. A list of the SPS TPF sites included in different load spectra clusters for this sensitivity test is included in appendix C of this report.

Vehicle classes and axles types (referred to as class-axle) where several statistically different axle loading conditions were identified are marked as “Y” in table 25.

Table 25. Class-axle combinations for which NALS clusters were developed.

Class	Single	Tandem	Tridem	Quad
4	Y	Y		
5	Y	Y*		
6	Y	Y		
7	Y	Y	Y	Y
8	Y	Y		
9	Y	Y		
10	Y	Y	Y	Y
11	Y			
12	Y	Y		
13	Y	Y	Y	Y

*Based on LTPP vehicle classification scheme. Blank cells indicate data are unavailable.

Each of the 25 class-axle combinations had three to six clusters representing different axle loading conditions. The cluster that had the largest number of SPS TPF sites for each class-axle was called “typical.” RANALS for the sites with the same cluster assignment were averaged to compute representative NALS for each cluster for each of the 25 class-axle combinations, resulting in 109 NALS used for the sensitivity analysis.

SENSITIVITY ANALYSIS OF LOAD SPECTRA CLUSTERS

Analysis Objective and Approach

The goal of the analysis was to assess if use of NALS representing different loading conditions, as determined based on statistical clustering analysis, would result in different MEPDG outcomes for a given class-axle combination. Significant differences in outcomes using different load spectra clusters for a given vehicle class and axle group type would support the need for alternatives to a single set of default load spectra, while the absence of differences would indicate that statistically identified load spectra clusters could be combined for a given vehicle class and axle group type.

The following criteria were used to identify significant differences between MEPDG design outcomes:

- Pavement thickness, as determined to support the selected design life at the specified level of reliability. A thickness difference for the top layer (AC or PCC) of over 0.5 inch was selected as significant for this analysis.

- Pavement life, as determined when the value in one of the performance criteria reaches its terminal value at the selected level of reliability for a fixed pavement structure. Pavement life differences of over 20 percent of design life were selected as significant for this analysis based engineering judgment.

All the pavement section designs were hypothetical. Where applicable, material types and design features were based on recommendations provided in the NCHRP 1-37A report and on typical values encountered in the LTPP database.(3)

This analysis was also used to provide insights into what class-axle combinations were most likely to have the most impact on pavement design when using the MEPDG. This was accomplished by comparing pavement thicknesses computed using typical axle load spectra with results predicted when load spectra was adjusted to a different load cluster default (e.g., keeping the axle load spectra for all vehicle classes and axle group types as typical in the base MEPDG run and then changing the typical spectra to the heavy spectra for class only 9 tandems in a subsequent MEPDG run).

MEPDG Traffic Inputs

Sensitivity of MEPDG outcomes to NALS was investigated independently for each vehicle class and axle group type. Considering that contribution of vehicle classes to total truck volume varies, the first step in selecting traffic inputs for analysis was to identify a most significant traffic volume by vehicle class scenario for each of the 25 class-axle combinations. The most significant scenario was defined to maximize the effect of a given vehicle class and axle group type on pavement performance. Truck volume by class data from all available LTPP sites (SPS and GPS combined) were used to define AADTT and the VCD for each truck class-axle group type combination using the following two criteria:

- Maximum percentage of trucks in a given class.

- Maximum AADTT volume.

The goal was to identify realistic truck traffic volume scenarios in the LTPP database that are likely to cause maximum damage for each specific class of truck and axle group type. Since realistic truck volume by class scenarios were used, some classes had much higher maximum volumes then others. For example, maximum class 9 volumes far exceeded maximum class 6 volumes in our tests because those were the conditions observed in the LTPP database. As a result, MEPDG sensitivity was influenced by observed volumes of vehicles in given vehicle classes. Such results cannot be used directly to evaluate if the class 9 tandem axle load spectrum is more damaging than the class 6 type tandem axle load spectrum, but this analysis is useful to evaluate if different class 6 load spectrum clusters are likely to produce different pavement design outcomes under realistic traffic conditions.

The search for truck volume data was done separately for flexible and for rigid pavements based on the observation that for the pavement sections included in the LTPP database, rigid pavement sections were more likely to have higher truck volumes than flexible pavement sections.

Table 26 shows the AADTT and percent trucks used for the analysis for each vehicle class. For example, MEPDG flexible pavement sensitivity analysis for class 9 load spectra was conducted for AADTT equal to 3,043 with 85.7 percent class 9 trucks. The corresponding LTPP section that provided the data for the analysis is shown in table 25.

Table 26. AADTT and percentage of test classes used for the analysis.

Pavement Type	**Class**	**State Code SHRP ID**	**AADTT**	**VCD for Vehicle Class (Percent)**									
				4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Flexible	4	49-1008	554	50.5	3.8	0.0	14.9	21.4	0.1	0.3	2.2	6.6	0.0
	5	15-1006	1,555	6.4	75.3	14.9	0.0	0.7	2.6	0.1	0.0	0.0	0.0
	6	48-1094	451	1.5	19.2	53.6	9.3	7.1	5.5	1.3	0.5	0.0	2.0
	7	34-0500	1,207	2.9	27.1	17.0	10.6	8.0	32.6	1.0	0.8	0.1	0.0
	8	35-1005	609	15.0	22.1	7.9	5.9	38.4	5.9	2.3	0.3	0.2	2.1
	9	35-6035	3,043	0.3	4.8	1.6	0.1	2.3	85.7	0.5	3.1	1.3	0.2
	10	81-1803	1,887	4.5	8.8	5.2	3.3	1.1	14.3	28.9	0.0	0.6	33.2
	11	6-8150	1,857	1.1	45.0	9.6	0.7	6.6	24.3	0.0	12.3	0.1	0.2
	12	87-1622	1,220	2.7	25.9	6.1	0.8	3.7	33.0	4.9	0.6	7.8	14.6
	13	81-1803	1,887	4.5	8.8	5.2	3.3	1.1	14.3	28.9	0.0	0.6	33.2
Rigid	4	49-7085	852	42.6	2.5	0.0	9.3	27.6	0.2	0.4	4.3	13.1	0.0
	5	40-3018	2,575	0.8	59.9	5.9	0.4	8.3	24.0	0.0	0.7	0.0	0.0
	6	48-4146	726	1.6	23.1	43.0	0.1	7.6	23.8	0.8	0.0	0.0	0.0
	7	21-4025	1,884	2.5	8.5	2.5	12.0	1.5	69.2	0.9	1.8	0.6	0.4
	8	53-3812	2,034	5.6	23.7	4.9	0	32.4	24.2	1.8	1.5	1.9	4
	9	39-9006	4,358	2.9	3.2	1.5	0.0	5.9	77.7	0.5	7.0	1.3	0.1
	10	53-3019	1,686	1.7	4.4	1.6	0.0	11.0	36.7	8.5	1.9	10.8	23.4
	11	6-3042	5,418	1.1	13.9	1.9	0.0	11.0	49.3	0.4	19.9	2.2	0.2
	12	53-3011	1,448	3.7	10.0	10.7	0.6	21.5	9.4	3.7	5.0	14.3	21.1
	13	41-5021	3,694	3.7	8.4	3.1	0.2	3.5	41.0	7.9	7.5	0.1	24.6

For each class-axle combination, three to six different NALS representing different load cluster groups (GPs) were used in the MEPDG sensitivity analysis. For each GP, NALS were computed by averaging RANALS for the SPS TPF sites included in a given cluster. This was done separately for each vehicle class and each axle group. As a result, each of the 25 class-axle combination had several load spectra identified for sensitivity analysis. These spectra were coded as GP1, GP2, GP3, ...up to GP6. For a given class-axle combination, GP1 represented the lightest load spectrum, and the GP with the highest index represented the heaviest load spectrum (GP3 to GP6 based on the number of load spectra groups identified for a given class-axle combination).

Load spectra clusters identified as typical for each class-axle combination were used to define overall typical load spectra for the development of base MEPDG designs. The typical cluster was defined as the one that had the largest number of SPS TPF sites assigned to it. The assumption was made that this cluster likely would represent the most frequently observed traffic loading condition for a given class-axle combination in the LTPP database.

MEPDG Pavement Designs and Analysis Execution

To conduct MEPDG sensitivity analyses, pavement designs were developed for different traffic input scenarios. The climatic condition for the MEPDG analyses was selected as the one likely to cause the worst pavement performance. Previous studies in which the LTPP database was used suggested that the wet-freeze condition is the one most likely to cause more damage to the pavement. (17,18)

The pavement design life was set to 15 years for flexible pavements and 20 years for rigid-based on average service life computed for LTPP GPS flexible and rigid pavement sections (prior to first major rehabilitation activity). Traffic volume and class distribution were set according to table 26. MEPDG outputs were obtained using the 90 percent reliability option (default MEPDG option).

The design criteria used in the analysis are shown in table 27. The terminal values were based on defaults included in the MEPDG version 1.1 software. Failure modes were selected based on observed sensitivity of MEPDG models calibrated to global conditions. Different failure modes (critical distresses) and sensitivity analysis outcomes are possible for models calibrated to local conditions.

Table 27. Design criteria.

Failure Mode	Terminal Value
AC bottom-up cracking (alligator cracking) (percent)	25
Flexible pavement top down cracking (ft/mi)	2,000
Permanent deformation for the total pavement (inch)	0.75
Rigid pavement slab cracking (percent)	15
IRI (inches/mi)	172

Exploratory MEPDG analysis involving joint faulting indicated that this distress is much more sensitive to the number of heavy repetitions (i.e., volume of heavy trucks) than to the difference in loading within a given heavy truck class. This is because pumping of base and subbase/

subgrade material is a precursor of faulting, and that mechanism is highly sensitive to the number of load applications. In addition, the MEPDG provides detailed design guidelines for selection of erosion-resistant base material and dowel design to mitigate the development of this distress mode. Therefore, it is not expected that differences in the NALS, within a given truck class, would result in significantly different MEPDG design outcomes for properly designed PCC joints.

All design inputs selected were default values in the MEPDG software, with the exception of design features shown in table 28 for flexible pavement and table 29 for rigid pavement. Three designs were considered for flexible pavements. The reason for the use of these design inputs was to study MEPDG sensitivity under different failure modes: longitudinal top-down cracking (F1), rutting (F2), and bottom-up alligator cracking (F3). For rigid pavements, five designs were developed based on the MEPDG recommendations to minimize erosion and provide for load transfer at the joints based on observed AADTT levels.

Table 28. Summary of flexible pavement design categories and major design features used for MEPDG analysis.

Pavement Type	Design Category and Pavement Structure
F1	• **AC**: 5 percent air voids, 10 percent effective binder content, binder grade PG 70-22 • **Base**: Crushed stone, 12 inches, 30,000 psi • **Subgrade**: A-1-b, 26,500 psi (coarse)
F2	• **AC**: 5 percent air voids, 10 percent effective binder content, binder grade PG 64-22 • **Base**: Crushed stone, 12 inches, 30,000 psi • **Subgrade**: A-7-6,11,500 psi (fine)
F3	• **AC1**: 2 inches, 5.5 percent air voids, 11 percent effective binder content, binder grade PG 76-22 • **AC2**: 8 percent air voids, 8 percent effective binder content, binder grade PG 64-22 • **Base**: Crushed stone, 12 inches, 30,000 psi • **Subgrade**: A-1-b, 26,500 psi (coarse)

F = Flexible.

Table 29. Summary of rigid pavement design categories and major design features used for MEPDG analysis.

Design ID	Design Features	AADTT Level
R1	• JPCP, 28-day PCC modulus of rupture = 650 psi • **Base**: Cement stabilized, 2,000,000 psi • **Dowels**: Yes **Erodibility Index**: Extremely resistant (1) • **Subbase**: A-1-a, 12 inches, 40,000 psi • **Subgrade**: A-6, 18,000 psi	≥ 3,000
R2	• JPCP, 28-day PCC modulus of rupture = 650 psi • **Base**: Cement stabilized, 1,000,000 psi • **Dowels**: Yes • **Erodibility Index**: Extremely resistant (1) • **Subbase**: A-1-a, 12 inches, 40,000 psi • **Subgrade**: A-6, 18,000 psi	1,500–2,000
R3	• JPCP, 28-day PCC modulus of rupture = 620 psi • **Base**: Soil cement, 500,000 psi • **Dowels**: Yes • **Erodibility Index**: Very erosion resistant (2) • **Subbase**: A-1-a, 12 inches, 42,000 psi • **Subgrade**: A-6, 18,000 psi	1,000
R4	• JPCP, 28-day PCC modulus of rupture = 620 psi • **Base**: Soil cement, 50,000 psi • **Dowels**: Yes • **Erodibility Index**: Erosion resistant (3) • **Subbase**: A-1-a, 12 inches, 42,000 psi • **Subgrade**: A-6, 18,000 psi	500
R5	• JPCP, 28-day PCC modulus of rupture = 620 psi • **Base**: Crushed stone, 30,000 psi • **Dowels**: Yes • **Erodibility Index**: Fairly erodible (4) • **Subbase**: A-1-a, 12 inches, 42,000 psi • **Subgrade**: A-6, 18,000 psi	< 500

R = Rigid.

MEPDG designs were developed for each case of truck class-axle combination and for each GP. This was done by changing the axle load spectra input and observing differences in pavement performance predictions or by adjusting thickness of the top structural pavement layer to achieve fixed pavement service life. For example, for the analysis of MEPDG sensitivity to class 9 tandem axle load spectra, the AADTT and VCD corresponding to class 9 in table 26 were used along with the typical load spectra for all vehicle classes and axle group types to develop a base design. Then, in subsequent MEPDG analyses, the typical load spectrum for class 9 tandems was changed so that the load spectra from different clusters (e.g., light or heavy) for class 9 tandems were used.

Since only the thickness of the surface layer was modified in each of these designs involving different load spectra clusters for a given vehicle type, the impact of different load spectra clusters on the design could be evaluated by simply comparing the differences in thickness of the surface layer.

Discussion of Findings

Flexible Pavements

The results for flexible pavements are provided in table 29 through table 31. Top-down cracking (F1 designs) was found to be the critical failure mode for all classes and combinations of axle load groups using globally calibrated MEPDG models with 90 percent design reliability. This finding is in part due to the high error term associated with top-down cracking that translates into a higher safety factor when designed for 90 percent reliability.

To study sensitivity of MEPDG bottom-up cracking mode to different axle load spectra clusters, a design that minimizes top-down cracking was developed: this is design F3 in table 28. However, even with this design, top-down cracking was significant. For the purpose of this investigation, top down cracking was not considered in the sensitivity analysis involving F3 designs and effect of NALS clusters on pavement failure in bottom-up failure mode was investigated for all classes and combinations of axle-load groups.

When the design inputs were adjusted to make pavements more susceptible to rutting as the failure mode (F2 designs), only those combinations of vehicle class and axle group type that produced a high percentage and volume of heavy trucks resulted in rutting failure. This applied to classes 9, 10, and 13. All others, despite the design inputs, ended up still failing in top-down cracking. Rutting is a primary distress in which a high percentage of heavy trucks have significant influence on magnitude and rate of deterioration. Consequently, only the class-axle combinations with high percentage of class 9 and above had rutting failure, when designed for highway speeds. For the roads with lower percentages of heavy truck volumes, rutting is possible under stop-and-go traffic conditions; however, these cases were not considered in this sensitivity analysis.

Table 30. Predicted AC thickness and service life results for top-down cracking failure mode for flexible pavements.

Test Class	Cluster	AADTT	Percentage of Test Class	Percentage of Heavy Classes (C9 and Higher)	AC Design Thickness Needed to Support 15 Year Life (Inches)						Pavement Life at Failure Point Using the Base Design Thickness (Years)						Significance	
					GP1	GP2	GP3	GP4	GP5	GP6	GP1	GP2	GP3	GP4	GP5	GP6	Thickness	Life
4	Single	554	50.5	9.2	6.4	6.4	**6.4**				15.7	15.7	**15.7**					
	Tandem				6.0	6.1	**6.4**	6.6			18.7	17.7	**15.7**	14.7			Y	Y
5	Single	1,555	75.3	2.7	5.8	**5.8**	5.8	5.8			15.5	**15.5**	15.2	15.0				
	Tandem				**5.8**	5.8	5.8				**15.5**	15.5	15.0					
6	Single	451	53.6	9.3	**6.2**	6.2	6.2	6.2	6.2		**15.6**	15.6	15.6	15.6	15.6			
	Tandem				**6.2**	6.6	6.8	6.9	7.1		**15.6**	12.8	11.6	10.8	9.7		Y	Y
7	Single	1,207	10.6	34.5	7.7	7.7	**7.7**	7.7	7.7		15.6	15.6	**15.6**	15.6	15.6			
	Tandem				**7.7**	7.8	7.9	8.0	8.2		**15.6**	14.6	13.6	12.7	10.9		Y	Y
	Tridem				**7.7**	8.0	8.1	8.1	8.3		**15.6**	12.8	11.8	11.6	9.8		Y	Y
	Quad				**7.7**	7.8	7.8				**15.6**	14.7	13.8					
8*	Single	609	38.4	10.8	6.4	**6.4**	6.4	6.4			15.8	**15.8**	15.8	15.7				
	Tandem				6.3	6.4	6.4	**6.4**	6.4	7.2	16.5	15.9	15.8	**15.8**	15.6	9.7	Y	Y
9	Single	3,043	85.7	90.8	9.2	**9.2**	9.2	9.2			15.9	**15.9**	15.9	15.9				
	Tandem				8.9	**9.2**	9.4	9.7			20.7	**15.9**	13.8	10.7			Y	Y
10	Single	1,887	28.9	77.0	**10.0**	10.0	10.0	10.0			**15.7**	15.6	15.6	15.6				
	Tandem				10.0	**10.0**	10.1	10.1	10.1		15.8	**15.7**	14.8	14.8	14.8			
	Tridem				10.0	10.0	**10.0**	10.1	10.2		15.8	15.8	**15.7**	14.8	13.8			
	Quad				**10.0**	10.1	10.1				**15.7**	14.9	14.8					
11	Single	1,857	12.3	36.9	7.6	7.6	**7.6**	7.6	7.6		15.9	15.9	**15.9**	15.9	15.8			
12	Single	1,220	7.8	60.9	8.7	8.7	8.7	**8.7**	8.7		15.7	15.7	15.7	**15.7**	15.7			
	Tandem				8.7	8.7	**8.7**	8.7	8.7		15.7	15.7	**15.7**	15.6	15.6			
13	Single	1,887	33.2	77.0	**10.0**	10.0	10.0	10.0			**15.6**	15.6	15.6	15.6				
	Tandem				10.0	**10.0**	10.1	10.2			15.8	**15.6**	14.8	14.6				
	Tridem				9.8	**10.0**	10.2	10.3	10.4		17.8	**15.6**	13.8	12.8	12.7		Y	Y
	Quad				9.6	9.7	9.7	**10.0**			20.8	19.8	19.8	**15.6**				Y

*High sensitivity of class 8 tandems is due to a single site, Florida SPS 1 site that forms tandem GP6. No other SPS TPF sites have this distribution.

Note: Bold values represent designs based on the typical NALS for all vehicle classes and axle group types. Blank cells indicate the group was not available.

Table 31. Predicted AC thickness and service life results for bottom up cracking failure mode for flexible pavements.

Test Class	Cluster	AADTT	Percentage of "Test" Class	Percentage of Heavy Classes (C9 and Higher)	AC Design Thickness Needed to Support 15 Year Life (Inches)						Pavement Life at Failure Point Using the Base Design Thickness (Years)						Significance	
					GP1	GP2	GP3	GP4	GP5	GP6	GP1	GP2	GP3	GP4	GP5	GP6	Thickness	Life
4	Single	554	50.5	9.2	4.7	4.8	**5**				18	17.7	**15.5**					
	Tandem				4.9	4.9	**5**	5.1			16.5	15.8	**15.5**	14.8				
5	Single	1,555	75.3	2.7	4.8	**4.8**	5	5.1			15.8	**15.8**	14.1	13.6				
	Tandem				**4.8**	4.8	4.8				**15.8**	15.8	15.8					
6	Single	451	53.6	9.3	**4.4**	4.5	4.5	4.6	4.7		**15.8**	14.9	14.7	13.7	13			
	Tandem				**4.4**	4.6	4.7	4.7	4.9		**15.8**	13.9	12.8	12.6	10.9		Y	Y
7	Single	1,207	10.6	34.5	5.6	5.7	**5.7**	5.8	5.8		16.6	15.8	**15.6**	14.8	14.8			
	Tandem				**5.7**	5.8	5.9	6.1	6.2		**15.6**	14.7	13.8	13.5	12.4		Y	Y
	Tridem				**5.7**	5.8	5.8	5.9	6		**15.6**	14.7	14.5	13.9	13.6			
	Quad				**5.7**	5.7	5.7				**15.6**	15.5	15					
8*	Single	609	38.4	10.8	4.6	**4.8**	4.9	5.3			17.7	**15.7**	14.8	11.5			Y	Y
	Tandem				4.7	4.7	4.7	**4.8**	4.8	5.3	16.6	16.5	16.4	**15.7**	15.8	11.8	Y	Y
9	Single	3,043	85.7	90.8	7.5	**7.6**	7.7	7.7			16.8	**15.8**	14.7	14.7				
	Tandem				7.3	**7.6**	7.8	8.2			18.7	**15.8**	13.8	11.7			Y	Y
10	Single	1,887	28.9	77.0	**7.3**	7.3	7.3	7.4			**15.7**	15.7	15.6	14.9				
	Tandem				7.2	**7.3**	7.4	7.4	7.5		16.5	**15.7**	14.8	14.7	13.8			
	Tridem				7.3	7.3	**7.3**	7.3	7.4		15.8	15.8	**15.7**	15.5	14.8			
	Quad				**7.3**	7.3	7.3				**15.7**	15.7	15.7					
11	Single	1,857	12.3	36.9	5.8	5.9	**6.1**	6.3	6.5		18	16.8	**15.1**	13.7	12.5		Y	Y
12	Single	1,220	7.8	60.9	6.2	6.2	6.2	**6.3**	6.3		16.8	16.7	16	**15.8**	15.6			
	Tandem				6.2	6.3	**6.3**	6.3	6.3		15.9	15.8	**15.8**	15.8	15.8			
13	Single	1,887	33.2	77.0	**7.3**	7.4	7.4	7.6			**15.7**	14.8	14.6	13.5				
	Tandem				7.1	**7.3**	7.5	7.6			17.8	**15.7**	13.8	12.8			Y	Y
	Tridem				7.2	**7.3**	7.4	7.5	7.5		16.8	**15.7**	14.8	13.8	13.8			Y
	Quad				7.2	7.2	7.2	**7.3**			15.8	15.8	15.8	**15.7**				

*High sensitivity of class 8 tandems is due to a single site, Florida SPS 1 site that forms tandem GP6. No other SPS TPF sites have this distribution.

Note: Bold values represent designs based on the typical NALS for all vehicle classes and axle group types. Blank cells indicate the group was not available.

Table 32. Predicted AC thickness and service life for rutting failure mode for flexible pavements.

Test Class	Cluster	AADTT	Percentage of "Test" Class	Percentage of Heavy Classes (C9 and higher)	AC Design Thickness Needed to Support 15 Year Life (Inches)						Pavement Life at Failure Point Using the Base Design Thickness (Years)						Significance	
					GP1	GP2	GP3	GP4	GP5	G6	GP1	GP2	GP3	GP4	GP5	GP6	Thickness	Life
9	Single	3,043	85.7	90.8	8.9	**9.0**	9.2	9.3			15.7	**15.0**	14.8	14.8				
	Tandem				8.1	**9.0**	9.8	10.7			17.7	**15.0**	13.8	11.7			Y	Y
10	Single	1,887	28.9	77.0	**10.1**	10.1	10.1	10.1			**15.7**	15.6	15.6	15.5				
	Tandem				9.8	**10.1**	10.2	10.3	10.5		15.8	**15.7**	14.8	14.8	14.7		Y	
	Tridem				9.8	9.8	**10.1**	10.2	10.5		15.8	15.8	**15.7**	14.8	14.7		Y	
	Quad				**10.1**	10.1	10.1				**15.7**	15.6	15.6					
13	Single	1,887	33.2	77.0	**10.1**	10.2	10.2	10.3			**15.7**	14.9	14.8	14.8				
	Tandem				9.5	**10.1**	10.4	10.7			16.7	**15.7**	14.7	13.8			Y	
	Tridem				9.3	**10.1**	10.6	11.1	11.2		17.7	**15.7**	13.8	12.8	12.7		Y	Y
	Quad				9.5	9.5	9.5	**10.1**			16.8	16.8	16.8	**15.7**			Y	

Note: Bold values represent designs based on the typical NALS for all vehicle classes and axle group types. Blank cells indicate the group was not available.

Under the truck volume and VCD conditions analyzed in this study, all classes except 5, 8, and 12 showed sensitivity to different axle load spectra that resulted in design thickness difference of 0.5 inch or more in one or more of the failure modes. Lack of class 5 load spectra sensitivity is explained by the low axle weight of class 5 vehicles, while low or no sensitivity of class 12 vehicles is explained by the low volumes and percentages of these vehicles compared to the other heavy vehicle types observed under typical traffic conditions. For class 8, only the Florida SPS-1 site showed design outcomes different from other clusters. This site had a high percentage of overweight class 8 trucks, and all other sites had much lighter axle weights.

When MEPDG sensitivity for specific axle group types was evaluated, NALS for single axles resulted in low MEPDG sensitivity for all vehicle classes, with the exception of class 8 (Florida SPS-1 site) and class 11 vehicles. Tandem axle loads showed the highest sensitivity among all axle group types. Pavement designs also were found to be sensitive to tridem and quad axles; however, for some cases, sensitivity was low primarily due to low percentages of tridem and quad axle load applications compared to other axles.

Class 9 tandems produced the greatest difference in pavement thickness prediction: up to 0.9 inch for bottom-up cracking, 0.8 inch for top-down cracking, and 2.6 inches in total rutting failure mode. This is the most frequently observed heavy truck class on U.S. interstates and principal arterial roads. Therefore, use of different axle load spectra for class 9 is likely to carry practical consequences in terms of costs and performance.

The summary of vehicle classes and axle group types that resulted in significant difference in design thickness and/or pavement service life based on MEPDG sensitivity analysis for flexible pavements is as follows:

- Class 4 tandem axles.
- Class 6 tandem axles.
- Class 7 tandem and tridem axles.
- Class 8 single and tandem axles (Florida site only).
- Class 9 tandem axles.
- Class 10 tandem and tridem axles.
- Class 11 single axles.
- Class 13 tandem, tridem, and quad axles.

The scenarios tested were based on truck traffic composition that had test class carrying the largest percentage of the total load observed among all LTPP sites. These scenarios represent the worst, rather than typical, condition that magnifies the effect of NALS associated with the test truck.

The results of the MEPDG sensitivity analyses for flexible pavements suggest that load spectra clusters defined in this study can yield differences in MEPDG-based designs that are of practical significance. Therefore, use of load spectra clusters that best represent axle loading condition at a given site is recommended for MEPDG-based flexible pavement designs.

Rigid Pavements

The results for rigid pavements are provided in table 33. Among all of the class-axle combinations investigated, only tandem axles in classes 4, 8, 9, and 13 had two or more cluster groups producing design slab thickness difference of 0.5 inch or more. Class 9 tandems produced the highest difference in pavement thickness prediction: 1.1 inches. Therefore, the selection of different load spectra for class 9 carries practical consequences in terms of rigid pavements costs and performance. Class 8 sensitivity was due to a single site, the Florida SPS-1 site. This site has very high percentage of overweight class 8 trucks. No other SPS TPF sites had this distribution.

From the service life perspective, observations were similar to the thickness analysis. In addition to the sensitive class-axle instances reported for thickness analysis, NALS clusters for class 6 tandem axles also showed a significant impact on service life, which was defined as differences in service life above 20 percent, or 4 years. These differences in design service life could have important economic impact on the life cycle cost of the pavement.

The summary of vehicle classes and axle group types that resulted in significant difference in design thickness and/or service life predictions based on MEPDG sensitivity analysis for rigid pavements is as follows:

- Class 4 tandem axles.
- Class 6 tandem axles.
- Class 8 tandem axles.
- Class 9 tandem axles.
- Class 13 tandem axles.

The results of MEPDG sensitivity analyses for rigid pavements suggest that load spectra clusters can yield differences in MEPDG-based designs that are of practical significance, specifically in the case of NALS for tandem axles. Since none of the single, tridem, or quad axle clusters resulted in significant changes in MEPDG outcomes, there is no evidence from this study that multiple axle loading defaults for single, tridem, or quad axles would result in significant benefits for rigid pavement designs. The scenarios tested were based on truck traffic composition that had test class carrying the largest percentage of the total load observed among all LTPP sites. These scenarios represent the worst, rather than typical, condition that magnifies the effect of NALS associated with the test truck.

Table 33. Predicted PCC thickness and service life results for slab cracking failure mode for rigid pavements.

Test Class	Cluster	AADTT	Percentage of "Test" Class	Percentage of Heavy Classes (C9 and higher)	PCC Design Thickness Needed to Support 20 Year Life (inches)						Pavement Life at Failure Point using the Base Thickness (Years)						Significance	
					GP1	GP2	GP3	GP4	GP5	GP6	GP1	GP2	GP3	GP4	GP5	GP6	Thickness	Life
4	Single	852	42.60	18.00	10.3	10.3	**10.3**				20.8	20.8	**20.8**					
	Tandem				10	10.1	**10.3**	10.5			24.9	23.8	**20.8**	18.7			Y	Y
5	Single	2,575	59.90	24.70	**9.2**	9.3	9.3	9.4			**20.2**	19.5	19	17.4				
	Tandem				**9.2**	9.2	9.2				**20.2**	20.1	20.1					
6	Single	726	43.00	24.60	**9.4**	9.4	9.4	9.4	9.4		**20.3**	20.1	20	19.8	19.8			
	Tandem				**9.4**	9.7	9.7	9.7	9.8		**20.3**	17.2	16.8	16.8	15.8			Y
7	Single	1,884	12.00	72.90	10	10	**10**	10	10		20.1	20.1	**20**	20	20			
	Tandem				**10**	10.1	10.2	10.2	10.3		**20**	19.5	18.8	18	16.9			
	Tridem				**10**	10	10	10.1	10.1		**20**	20	20	19.9	19.9			
	Quad				**10**	10	10				**20**	20	20					
8*	Single	2,034	32.40	33.40	9.9	**9.9**	9.9	10			20.1	**20**	20	19				
	Tandem				9.9	9.9	9.9	**9.9**	10	10.5	20.9	20.8	20.7	**20**	19.8	14.7	Y	Y
9	Single	4,358	77.60	86.60	11.1	**11.1**	11.1	11.1			20.8	**20.8**	20.8	20.8				
	Tandem				10.6	**11.1**	11.4	11.7			27.4	**20.8**	17	12.8			Y	Y
10	Single	1,686	8.50	81.30	**10.1**	10.1	10.1	10.1			**20**	20	20	20				
	Tandem				10.1	**10.1**	10.2	10.2	10.2		20.8	**20**	19.6	19.5	19.3			
	Tridem				10.1	10.1	**10.1**	10.1	10.1		20	20	**20**	20	20			
	Quad				**10.1**	10.2	10.2				**20**	19.9	19.9					
11	Single	5,418	19.90	72.00	11.2	11.2	**11.2**	11.2	11.2		20.7	20.7	**20.7**	20.7	20.7			
12	Single	1,448	14.30	53.50	10.4	10.4	10.4	**10.4**	10.4		20.3	20.3	20.3	**20.3**	20.3			
	Tandem				10.3	10.4	**10.4**	10.5	10.6		21.7	20.9	**20.3**	19.8	19.8			
13	Single	3,694	24.60	81.10	**11**	11	11	11			**20.8**	20.8	20.8	20.8				
	Tandem				10.7	**11**	11.1	11.4			24.8	**20.8**	17.8	16.8			Y	Y
	Tridem				11	11	**11**	11	11		20.8	20.8	**20.8**	20.8	20.8			
	Quad				11	11	11	**11**			20.8	20.8	20.8	**20.8**				

*High sensitivity of class 8 tandems is due to a single site, Florida SPS-1that forms tandem GP6. No other SPS TPF sites have this distribution.

Note: Bold values represent designs based on typical NALS for all vehicle classes and axle group types. Blank cells indicate the group was not available.

Summary of Findings

Different MEPDG distress prediction models exhibit different relationships between design thickness and service life due to differences in pavement failure mechanics, as well as transfer functions used to relate mechanistic predictions to pavement distresses. In the case of rigid pavements, where the highest difference in the class 9 tandem axle scenario was about 1.1 inches, the impact in service life was over 14 years. Conversely, the same class-axle scenario for flexible pavement had the highest thickness difference of 0.8 and 2.6 inches for top-down cracking and rutting, respectively, but yielded differences in service life of 10 and 6 years, respectively. This finding emphasizes the importance of considering both design thickness and service life in the evaluation of the axle load spectra clusters.

Findings regarding individual axle group types and the impact of using different NALS clusters on MEPDG-based pavement design and performance prediction include the following:

- **Single axles:** The majority of analyses involving single-axle load spectra did not result in significant differences in pavement design thickness or service life. The exceptions are findings for bottom-up cracking in flexible pavements involving classes 8 (case of high overloads in Florida only) and 11. This finding does not support the need for multiple load spectra defaults (on the national level) for single axles, except for class 11.

- **Tandem axles:** Most of the tandem axle load spectra clusters resulted in significant differences in design thickness or service life of both flexible and rigid pavements. Exceptions are tandems for classes 5, 8, and 12 as follows:

    - Class 5 tandems are allowed by the LTPP vehicle classification scheme (light duty trailers on pick-up trucks or sport utility vehicles) and are expected to be light. These tandems are atypical for the majority of class 5 vehicles. Hence, they represent a very small percentage of axles and therefore cause insignificant damage.

    - Sensitivity of class 8 was found to be due to a single site located in a Florida agricultural region that had very different class 8 single and tandem NALS distribution compared to other SPS TPF sites, large percentage of overloaded tandem axles (40,000–44,000 lb). Use of alternative class 8 NALS defaults would not benefit MEPDG design accuracy for the sites that do not have significant percentages of overloaded class 8 tandems.

    - Class 12 has moderate-to-heavy loaded tandem axles, but for the VCD cases observed in LTPP database, the percentile contribution of class 12 trucks by volume was too small to produce significant variation in design thickness or service life. This finding may be different for states or regions that utilize high volumes of class 12 trucks.

    This finding supports the need for multiple load spectra defaults for tandem axles for all vehicle classes except classes 5, 8, and 12.

- **Tridem axles:** All class-axle combinations that involved tridem load spectra clusters (classes 7, 10, and 13) resulted in differences in design thickness or service life for flexible but not for rigid pavements. This finding supports the need for multiple load spectra defaults for tridem axles to be used in flexible pavement design.

- **Quad axles:** With the exception of class 13 results for flexible pavements (rutting failure mode), no significant differences in pavement design outcomes were found when different quad axle load spectra clusters were used. This can be explained by the low percentages of quads, compared to other axle group types observed in the LTPP database, which is insignificant to produce large variation in design thickness or service life. This finding may be different for States or regions that utilize high volumes of trucks with quad axles. This current finding does not support the need for multiple load spectra defaults for quad axles, with the exception of class 13 quads when used for flexible pavement design. This conclusion is influenced by the vehicle classification data available at the time of study. However, in summer 2012, LTPP made a change to how vehicle classes 7, 10, and 13 are being classified, which may lead to a different conclusion in the future.

Findings regarding different vehicle classes and the impact of using different axle load spectra clusters on MEPDG-based pavement design and performance prediction are as follows:

- **Classes not sensitive to NALS clusters:** This finding does not support the need for multiple load spectra defaults for classes 5, 8, and 12.

    - Class 5 load spectra clusters for all axle group types did not result in significant differences in design thickness or service life in both pavement types. Two main reasons are: (1) class 5 trucks are light; the RPPIF for single and tandem clusters are among the lightest found in the all clusters evaluated in this study, and (2) although there were four single axle clusters and three tandem clusters identified through statistical clustering for this class, the differences among RPPIF's are very small, resulting in the low MEPDG sensitivity.

    - Class 8 load spectra clusters for single and tandem axle group types did not result in significant differences in design thickness or service life in both pavement types, with the exception of spectra for one site in Florida where many overloaded axles were observed. Class 8 axles observed at all other sites were lightly or moderately loaded.

    - Class 12 load spectra clusters for all axle group types did not result in significant differences in design thickness or service life in both pavement types. Although class 12 axles carry heavy loads, for the VCD cases observed in the LTPP database, the percentage contribution of class 12 was too small to warrant significant variation in design thickness or service life. This finding may be different for States or regions that utilize high volumes of class 11 or 12 trucks.

- **Classes sensitive to NALS clusters:** This finding indicates the need for multiple load spectra defaults for classes 4, 6, 7, 9, 10, 11, and 13.

    - MEPDG outcomes were sensitive to different NALS assigned to multi-axle groups (tandem, tridem, and quad) but not to single axle NALS groupings. Two exceptions where single axle NALS resulted in different outcomes are class 8 (case of high overloads only) and class 11 analysis for bottom-up cracking of flexible pavements.

- Among all vehicle classes and axle group types, MEPDG outcomes were found to be the most sensitive to class 9 tandems. This is explained by high volumes of class 9 tandems coupled with variation of loads carried by class 9 vehicles.

Disclaimer

The conclusions presented in this chapter are based on the analysis of the traffic loading scenarios described in table 26. While the best attempt was made to select realistic traffic volume scenarios (AADTT and VCD) that would result in the highest sensitivity of pavement design outcomes to alternative load spectra groups, different traffic and pavement structure inputs may result in different analysis outcomes. It is recommended that State and local highway agencies conduct their own sensitivity analysis using State-specific truck traffic volume and classification inputs, as well as locally calibrated distress prediction models and local pavement design/ performance criteria.

SENSITIVITY OF DIFFERENT ROAD AND PAVEMENT TYPES TO AXLE LOADING DISTRIBUTIONS

Analysis Objective

The purpose of this analysis was to determine if sensitivity of MEPDG outcomes to differences in NALS varies for pavements designed for different AADTT levels. The questions to be answered were as follows:

- Is pavement design sensitivity to NALS affected by pavement and road type?
- Would thin pavement structures designed for lower volume arterial roads show different sensitivity to NALS changes compared to thick pavement structures designed for high volume interstate roads?

Analysis Scope

The scope of the analysis was limited to MEPDG sensitivity to load spectra developed for class 9 tandem axles under different truck volume scenarios. This is by far the most dominant type of heavy axles observed on interstate roadways in the United States. Even for non-interstate highways, once class 5 axles are discounted due to their light weight, class 9 axles dominate the overall axle load spectra for most highway pavements. For the analyses conducted in this study, the presence of class 9 vehicles in the VCD was set to 85 percent to increase the potential MEPDG sensitivity to changes in loading of class 9 tandems. AADTT per lane values varied to capture the range of values observed on principal arterial interstates and rural highways.

Class 9 tandem load spectra representing typical, light, or heavy loading conditions developed based on SPS TPF WIM data were used in the analyses. For all other axle load spectra, the typical loading condition was kept constant through the analysis. Figure 37 shows class 9 tandem load spectra for the three identified conditions.

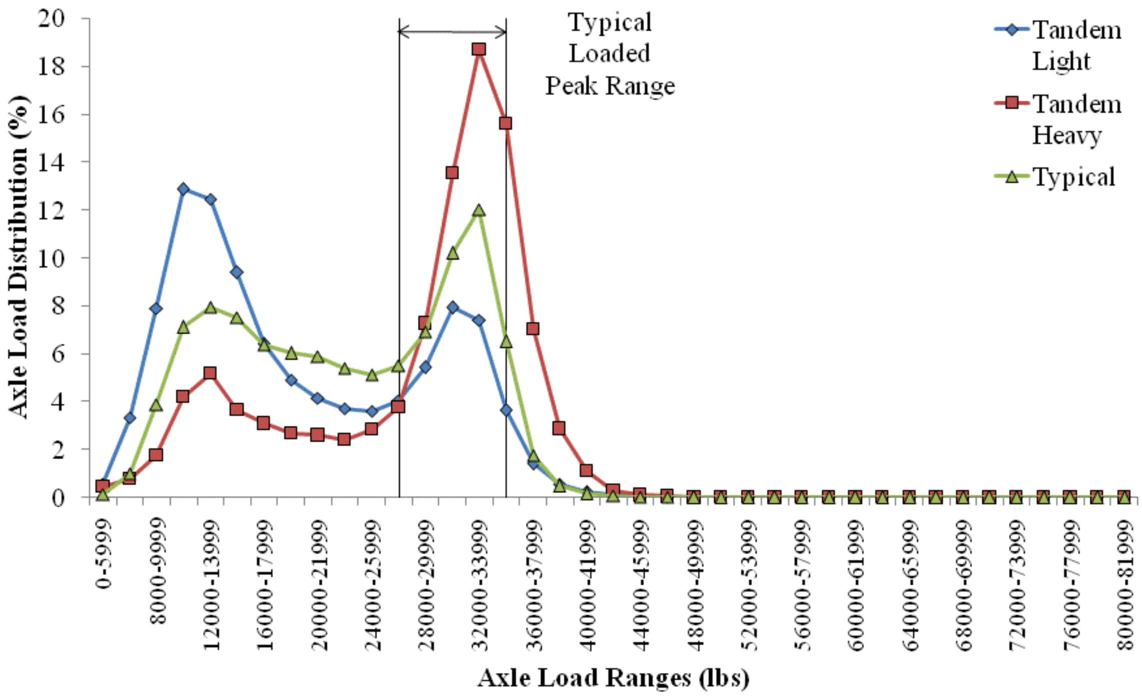

Figure 37. Graph. Class 9 tandem load spectra for identified clusters.

Several typical pavement designs were identified and analyzed for different AADTT levels. Both rigid and flexible pavement designs were included. With the exception of thickness of AC layer or PCC slab thickness, which varied by design, the design inputs shown in table 28 and table 29 were used in this MEPDG sensitivity study.

Analysis Execution

To conduct MEPDG sensitivity analyses, pavement designs were developed for different traffic input scenarios using the 90 percent reliability option (default MEPDG option). The wet-freeze climatic condition was used for all analyses as the condition most likely to cause more damage to the pavement based on previous LTPP studies.[17,18] The pavement design life was set to 15 years for flexible pavements and 20 years for rigid based on average pavement design life observed for LTPP GPS sections. A range of AADTT per lane values was determined based on analysis of VCDs from LTPP database for the sites that had high percentage of heavy trucks, as presented in figure 38 through figure 40.

For each AADTT level, the pavement structure was designed twice. The first design was done using the light NALS for class 9 tandems and typical for all other class-axle load spectra. In the second design, the load spectrum for class 9 tandems was changed to heavy, while all other traffic inputs were kept the same. Light and heavy spectra were based on the lightest and the heaviest load spectra clusters for class 9 tandems, respectively. Only the thickness of the surface layer was modified in each of these designs. These two loading conditions resulted in the thinnest and thickest surface layer. The impact of different class 9 tandem load spectra on the design was evaluated by comparing the differences in the surface layer design thickness. The results of the analysis and relevant conclusions are provided in the following section.

Discussion of Findings

Flexible Pavements

The changes in design thicknesses using light and heavy NALS for class 9 tandems were investigated for a range of AADTT values and pavement failure modes (longitudinal top-down cracking, bottom-up alligator cracking, and rutting). Figure 38 illustrates the variations of design thickness versus AADTT for the top-down cracking failure mode. Figure 39 shows the variation of design thickness versus AADTT for the bottom up cracking failure mode. Figure 40 shows the variations of design thickness versus AADTT for the rutting failure mode.

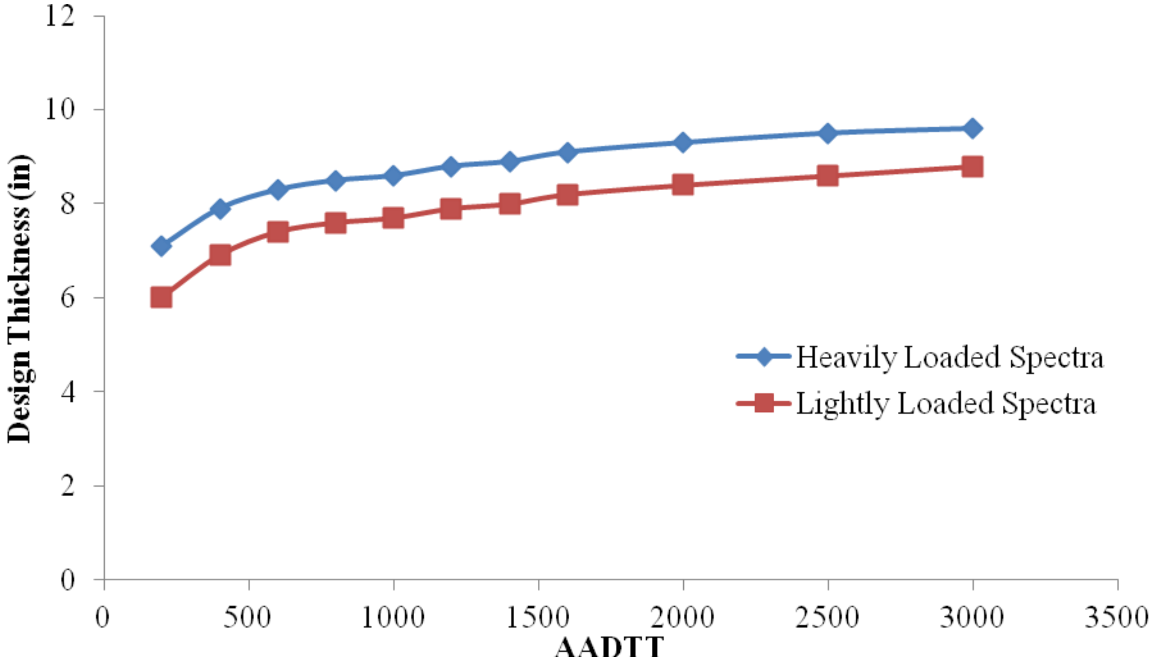

Figure 38. Graph. Results of AC layer thickness sensitivity to class 9 load spectra for flexible pavements with top-down cracking failure mode.

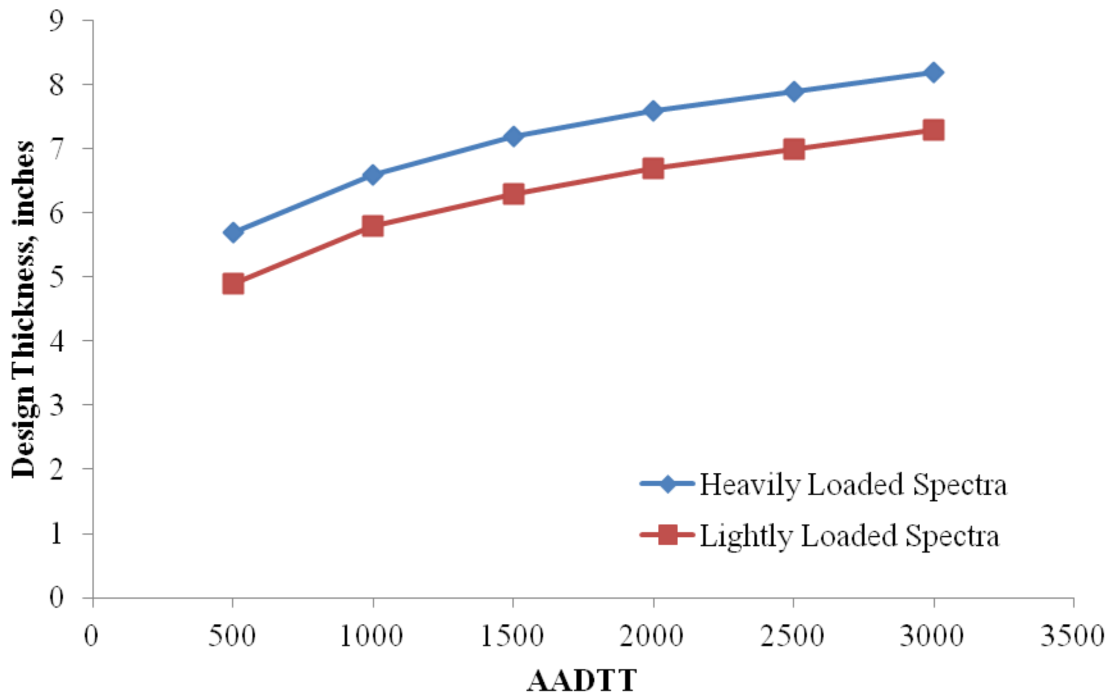

Figure 39. Graph. Results of AC layer thickness sensitivity to class 9 load spectra for flexible pavements with bottom-up cracking failure mode.

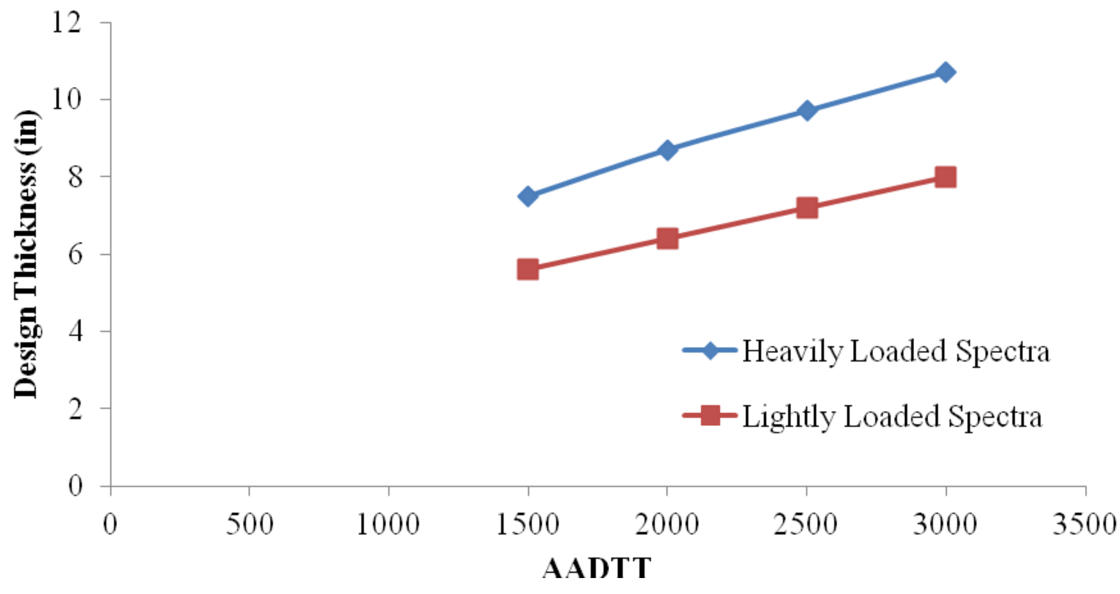

Figure 40. Graph. Results of AC layer thickness sensitivity to class 9 load spectra for flexible pavements with rutting failure mode.

In the case of cracking failure modes, the difference in AC thickness between lightly and heavily loaded designs is somewhat uniform at about 1 inch. For practical purposes, the impact of class 9 load spectra was found significant for all AADTT levels investigated (i.e., difference in thickness higher or equal 0.5 inch).

In the case of rutting failure mode, it was only possible to investigate designs with AADTT values above 1,500. Below this level, the failure mode shifted from rutting to cracking. This is explained by globally calibrated models used and the design properties selected. The differences in thickness were much higher than previously seen for cracking, ranging from 1.9 to 2.7 inches for the AADTT analyzed. However, the approach of mitigating rutting by increasing AC thickness only may not be practical.

Overall, the results of flexible pavement analysis indicate that for all AADTT levels and design types investigated, the variation in load spectra between light and heavy loading conditions resulted in different AC surface thicknesses with practical consequences (i.e., differences higher than 0.5 inch). This indicates the importance of accurate axle loading characterization for AC pavements designed for all AADTT levels if heavy trucks dominate VCD.

Rigid Pavements

Similar to the flexible pavement analysis, the design thicknesses of PCC slab predicted based on the light and heavy load conditions of class 9 tandems were compared. Five different JPCP structural designs were used based on AADTT levels, as summarized in table 29. Figure 41 shows the PCC slab design thicknesses predictions for different AADTT levels.

There was only one critical distress observed throughout the analysis of all design cases: transverse slab cracking. As expected, the design thickness increased with the increase in traffic volume for both load conditions. However, the difference in thickness between the two loading conditions stayed almost the same for different AADTT levels (slightly higher difference for high AADTT compared to low AADTT). Even at the lowest truck volume level, when AADTT per lane was 250 vehicles and the slab thickness varied from 7.9 to 8.8 inches, the difference between the two load conditions was 0.9 inch. This difference is considered significant for practical purposes.

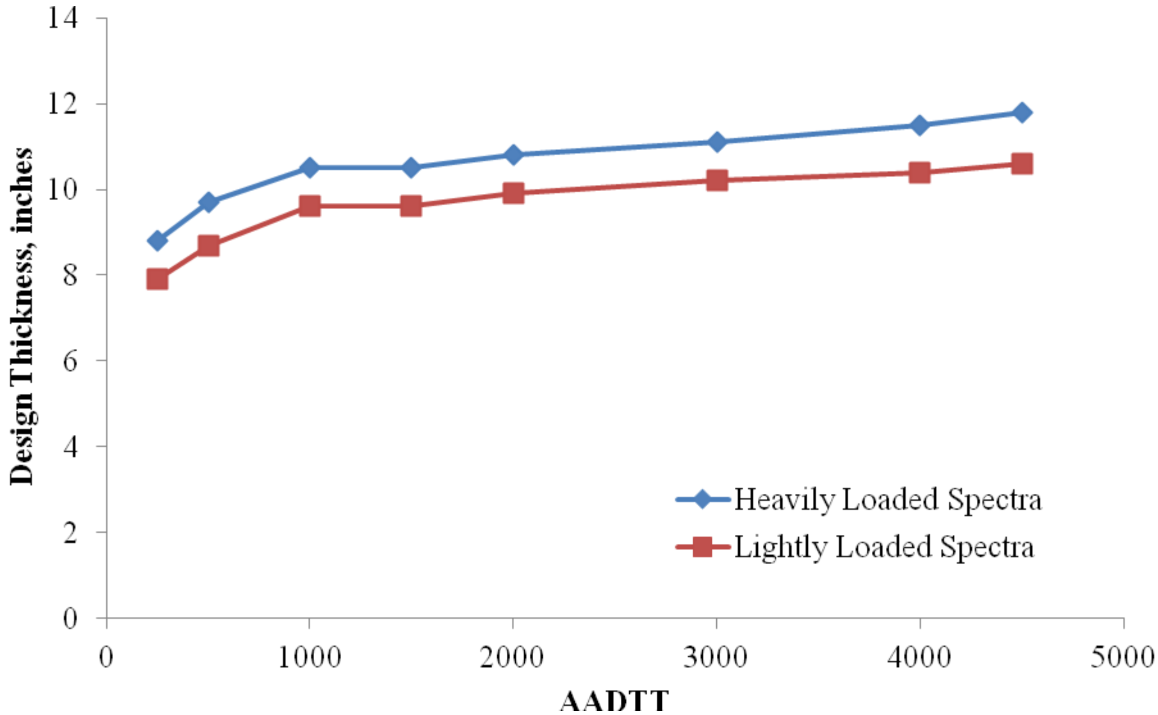

Figure 41. Graph. Results of PCC slab thickness sensitivity to class 9 load spectra for rigid pavements.

Conclusions

The results from the analyses for flexible and rigid pavements suggest that differences in design thickness will occur with practical implications for construction when one chooses a lightly loaded class 9 tandem load spectrum or a heavily loaded class 9 load spectrum, with no regards to truck traffic volume and pavement type, and pavement failure mode, provided the percentage of class 9 trucks remains high compared to other truck classes (class 5 excluded). For the range of traffic volumes considered in this analysis, differences in AC design thickness were observed between 2.7 and 0.8 inches depending on which load spectra and traffic level were chosen and which failure model governs the design. In the case of rigid pavements, the difference in design thickness was observed between 0.9 and 1.2 inches.

Based on the analysis findings, the following answers could be provided to the questions posted in the research objective:

- **Is pavement design sensitivity to traffic loading affected by pavement and road type?** All the designs showed sensitivity to difference in NALS for the class 9 trucks high enough to result in thickness differences that would have practical significance on the cost of the project. This indicates the importance of accurate characterization of axle loading for the heavy tuck types for all pavements types designed for all road types that have heavy trucks dominating VCD.

- Would thin pavement structures designed for lower volume arterial roads show different sensitivity to NALS changes compared to thick pavement structures designed for high volume interstate roads? Based on the differences in predicted thickness of the top structural layer (AC layer thickness or PCC slab thickness), there is no strong evidence that thin pavement structures designed for lower volume arterial roads are more or less sensitive to changes in NALS than thick pavement structures designed for high volume interstate roads, provided that each structure is adequately designed for a given truck volume and VCD. The MEPDG results indicate that change of load spectra results in similar changes of layer thickness for all AADTT levels, with pavement designed for lowest truck volumes showing slightly lesser differences in design thickness (in absolute values [inches], not in percentages). The magnitude of the difference in layer thickness is a function of pavement type and failure mode.

ANALYSIS OF TRUCK VOLUME AND DISTRIBUTION SCENARIOS LEADING TO HIGH SENSITIVITY OF MEPDG OUTCOMES TO CLASS 9 NALS

Analysis Objective and Scope

The purpose of this analysis was to identify traffic conditions (combinations of truck volume and VCD characteristics) when differences in load spectra defaults have a significant impact on MEPDG pavement design and analysis outcomes. The analysis was limited to tandem axles for class 9. These spectra were selected as the ones that have the most significant pavement damaging potential both due to the weight and the number of axle load applications. The question to be answered was, what combinations of AADTT and percentages of class 9 vehicles would require the use of axle load spectra that characterize a specific loading condition (versus use of global default) and what combinations of AADTT and percentages of class 9 vehicles would only marginally benefit from load spectra that accurately describe a specific loading condition?

These conditions would indicate at what point the presence of class 9 vehicles becomes too low to cause practical differences in pavement design outcomes with respect to differences in default axle load spectra selection.

Analysis Execution

This analysis started with the evaluation of truck volume data available in the LTPP database. Table 34 and table 35 show the distribution of LTPP sites by AADTT and percentage of class 9 trucks observed for LTPP flexible and rigid pavement sections. This information was used to identify plausible AADTT and class 9 percentage scenarios for the analysis. Based on LTPP information available with regard to AADTT, VCD, and pavement type, a total of 841 LTPP sections' AADTT and VCD values were analyzed from all the SPS and GPS sites. The computations were done based on the most recent year of data available in the LTPP SDR 24 database.

Table 34. Distribution of LTPP sites by AADTT and percentage class 9 trucks observed for LTPP flexible sections.

AADTT Range	Number of Sites with Corresponding Class 9 Percentage					
	≥ 85	≥ 65 and < 85	≥ 45 and < 65	≥ 25 and < 45	≥ 15 and < 25	< 15
> 3,000	1	12	7	0	0	0
> 2,500 and ≤ 3,000	0	11	3	0	0	0
> 2,000 and ≤ 2,500	1	12	12	2	1	0
> 1,500 and ≤ 2,000	0	7	12	1	1	2
> 1,000 and ≤ 1,500	0	9	21	12	1	1
> 500 and ≤ 1,000	0	13	39	32	13	12
> 200 and ≤ 500	0	18	50	57	19	8

Table 35. Distribution of LTPP sites by AADTT and percentage class 9 trucks observed for LTPP rigid sections.

AADTT Range	Number of Sites with Corresponding Class 9 Percentage			
	≥ 75	≥ 50 and < 75	≥ 25 and < 50	≥ 10 and < 25
≥ 4,500	0	3	1	0
≥ 4,000 and < 4,500	2	3	0	0
≥ 3,000 and < 4,000	7	18	8	0
≥ 2,000 and < 3,000	1	36	6	3
≥ 1,500 and < 2,000	3	25	3	1
≥ 1,000 and < 1,500	6	21	16	5
≥ 500 and < 1,000	2	34	33	10
≥ 250 and < 500	2	9	21	12

These AADTT ranges and class 9 percentages were used to identify truck volume scenarios. Once truck volume scenarios were identified, tandem axle load spectra clusters for class 9 vehicles that resulted in the thinnest (light NALS) and thickest (heavy NALS) pavement sections were selected for analysis, while typical NALS were used for all other vehicle classes and axles types (see figure 37).

AC and JPCP pavement structures were designed for each truck volume and NALS scenario, and differences in the resulting pavement thicknesses were analyzed. With the exception to thickness of AC layer or PCC slab thickness, which varied by design, the design inputs shown in table 28 and table 29 were used in this MEPDG sensitivity study.

Discussion of Findings

Flexible Pavements

Three design cases were used: one to mitigate rutting failure, one to mitigate top-down cracking failure, and one to mitigate bottom-up cracking failure. For each of these design cases, the analysis process began with the design scenario representing the highest AADTT and class 9 percentage identified in table 36 (AADTT per lane of 3,000 and 85 percent class 9 vehicles). Using the selected traffic volume scenario, the pavement was designed twice: once using load spectra with light class 9 tandem NALS and another time using heavy class 9 tandem NALS. After both designs were completed, the differences in surface layer thickness were computed and reported in table 36 (value = 0.8 inch). In subsequent steps, the AADTT and percentage class 9 were reduced in fixed steps. For each new AADTT class 9 scenario, pavement designs were adjusted to new traffic levels and the difference in top layer thickness (between light and heavy class 9 tandem NALS scenarios) was computed.

Table 36 provides the thickness difference matrix for the design case in which top-down cracking was observed as critical distress failure mode. The results suggest that the difference in design thickness between the designs using lightly and heavily loaded class 9 tandem spectrum remains at or above 0.5 inch at all levels for all the cases tested. This thickness was considered as the limit for a practical difference for this investigation.

Table 36. AC thickness difference due to different class 9 tandem load spectra (critical distress is top-down cracking).

AADTT per Lane	Difference in AC Thickness by Percent of Class 9 Vehicles (Inches)				
	85 Percent	65 Percent	45 Percent	25 Percent	15 Percent
3,000	0.8	0.7	0.7		
2,500	0.9	0.8	0.7		
2,000	0.9	0.8	0.8	0.7	
1,500		0.9	0.8	0.7	0.5
1,000		0.9	0.9	0.7	0.6
500		0.9	0.9	0.8	0.6
250		1.0	1.1	1	0.9

Note: Blank cells indicate that no LTPP AC sections had this combination of AADTT and percent class 9.

Table 37 provides the thickness difference matrix for the design case in which bottom-up cracking was observed as critical distress failure mode. The results suggest that the difference in design thickness between the designs using lightly and heavily loaded class 9 tandem spectrum remained at or above 0.5 inch at all AADTT levels that had 45 percent or more on class 9 vehicles in VCD (for classes 4 through 13).

Table 37. AC thickness difference due to different class 9 tandem load spectra (critical distress is bottom-up cracking).

AADTT per Lane	Difference in AC Thickness by Percent of Class 9 Vehicles (Inches)				
	85 Percent	65 Percent	45 Percent	25 Percent	15 Percent
3,000	0.9	0.7	0.5		
2,500	0.9	0.8	0.7		
2,000	0.9	0.8	0.7	0.3	
1,500		0.6	0.5	0.4	0.2
1,000		0.7	0.6	0.4	0.2
500		0.6	0.5	0.4	0.2
250		0.6	0.7	0.5	0.4

Note: Blank cells indicate no instances were recognized.

Table 38 provides the thickness difference matrix for the design with rutting failure mode. Similar to what was found in the cracking failure analysis, the results suggest that when the design is driven by rutting failure, the impact of selecting the load spectrum can have significant consequences on the outcome of the design (variation in thickness). Even at the lowest level of AADTT and percentage class 9 investigated, the difference in surface layer thickness was well above the 0.5-inch threshold. In addition to rutting failure, some cells also exhibited roughness and top-down cracking failure as a concomitant. This happened due to design characteristics and because the roughness model in the MEPDG had components that were output from other distress models. When the volume of class 9 starts to diminish, and consequently the design thickness decreases, distresses such as cracking start to increase, which contributes to the increase in roughness observed in the predictions. Lower AADTT values were not tested for rutting failure mode, as this mode is dominant for roads with high volumes of trucks operated at highway speeds.

Table 38. AC thickness difference due to different class 9 tandem load spectra (critical distress is rutting).

AADTT per Lane	Difference in AC Thickness by Percent of Class 9 Vehicles (Inches)				
	85 Percent	65 Percent	45 Percent	25 Percent	15 Percent
3,000	2.7	2.4	1.7		
2,500	2.5	2.2	1.7		
2,000	2.3	1.8	1.4	0.8	0.5
1,500		1.5*	1*	0.7*	0.5*

*These designs also failed in top-down cracking mode.

Note: Blank cells indicate that no LTPP AC sections had this combination of AADTT and percent class 9.

The results for flexible pavement designs indicate that even when lower a percentage of class 9 was considered in VCD and a lower volume of trucks was used, the variation in load spectra between lightly and heavily loaded resulted in different AC surface thicknesses with practical consequences (i.e., differences higher or equal to 0.5 inch). Moreover, if the design was governed by rutting, the differences in thickness were even more significant. One exception was for roads with less than 45 percent of class 9 vehicles that failed in bottom-up cracking mode.

Rigid Pavements

In the case of rigid pavements, only one failure mode was observed—slab cracking. The designs were adjusted based on the MEPDG recommendations (e.g., dowel bar diameters and spacing, base layer thickness, and material type) to mitigate the potential of joint faulting. The rigid pavement design characteristics were the same as the ones described in table 29.

Table 39 provides the differences in the predicted PCC pavement design thickness obtained from analysis of light and heavy class 9 tandem load spectra clusters using various AADTT and percentage of class 9 values. The results show that rigid pavements designs are sensitive to variation in NALS for class 9 tandem axles at all AADTT levels tested, especially when 15 percent or more class 9 vehicles are present in the VCD. Differences at or above 0.5 inch observed in table 39 were considered of practical significance.

Table 39. Class 9 tandem load spectra results for rigid pavements in thickness difference.

Design ID	AADTT	Difference in PCC Thickness by Percent of Class 9 Vehicles (Inches)				
		75 Percent	50 Percent	25 Percent	15 Percent	10 Percent
R1	4,500	1.2	1	0.8	0.7	0.5
	4,000	1.1	0.9	0.9	0.8	0.6
	3,000	0.9	1	0.8	0.6	0.4
R2	2,000	0.9	0.8	0.7	0.6	0.4
	1,500	0.9	0.9	0.6	0.6	0.4
R3	1,000	0.9	0.8	0.7	0.6	0.5
R4	500	1	0.9	0.8	0.6	0.4
R5	250	0.9	0.8	0.6	0.5	0.3

Conclusions

MEPDG sensitivity to different NALS for class 9 tandem axle loads was investigated for various truck volume and class 9 percentage scenarios. The results for both rigid and flexible pavements suggest that the impact of selecting a lightly or heavily loaded spectrum for class 9 tandem axles is significant under most traffic scenarios included in the study. Overall, the results indicate that even when a low percentage of class 9 vehicles (e.g., 15 percent) is considered in VCD and a low volume of trucks is used (AADTT per lane is 250), the variation in load spectra between lightly and heavily loaded class 9 tandems resulted in significant differences in the AC surface thickness and PCC slab thickness.

The results of the analysis indicate that it is important to have accurate characterization of class 9 tandem axle load spectra under all traffic conditions observed for interstate and primary arterial roads, and that local knowledge of loading conditions is important for accurate pavement design.

ANALYSIS OF MEPDG OUTCOMES USING CLASS 9 NALS FOR 26 SPS TPF SITES

Analysis Objective and Scope

In this analysis, class 9 tandem NALS computed for 26 SPS TPF sites were used to predict pavement design life for several hypothetical pavement designs. The purpose of the analysis was to see if MEPDG outcomes would form clusters based on the class 9 tandem NALS inputs and whether outcomes obtained using NALS for the sites located on interstate roads would be different from NALS for the sites located on the non-interstate principal arterial roads. In addition, correlation RPPIF and percent heavy axles statistics and pavement design life was investigated.

The design inputs shown in table 28 and table 29 for high-volume roads (AADTT > 3,000, TTC1) were used in this MEPDG sensitivity study. Class 9 tandem NALS was the only parameter changing within a given MEPDG design.

Analysis Findings

Figure 42 through figure 45 show the relationship between MEPDG-predicted pavement life and one of the two traffic loading statistics: percentage of heavy loads or average RPPIF associated with a given class 9 tandem NALS. Each symbol on the plot represents one of 26 cases of class 9 tandem NALS used in MEPDG pavement life prediction. To investigate whether pavement life predictions group in clusters based on the road functional class, two separate symbols were used, one for interstates and another for non-interstate roads. In addition, percentage of heavy loads (over 80 percent of the legal limit) and average RPPIF values were used to see if these values would form clearly defined clusters or trends with respect to pavement life.

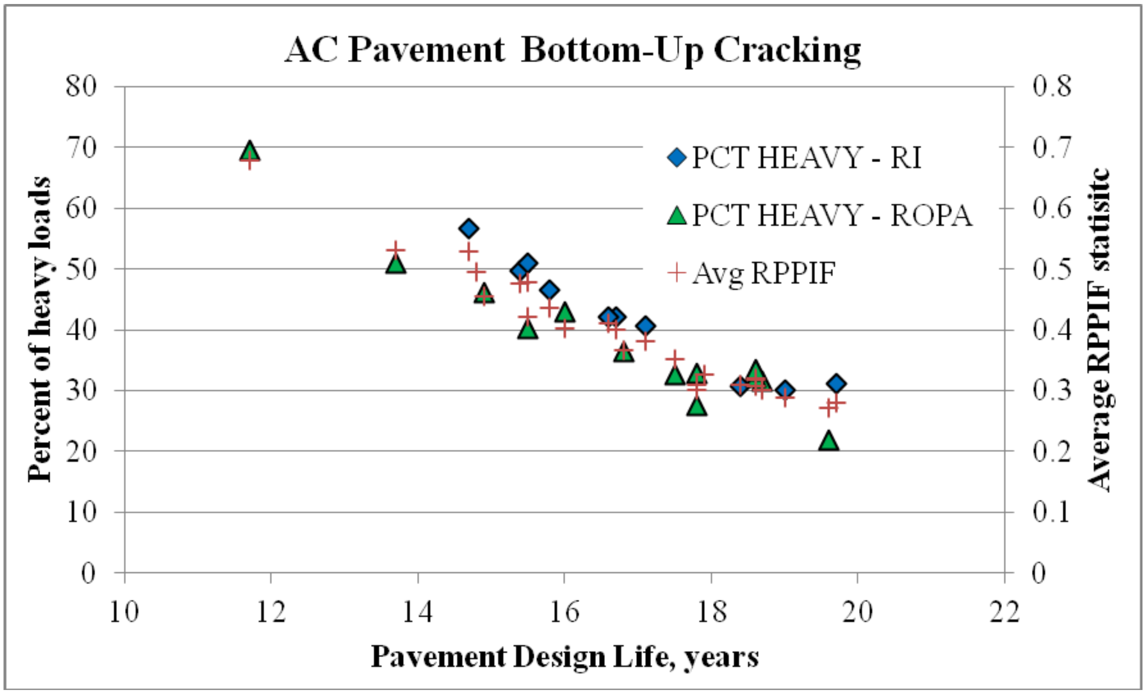

Figure 42. Graph. Results of pavement life prediction for bottom-up cracking mode.

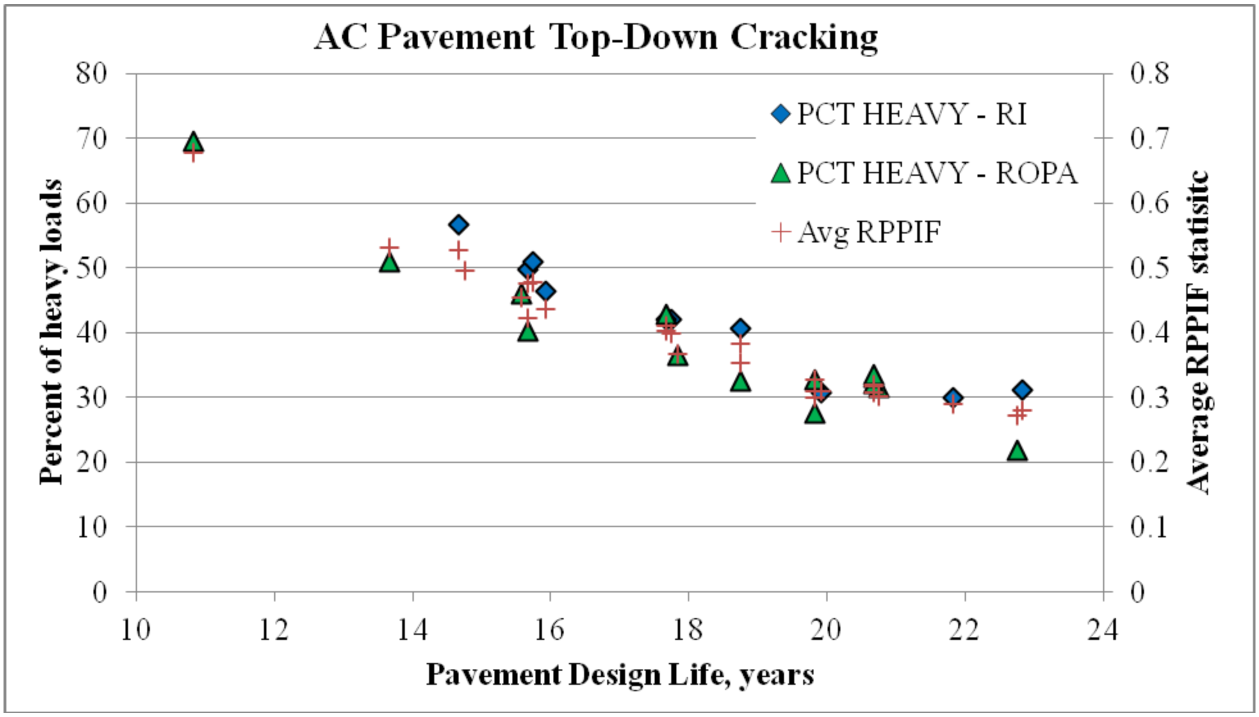

Figure 43. Graph. Results of pavement life prediction for top-down cracking mode.

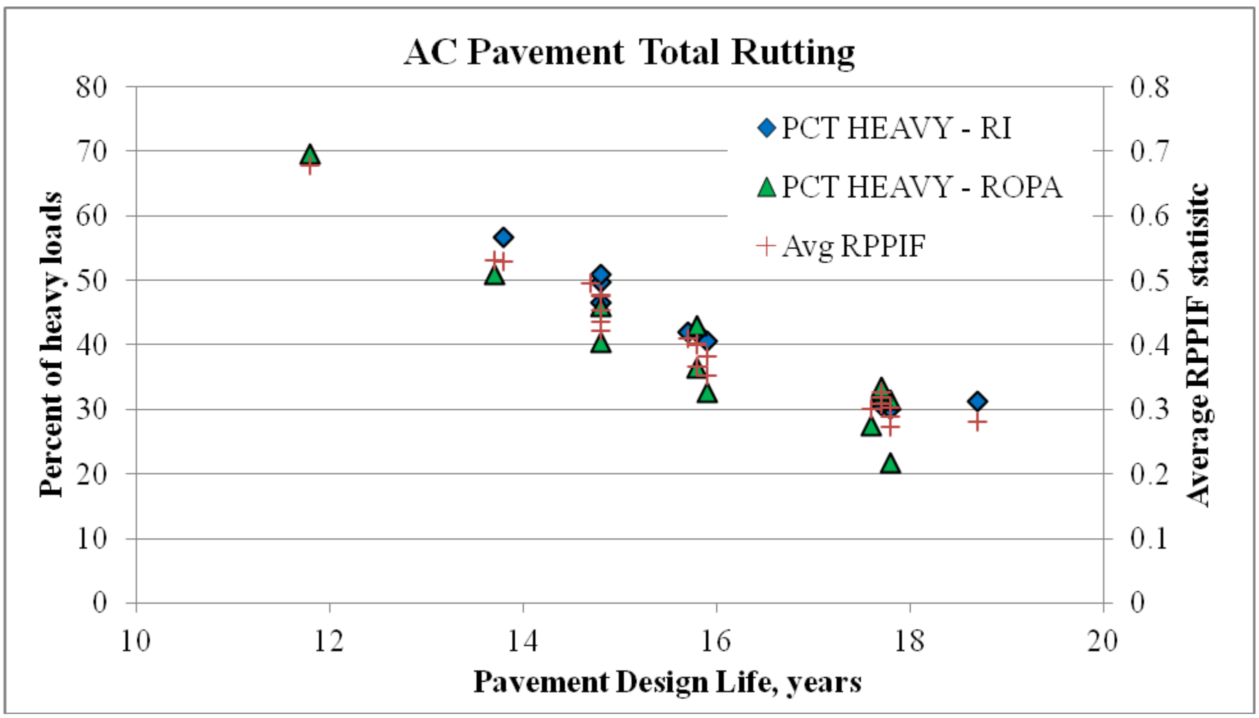

Figure 44. Graph. Results of pavement life prediction for rutting failure mode.

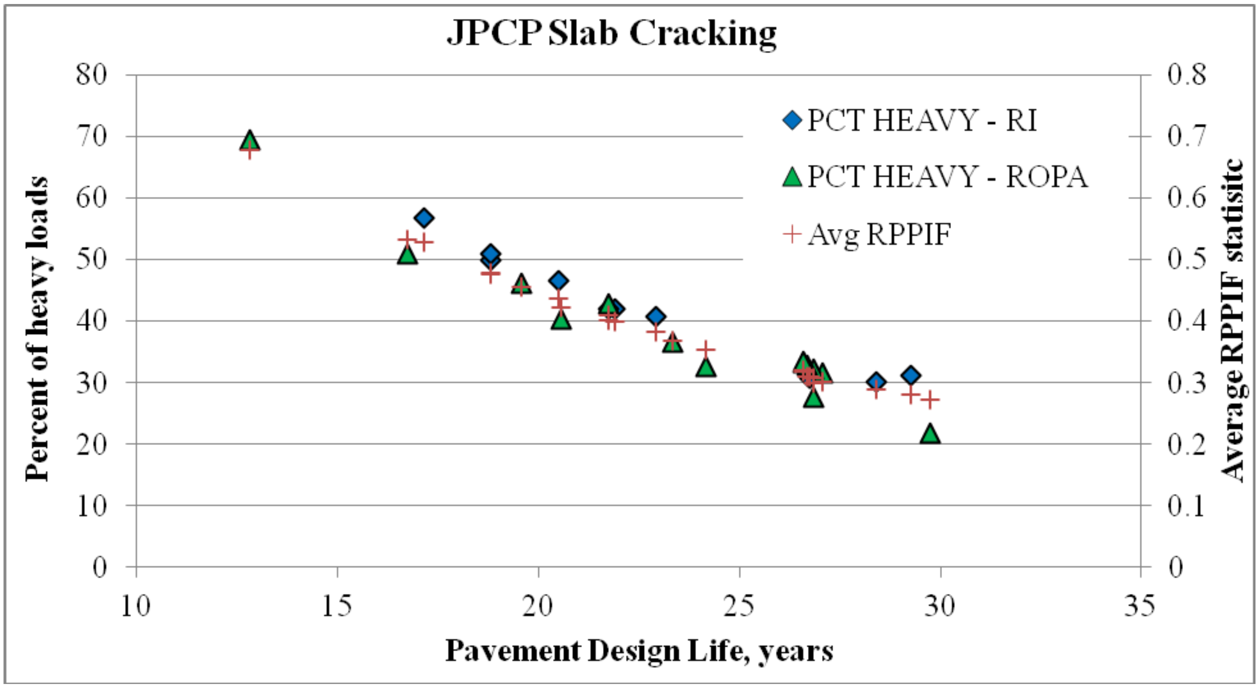

Figure 45. Graph. Results of pavement life prediction for slab cracking mode.

The results shown on the plots led to the following conclusions:

- Class 9 tandem NALS computed for RI and ROPA show similar ranges of heavy axle loads and similar ranges of pavement deign life predictions. Difference in average pavement design life using RI and ROPA NALS was less than 2 years. On average, ROPA NALS had higher percentage of light loads and loads over Federal legal limit, but these differences did not translate in significant differences in MEPDG outcomes. Therefore, no clustering of the MEPDG results based on road functional class were observed for these two road types.

- There is a strong corelation between RPPIF and pavement deign life—high RPPIF relates to short pavement design life, and low RPPIF relates to long pavement design life. RPPIF is therefore considered an effective statistic for grouping NALS that are likely to result in similar MEPDG outcomes (NALS with similar RPPIF values should be grouped togetther). Least squared difference statistic for linear regression models relating RPPIF to predicted pavement design life ranged from 94 to 96 percent for different distress types.

- A correlation was also observed between the percentage of heavy loads and the pavement deign life. Therefore, percentages of heavy loads could be used to assign site-specific NALS to the appropriate GP or to describe RPPIF-based NALS clusters.

- Results of pavement design life predictions based on different class 9 tandem NALS obtained from 26 SPS PFS sites showed fairly continuous outcomes without clearly defined clusters, with the exception of rutting, thus making it challenging to provide logical breakouts for load clusters to define light, moderate, and heavy loading conditions. In other words, changes in class 9 tandem spectra (and resulting MEPDG outcomes) from one SPS TPF site to another are gradual, without clear definition of groups or clusters of sites with similar outcomes.

- For the cases tested, a difference of 0.9 to 0.16 in the RPPIF statistic for class 9 tandem NALS resulted in a 20 percent difference in pavement life prediction. Pavement life prediction was most sensitive for the JPCP slab cracking mode, with a difference of 0.09 in the RPPIF statistic corresponding to a 20 percent difference in pavement life prediction. Total rutting was least sensitive to a difference in the RPPIF statistic for class 9 tandem NALS, with a 0.16 difference in the RPPIF statistic corresponding to a 20 percent difference in pavement life prediction.

RECOMMENDATIONS

MEPDG analysis of NALS developed for different vehicle classes and axle group types was conducted to determine what classes and axle load distributions cause the most impact on MEPDG outcomes. Specifically, differences in axle load distributions observed within each vehicle class and axle group type and the effect of these differences on MEPDG outcomes were evaluated. Based on the findings from the sensitivity analyses, the following recommendations are made with respect to developing default NALS based on LTPP SPS TPF data:

- **Single axles:** None of the single-axle load spectra clusters resulted in significant differences in design thickness or service life, with the exception of class 11. Therefore, the development of multiple load spectra defaults for single axles is not recommended, except for class 11.

- **Tandem axles:** Tandem-axle load spectra clusters for all vehicle classes, except classes 5, 8, and 12, resulted in significant differences in design thickness or service life predictions for both flexible and rigid pavements. Therefore, it is recommended that multiple load spectra default for tandem axles are to be developed and used in MEPDG applications except for classes 5, 8, and 12. Class 12 has heavy tandem axles and differences in load spectra that could result in differences in pavement thickness, for States or regions that utilize high volumes of class 12 trucks. In this case, multiple loading defaults for class 12 vehicles would be recommended.

- **Tridem axles:** All class-axle combinations that involved tridem load spectra clusters (classes 7, 10, and 13) resulted in differences in design thickness or service life for flexible but not for rigid pavements. Therefore, it is recommended that multiple default load spectra for tridem axles be developed and used in MEPDG applications involving flexible pavement design.

- **Quad axles:** With the exception of class 13 results for flexible pavements (rutting failure mode), no significant differences in pavement design outcomes were found when different quad axle load spectra clusters were used, mainly due to the low percentage of quads axles, compared to other axle group types. Therefore, the development of multiple load spectra defaults for quad axles is not recommended, except for class 13 quads when used for flexible pavement design. This finding may be different for States or regions that have high volumes of quad axles. In this case, multiple loading defaults for quad axles may be needed.

- **Highest MEPDG sensitivity:** Among all vehicle classes and axle group types, MEPDG outcomes were found to be the most sensitive to class 9 tandems. This is explained by high volumes of class 9 tandems compared to other class-axle combinations, coupled with high variation of loads carried by class 9 vehicles. Even when a low percentage of class 9 vehicles (15 percent) and a low volume of trucks (AADTT per lane is 250) were used in MEPDG analyses, the variation in load spectra between lightly and heavily loaded class 9 tandems resulted in significant differences in the AC surface thickness and PCC slab thickness. As little as 10 percent difference in the total percentage of heavy tandem axles could result in up to 20 percent difference in pavement design life for rigid pavements and 15 percent difference for flexible pavements. Therefore, it is recommended that pavement designers place high importance on accurate characterization of class 9 tandem axle load spectra under all traffic conditions observed for interstate and primary arterial roads when conducting MEPDG analysis.

- **Low volume of certain truck classes:** For specific pavement designs, when individual vehicle classes have very low volumes compared to other heavy truck classes, the choice of load spectra for those specific low-volume vehicle classes will not have an impact on pavement thickness. Conditions when different load spectra may have an effect on pavement design outcomes, as found through MEPDG sensitivity analysis, are summarized in table 23.

- **NALS representing "special case" loading:** In many cases, NALS that led to the most different MEPDG outcomes (thinnest or thickest pavement designs) were representing loading conditions observed in a single State or only at a specific SPS TPF site. While these NALS were very useful for MEPDG sensitivity analysis, it is recommended that these individual NALS or clusters be clearly identified and not recommended for general use as defaults, unless knowledge of local conditions supports use of these "special case" NALS.

- **NALS clusters:** Both RPPIF and percent heavy loads statistics were found to have high correlation with predicted pavement design life based on MEPDG method. These statistical parameters can be used to define/describe NALS clusters representing different axle loading conditions. It is recommended that any statistically defined clusters be further enhanced or revised based on the findings and recommendations from the MEPDG sensitivity analysis. Specifically, break down points similar to ones summarized in Table 23, as defined by difference between mean RPPIF values for two clusters, should be used in clustering analysis to identify clusters that are likely to result in significantly different MEPDG outcomes.

DISCLAIMER

All MEPDG sensitivity analyses were developed using the MEPDG version 1.1 software. The terminal values used for the design criteria were based on defaults included in this software. Failure modes were selected based on observed sensitivity of globally calibrated MEPDG models. Different failure modes (critical distresses) and sensitivities are possible for models calibrated to local conditions or for cases where different terminal values are used.

CHAPTER 10—DESCRIPTION OF THE NEW MEPDG TRAFFIC LOADING DEFAULTS FOR LTPP SITES

OVERVIEW OF DEFAULTS

All the defaults developed in this study are based on SPS TPF WIM data. These defaults include the following:

- NALS
- APC coefficients.
- Average wheelbase and axle spacing.

The following two sets of NALS defaults were computed:

- **Tier 1:** Global defaults based on all applicable SPS TPF data.
- **Tier 2:** Supplemental defaults based on subsets of SPS TPF data representing a specific loading condition.

Tier 1 global traffic loading defaults were developed based on averaging of MEPDG traffic loading inputs computed for individual SPS TPF sites and designed to represent global loading condition based on all the averaging of NALS for all SPS TPF sites. This approach is similar to the one used in NCHRP Project 1-37A to develop NALS defaults provided in the NCHRP 1-37A MEPDG software and in DARWin-ME™ software.(3)

Tier 2 supplemental traffic loading defaults were developed based on averaging of MEPDG traffic loading inputs computed for SPS TPF sites that had similar axle loading conditions. This computation was done separately for each vehicle class and axle group type. Thus, these defaults provide users with multiple choices with regard to selection of traffic loading conditions for different truck classes and axle group types.

GLOBAL AXLE LOADING DEFAULTS BASED ON LTPP SPS TPF SITES (TIER 1)

NALS defaults were computed based on a simple averaging of RANALS for 26 SPS TPF sites. Appendix D contains global NALS defaults for each vehicle class and axle group type and can be used to generate MEPDG and DARWin-ME™ axle load spectra input files.

Computed global NALS were compared to the NALS defaults included in the MEPDG software version 1.1. Comparisons of NALS are provided in figure 33 to figure 36. NALS and number of axles per truck were used in combination with TTC1 VCD to compute combined axle load spectra for each axle group type. These combined spectra were normalized and percentile distributions plotted for each axle group type.

The differences in tandem axle load spectra plot are of a particular interest, as tandem axle loads carry over 50 percent of all loads under typical highway loading conditions. As can be seen from the tandem plot (see figure 47), NCHRP 1-37A defaults had a larger number of overloads but lower percentage of heavy legal loads compared to the SPS TPF defaults. For the quad spectra plot, only the new spectra are displayed, as the number of axles per truck coefficients default is set to zero in the original MEPDG defaults (there were not enough quads in the original study to compute these values).

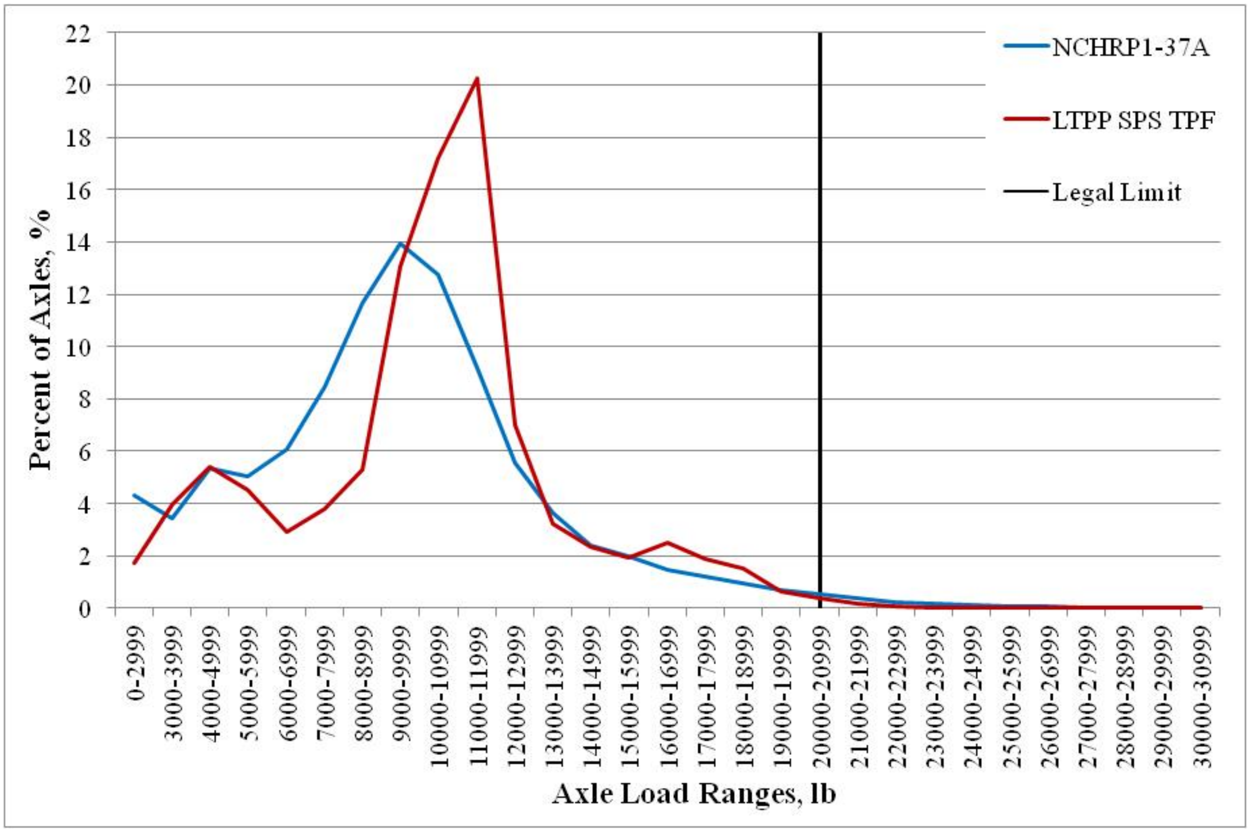

Figure 46. Graph. Comparison of NCHRP 1-37A and SPS TPF default NALS for single axles, all classes combined using TTC1.

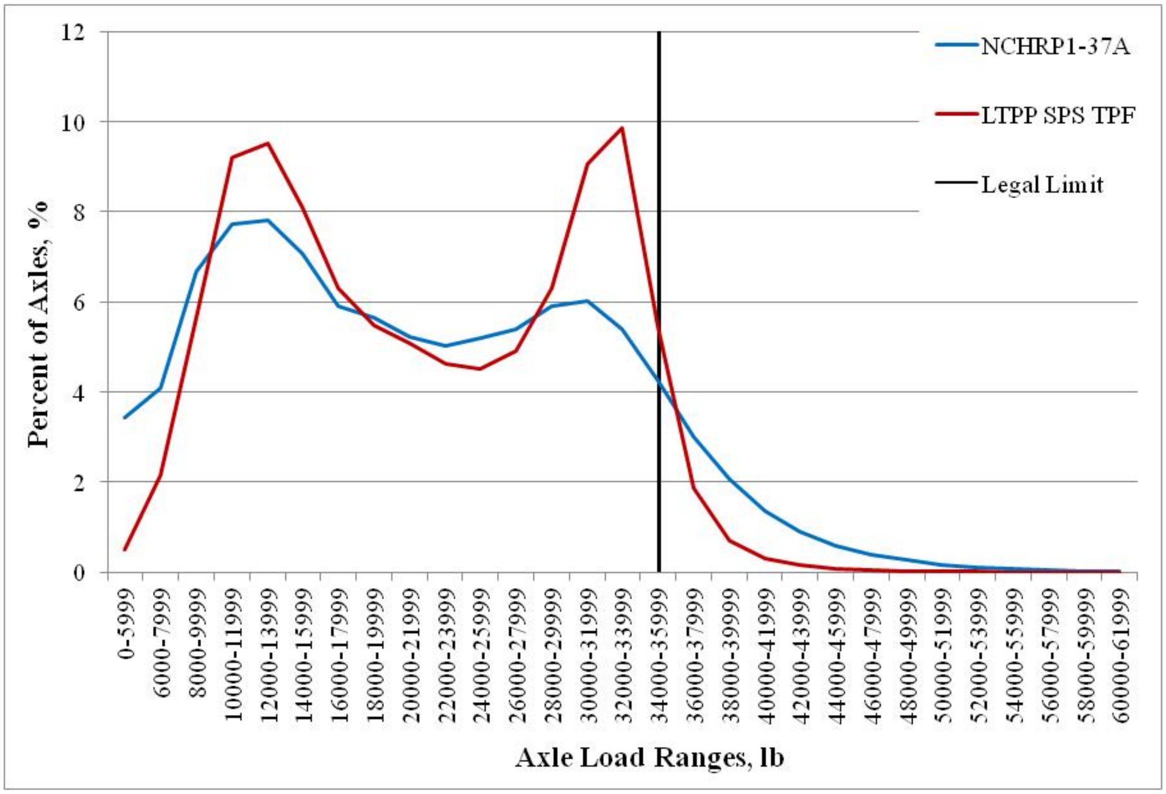

Figure 47. Graph. Comparison of NCHRP 1-37A and SPS TPF default NALS for tandem axles, all classes combined using TTC1.

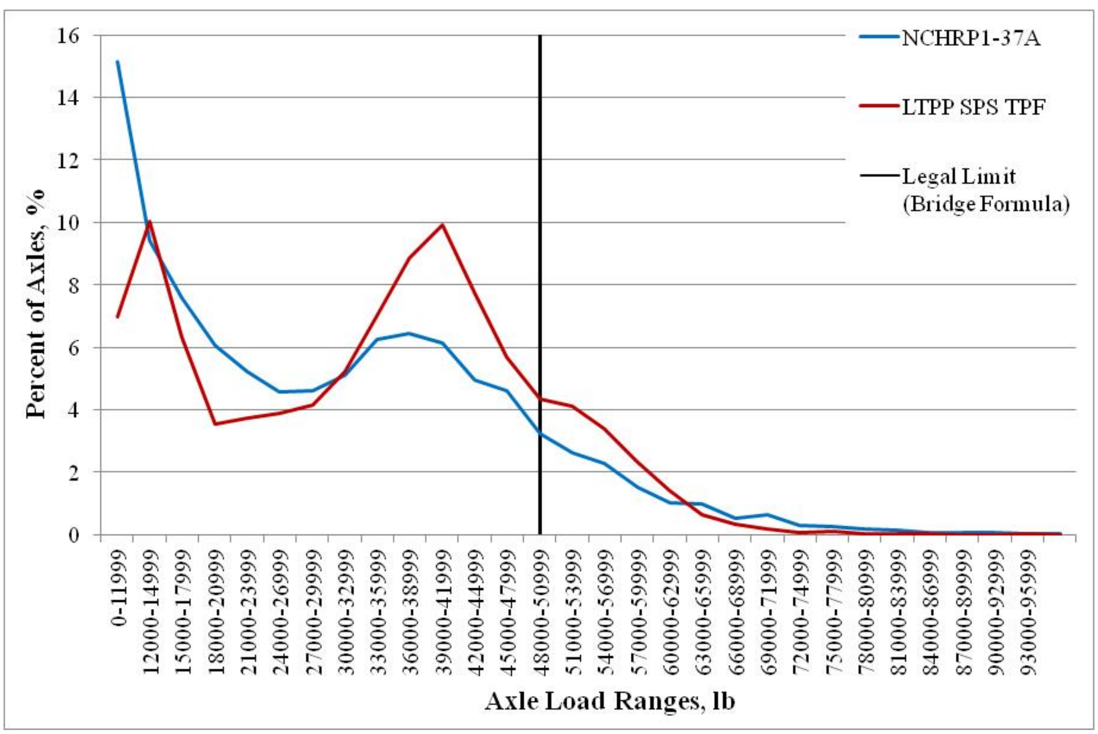

Figure 48. Graph. Comparison of NCHRP 1-37A and SPS TPF default NALS for tridem axles, all classes combined using TTC1.

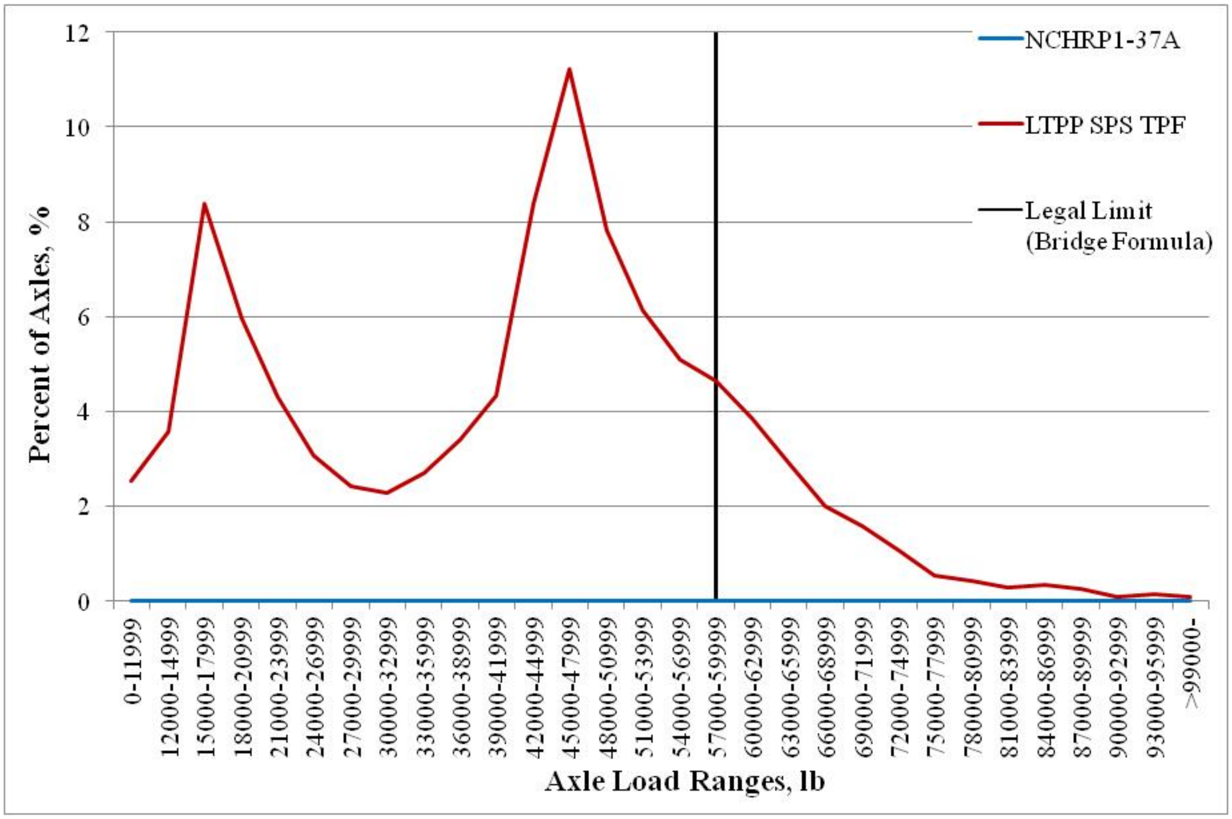

Figure 49. Graph. Comparison of NCHRP 1-37A and SPS TPF default NALS for quad axles, all classes combined using TTC1.

Conclusions from Comparison of Tier 1 and Original NALS Defaults

Visual comparison of SPS TPF-based tier 1 and original NALS defaults revealed that the newly computed defaults had fewer very light and fewer very heavy loads. This is most likely due to the fact that the new defaults were collected with more consistently calibrated WIM equipment. The better calibration of the WIM scales used to develop the new defaults means that fewer very light loads (caused by undercalibrated scales observing light loads) and fewer very heavy loads (caused by overcalibrated scales observing heavy loads) are observed in the new default database. Because the new NALS have smaller percentages of overloads[1], pavement life predicted using the new defaults is likely to be longer than using the old defaults. However, these differences are not expected to be dramatic because the new tier 1 defaults also have a higher percentage of legally loaded heavy axles. Assuming that the new defaults are more accurate and representative of typical loading conditions, a conclusion could be made that pavement designs using the old MEPDG defaults are more conservative, compared to the new defaults. However, from the practical perspective, the differences in the design thickness are not likely to be significant.

[1]Note that the term "overload" as used here means axles that exceed the legal Federal limit. The axles may or may not exceed the legal limit for the State in question or for the load being moved.

AXLE LOADING DEFAULTS REPRESENTING ALTERNATIVE AXLE LOADING CONDITIONS

As shown in chapter 9, MEPDG pavement performance estimates for many pavement design scenarios are sensitive to traffic load inputs. In addition, by analyzing the loading conditions observed in the LTPP SPS TPF study, it is obvious that truck loading characteristics (axle weights) can vary considerably from location to location. It was therefore determined that defaults should be developed that allowed users of the MEPDG and DARWin-ME^{TM} software to select loading conditions for their analyses that could account for these observed differences in traffic loading per vehicle.

Chapter 8 describes the methodology used by the project team to develop NALS groups representing alternative axle loading conditions for each of FHWA's truck classifications based on the SPS TPF data. This section provides description of the defaults developed using this methodology.

Description of NALS Clusters Representing Different Axle Loading Conditions

Table 40 shows the number and categories by weight of the NALS cluster groups representing different axle loading conditions developed based on the SPS TPF data. Table 24 provides a quantitative definition of the descriptive loading conditions used in table 40, developed based on analysis of SPS TPF data. Cluster groups presented in table 40 are based on the clustering analysis of axle loading characteristics presented by mean RPPIF values and the sensitivity tests of the MEPDG described in chapter 9. NALS for each cluster group are available in appendix D. The following paragraphs provide explanations for the information presented in table 40.

Default and Alternative Loading Conditions Observed Nationally

In table 40, the cluster group that contains the largest number of SPS TPF sites is identified as the default for each vehicle class and axle group type. In this case, "default" means that NALS describes the most frequently observed loading condition for a given vehicle class and axle group type among all SPS TPF sites. NALS representing default load spectra groups are recommended for MEPDG use when no information is available that would indicate that a particular vehicle class that is expected to use that roadway will have a loading condition that is either lighter or heavier than what was typically observed for this vehicle class or truck type based on sites included in SPS TPF study. The default condition is not always a moderate condition. It may be the lightest or heaviest condition observed for a particular class of vehicles and type of axle.

In addition to the default loading cluster, groups representing alternative loading conditions were identified to represent NALS that are either lighter or heavier than the default NALS. The decision whether to develop alternative NALS clusters and the number of alternative NALS clusters to create was made individually for each vehicle class and axle group type based upon the following considerations:

- The likelihood that a given axle group type and vehicle class will represent a significant percentage of total loading based on truck and axle group types and their frequency observed in United States.

- The potential for the alternative NALS, when used in place of the default load spectra, to produce significantly different MEPDG outcomes.

- The size of the difference (measured in either RPPIF or in the percentage of heavy axles, with heavy defined as 75 percent of the Federal legal limit or above) in load observed at SPS TPF sites for each type of axle and class of vehicle.

- The availability of data (the number of sites) representing specific axle loading conditions.

Some types of axles carried by some vehicle classes (e.g., single axles within class 6) have fairly consistent loading patterns (relative to pavement performance) and do not need to be represented by multiple load spectra. Other types of axles within specific classes of vehicles exhibit highly variable loading patterns (e.g., class 7 tandem axles); thus, users of the MEPDG software need to be able to choose between multiple loading conditions to represent expected traffic conditions.

Table 40. Summary of NALS cluster groups representing different loading conditions by vehicle class and axle group type.

FHWA Vehicle Class	Axle Group Type	Frequency of Vehicle Class (by Volume) on U.S. Primary Road System	Default NALS Category by Loading Condition	NALS Clusters Observed in Multiple States (Recommended for National Use)					NALS Clusters Observed in a Single State (Recommended for Use in that State on the Roads with Similar Truck Traffic)					Total NALS Clusters by Weight
				Very Light	Light	Moderate	Heavy	Very Heavy	Very Light	Light	Moderate	Heavy	Very Heavy	
4	1	Moderate	Moderate			M								1
	2		Very heavy				H	VH1, VH2						3
5	1	Frequent	Very light	VL						L (FL)				2
	2		Very light	VL										1
6	1	Low or moderate	Moderate			M				L (WA) L (OH)				3
	2		Moderate			M	H						VH(FL)	3
7	1	Low	Heavy			M	H		VL (WA)		M (OH)			4
	2		Heavy			M		VH	VL (WA)		M (OH)	H (OH)	VH (DE), VH (FL1), VH (FL2), VH (TN)	7
	3		Very heavy					VH1, VH2					VH (TN)	3
	4		Very heavy					VH						1
8	1	Moderate	Light		L							H (FL)		2
	2		Light		L					L (AZ)**			VH (FL)	3
9	1	Most frequent	Light		L									1
	2		Heavy			M	H1, H2				M (FL)		VH (AZ)*	5
10	1	Low	Light		L									1
	2		Very heavy			M		VH					VH (AZ)	3
	3		Heavy				H	VH		L (ME)	M (MN)			4
	4		Heavy				H							1
11	1	Low	Moderate		L	M						H (AZ)		3
12	1	Low	Light		L				VL (NM) VL(LA)		M (ME)			4
	2		Light		L									1
13	1	Low	Moderate			M	H				M (OH)**		VH (OH)	4
	2		Very heavy				H	VH1,VH2						3
	3		Very heavy				H	VH1,VH2				H (OH)		4
	4		Very heavy				H	VH				H (OH)**		3

* NALS has very heavy overloads.

**NALS identified as outlier based on classification issue (high percentage of very light weight axles).

Note: Blank cells indicate that no instances were identified.

Loading Conditions Considered Special Cases

In some cases, the analysis of site-specific RANALS also indicated that some States have unique loading conditions that do not cluster with RANALS from other SPS TPF sites. Possible reasons for these unique RANALS include the following:

- Specific commodity hauls and State/local trucking regulations are present that cause unusual truck types and loads unique to that location or State to dominate the loading characteristics of a given vehicle class at the site.

- Vehicle classification algorithm differences implemented on State-installed SPS TPF WIM sites can create some differences in classification outcomes when compared to the LTPP classification scheme, thus causing some differences in the load spectra for those affected classes at those sites.

- Axle weight limits implemented by the State are different from Federal limits.

- The road containing the SPS TPF WIM site may serve commodity movements that result in a larger than usual percentage of trucks operating by permit and thus have axles weighing more than at other sites.

- State trucking regulations differ. This means that some States encourage specific categories and actively discourage others. Consequently, States with unusual truck types (e.g., a few western States allow triple trailer trucks) can exhibit unusual loading conditions for the FHWA categories which contain those specific truck types. (Triple trailer trucks will be classified as class 13, where their presence will generally increase the number of single axles found on class 13 trucks, and will change the load distribution of class 13 single axles.)

To help illustrate the effects of these site, State, or even regional loading conditions, table 40 identifies sites and/or States where loading conditions were either much lighter or much heavier than observed at the remaining SPS TPF sites, as well as States that had significantly different RANALS most likely due to differences in the vehicle classification system being used by the WIM scale collecting the data. These RANALS, identified as special cases are summarized in columns the under “Clusters Observed in a Single State…” heading in table 40. These RANALS are either lighter or heavier than the default loading condition, with a large number of instances occurring where the unique loading condition was much lighter or much heavier than the default. Some of the RANALS were identified as significantly different based on classification. These RANALS had a very high percentage of light axles in the first (lightest) load bin (States: Ohio, Washington, Minnesota, and Maine). This generally means that passenger vehicles pulling trailers have been classified as trucks.

These load spectra are not recommended for general use within the MEPDG procedure unless they represent known loading conditions or a desired hypothetical condition at the site being evaluated. States that had the largest number of RANALS identified as special cases are Arizona, Florida, Ohio, Tennessee, and Washington.

NALS Clusters for Class 9 Tandems

While for many vehicle classes and axle group types there was a clearly defined default loading condition (i.e., the majority of SPS TPF sites had similar axle loading distribution), no single loading condition dominated the class 9 tandem data. The loading condition of class 9 tandems varied between the sites, ranging from moderately loaded conditions (less than 30 percent of tandem axles over 26 kip) to very heavily loaded (up to 70 percent of tandem axles over 26 kip). All of these conditions can be found routinely on U.S. roads. In addition, MEPDG analysis indicated that pavement design outcomes are very sensitive to selection of class 9 tandem NALS primarily because this heavy axle is the most frequently observed on U.S. primary roads. As a result, it has a large impact on pavement design. Therefore, instead of one default loading condition, all three NALS cluster groups develop for class 9 tandems (one moderate and two heavy) are recommended as defaults.

If no site-specific loading information is available, the moderate loading condition is recommended for roads dominated by urban delivery trucking patterns. The heavy #1 condition is recommended for roads where long haul trucking or heavy directional hauls overlap with urban delivery movements. The heavy #2 condition is recommended for rural roads where almost all class 9 truck traffic is oriented toward long haul traffic.

Characteristics of NALS Clusters Representing Different Axle Loading Conditions

To help characterize the NALS representing default and alternative axle loading conditions so that pavement designers can more easily choose between alternative loading conditions, several statistical parameters were computed. Table 41 shows average RPPIF values computed for the default and alternative loading conditions. Table 42 shows the average percentage of heavy axles (i.e., the percentage of axles that are at or above 75 percent of the Federal legal weight limit) computed for different NALS clusters.

Table 41. Average RPPIF values computed for different NALS clusters.

FHWA Vehicle Class	Axle Group Type	Default NALS Category by Weight	Observed in Multiple States (Recommended for National Use)					Observed in a Single State (Recommended for Use in that State on the Roads with Similar Trucks)				
			Very Light	Light	Moderate	Heavy	Very Heavy	Very Light	Light	Moderate	Heavy	Very Heavy
4	1	Moderate			0.20							
	2	Very heavy				0.42	0.56, 0.69					
5	1	Very light	0.13						0.13 (FL)			
	2	Very light	0.04									
6	1	Moderate			0.17				0.08 (WA), 0.1 (OH)			
	2	Moderate			0.24	0.43						0.63 (FL)
7	1	Heavy			0.26	0.41		0.04 (WA)		0.18 (OH)		
	2	Heavy			0.24		0.85	0.03 (WA)		0.29 (OH)	0.41 (OH)	2.42 (DE) 3.48 (FL1) 6.11 (FL2) 9.94 (TN)
	3	Very heavy					0.65, 1.55					2.25 (TN)
	4	Very heavy					0.78					
8	1	Light		0.11							0.34 (FL)	
	2	Light		0.10					0.09 (AZ)**			1.09 (FL)
9	1	Light		0.14								
	2	Heavy			0.30	0.38, 0.48				0.27 (FL)		0.68 (AZ)*
10	1	Light		0.12								
	2	Very heavy			0.18		0.52					1.04 (AZ)
	3	Heavy				0.35	0.56		0.09 (ME)	0.18 (MN)		
	4	Heavy				0.46						
11	1	Moderate		0.08	0.19						0.38 (AZ)	
12	1	Light		0.12				0.03 (NM), 0.04 (LA)		0.25 (ME)		
	2	Light		0.14								
13	1	Moderate			0.18	0.32				0.21 (OH)**		0.55 (OH)
	2	Very heavy				0.49	0.87, 1.46					
	3	Very heavy				0.47	1.12, 1.76				0.5 (OH) 0.44 (OH)	
	4	Very heavy				0.43	0.83				0.46 (OH)**	

* NALS has very heavy overloads; **NALS identified as outlier based on classification issue (high percentage of very lightweight axles). Blank cells indicate that no instances were identified.

Table 42. Average percentages of heavy axles computed for different NALS clusters.

FHWA Vehicle Class	Axle Group Type	Default NALS Category by Weight	Observed in Multiple States (Recommended for National Use)					Observed in a Single State (Recommended for Use in that State on the Roads with Similar Trucks)				
			Very Light	Light	Moderate	Heavy	Very Heavy	Very Light	Light	Moderate	Heavy	Very Heavy
4	1	Moderate			14							
	2	Very heavy				46	68, 85					
5	1	Very light	3						8 (FL)			
	2	Very light	0									
6	1	Moderate			10				3 (WA), 3 (OH)			
	2	Moderate			20	30						36 (FL)
7	1	Heavy			26	52		4 (WA)		18 (OH)		
	2	Heavy			22		64	3 (WA)			28 (OH)	81 (DE), 91 (TN), 98 (FL2), 100 (FL1)
	3	Very heavy					55, 96					98 (TN)
	4	Very heavy					31					
8	1	Light		9							31 (FL)	
	2	Light		5					6 (AZ)			56 (FL)
9	1	Light		9								
	2	Heavy			31	39, 49				22 (FL)		70 (AZ)
10	1	Light		4								
	2	Very Heavy			15		45					38 (AZ)
	3	Heavy				23	43***		5 (ME)*	9 (MN)*		
	4	Heavy				7						
11	1	Moderate		5	18						53 (AZ)	
12	1	Light		7				1 (NM), 3 (LA)		25 (ME)		
	2	Light		2								
13	1	Moderate			11	29***				21 (OH)		48 (OH)
	2	Very heavy				37	54, 58					
	3	Very heavy				28	76, 86				24 (OH1) 31 (OH2)	
	4	Very heavy				14	39				21 (OH)	

* NALS has very heavy overloads; **NALS identified as outlier based on classification issue (high percentage of very light weight axles). ***Outlier values based on rules in table 24. Blank cells indicate that no instances were identified.

Use of Loading Cluster NALS Defaults at the Global and Local Levels

Understanding of Local Loading Conditions

Before selection of the loading cluster NALS defaults, it is recommended that every effort is made to understand the expected traffic loading pattern at the site for which default NALS selections are being made. Dominant heavy vehicle classes (FHWA classes 4 and 6 through 13) should be identified and descriptive traffic loading conditions (see table 24) for the dominant heavy vehicle classes should be established.

For the majority of the LTPP sites (and a majority of U.S. primary roads), class 9 is the dominant heavy vehicle type. Therefore, special effort should be made for identifying loading conditions for class 9 vehicles. Class 5 vehicles frequently are more prevalent but are not heavy enough to make significant contribution to total traffic loading and may be excluded from determination of the dominant heavy vehicle classes, unless local knowledge exists of heavier-than-usual class 5 vehicles at the site.

If a State's truck sizes and weight laws allow loads exceeding Federal regulations 23 U.S.C. 127 and 23 CFR 658, and the site has a low percentage of interstate traffic, there is a higher likelihood of heavier-than-typical NALS, especially if there are heavy commodities being transported by certain vehicle classes.[19,20]

In some instances, historical WIM data or recently collected portable WIM data may be available for the site. These data may not be accurate enough to compute NALS for the site but may be useful in establishing a descriptive loading condition.

Table 40 provides information that could be used for evaluating the relative importance of NALS associated with different vehicle classes and axle group types for pavement design. For example, the combination of a frequently observed vehicle class with a heavy or very heavy axle group type is likely to produce the most impact on pavement design outcome, and vice versa. Accurate selection of NALS for these classes and axles is more important compared to light and/or infrequent vehicles classes.

Decision Tree for Selecting Default NALS Clusters for Pavement Design

Once descriptive loading categories are determined for the dominant vehicle classes, default NALS corresponding to the identified loading categories could be selected from the LTPP database. If no local knowledge exists, either tier 1 NALS defaults or tier 2 NALS defaults representing typical conditions could be used. For a more conservative analysis, tier 2 NALS defaults representing heavy conditions could be used. MEPDG analysis using different selection of default NALS clusters could be used to assess the effect of different NALS defaults selection on pavement design and analysis outcomes.

The following decision tree could be used for selecting default NALS for a given pavement design site (default NALS clusters should be assigned by vehicle class and axle group type):

1. Identify one or more dominant heavy vehicle class by weight at the site using the following guidance:

    - If this is FHWA vehicle class 4 or 6–13 and represents 30 percent or more of all vehicle classes 4–13.
    - If this vehicle class carries 25 percent or more of total load.
    - Class 5 vehicles are usually too light and should be excluded from evaluation unless this vehicle carries 25 percent or more of total load.

2. Identify if the dominant truck class is likely to have unusually heavy loads if one or more of the following applies:

    - High percentages of loads close to the Federal legal load limit (30,000 to 34,000 lb for tandems).
    - High percentages of loads above the Federal legal load limit due to lack of enforcement (> 34,000 lb for tandems).
    - High percentage of loads with permits above the Federal legal load limit (>34,000 lb for tandems).
    - Overloads due to illegal activity.
    - Legal load limits on this road are above Federal legal load limits.
    - If one or more of these applies, assign the heaviest default NALS cluster available for this class.

3. If no unusually heavy conditions are identified for the dominant class, use other means to identify the descriptive loading category defined in table 40 and table 24. This could include the following:

    - Review of historical loading data, such as axle load spectra or historical ESAL/ truck values.
    - Short-term portable WIM data collection to identify rough percentage of heavy loads per table 24.
    - Interview personnel from transportation planning and freight movement departments.
    - For class 9, the moderate loading condition is recommended for roads dominated by urban delivery trucking patterns. The heavy #1 loading condition is recommended for roads where long haul trucking or heavy directional hauls overlap with urban delivery

movements. The heavy #2 loading condition is recommended for rural roads where almost all Class 9 truck traffic is oriented toward long haul traffic.

4. Based on findings of the expected loading condition for dominant vehicle classes, assign default NALS cluster code using values in table 40 and table 24 as guidance.

5. In addition to dominant heavy vehicle classes, identify any other classes that are likely to routinely carry loads above Federal legal load limits. Assign the heaviest available default NALS cluster for identified classes.

6. Assign typical default NALS cluster for all other classes and axle group types.

Limitations of Loading Cluster NALS Defaults

Axle loading cluster defaults were developed based on the load spectra data from 26 WIM sites. The small number of SPS TPF WIM sites limits the geographic scope of the weight data, which in turn means that this table is not statistically representative of all roads in the country. It is not representative of specific roads in specific States where loading conditions are dominated by State regulations or specific commodity movements that differ from national norms. When State or site-specific trucking movements dominate the use of a road, those roadways may experience loading conditions that are different than those observed in the SPS TPF data.

SPS TPF Site Membership in Different NALS Loading Clusters

Table 43 provides information about different axle loading conditions observed at individual SPS TPF sites by vehicle class and axle group type. Cells in table 43 are populated with an abbreviated NALS cluster name to indicate SPS TPF site cluster membership for each vehicle class and axle group type. Information included in this table may be useful in identifying axle loading conditions for locations and roads related to the SPS TPF sites. In addition, this table could be used to identify locations where specific axle loading conditions were observed (very light, light, moderate, heavy, and very heavy). For example, site 4-0100 in Arizona experienced much more frequent heavy or very heavy loading compared to site 4-0200 in the same State.

Table 43. Summary of SPS TPF sites membership in different NALS clusters.

LTPP Site ID	Class																								
	4		5		6		7				8		9		10				11	12		13			
	Axle Type																								
	1	2	1	2	1	2	1	2	3	4	1	2	1	2	1	2	3	4	1	1	2	1	2	3	4
10-0100	M(T)	VH2	VL (T)	N/A	M(T)	H	H(T)	SP VH(DE)	VH2	N/A	L(T)	L(T)	L(T)	H2	L(T)	VH(T)	VH	N/A	L	M(T)	L(T)	M(T)	VH1(T)	N/A	H
12-0100	M(T)	H	SP VL (FL)	N/A	M(T)	SP VH (FL)	H(T)	SP VH (FL2)	VH2	N/A	SP H (FL)	SP VH (FL)	L(T)	H2	L(T)	VH(T)	VH	N/A	M(T)	M(T)	L(T)	M(T)	H	VH1(T)	N/A
12-0500	M(T)	H	VL (T)	N/A	M(T)	H	H(T)	SP VH (FL1)	VH2	N/A	L(T)	L(T)	L(T)	SP M (FL)	L(T)	VH(T)	H(T)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
17-0600	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	M	M	VH1(T)	N/A	L(T)	L(T)	L(T)	H2	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	VH(T)
18-0600	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	H	H(T)	N/A	VH2	VH(T)	L(T)	L(T)	L(T)	M	L(T)	VH(T)	VH	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	N/A
20-0200	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	H(T)	VH(T)	VH1(T)	N/A	L(T)	L(T)	L(T)	H1	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	VH(T)
22-0100	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	H	H(T)	N/A	VH1(T)	N/A	L(T)	L(T)	L(T)	M	L(T)	VH(T)	VH	N/A	M(T)	SP VL(LA)	L(T)	M(T)	VH2	VH2	VH(T)
23-0500	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	H(T)	N/A	VH1(T)	N/A	L(T)	L(T)	L(T)	M	L(T)	M	SP L (ME)	N/A	M(T)	SP M (ME)	L(T)	M(T)	VH2	VH2	VH(T)
24-0500	M(T)	VH1(T)	VL (T)	N/A	M(T)	M(T)	M	VH(T)	VH1(T)	VH(T)	L(T)	L(T)	L(T)	M	L(T)	VH(T)	H(T)	N/A	L	M(T)	N/A	M(T)	VH1(T)	VH1(T)	H
26-0100	M(T)	VH1(T)	VL (T)	N/A	M(T)	M(T)	H(T)	M	VH1(T)	VH(T)	L(T)	L(T)	L(T)	M	L(T)	VH(T)	H(T)	H(T)	M(T)	M(T)	L(T)	H	H	H	VH(T)
27-0500	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	M	VH(T)	VH1(T)	VH(T)	L(T)	L(T)	L(T)	M	L(T)	M	SP M(MN)	N/A	L	N/A	N/A	M(T)	VH1(T)	VH1(T)	H
35-0100	M(T)	H	VL (T)	VL(T)	M(T)	M(T)	M	VH(T)	N/A	N/A	L(T)	L(T)	L(T)	M	L(T)	VH(T)	H(T)	N/A	L	SP VL(NM)	L(T)	M(T)	H	VH1(T)	N/A
35-0500	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	M	N/A	N/A	N/A	L(T)	L(T)	L(T)	H2	L(T)	VH(T)	VH	N/A	M(T)	M(T)	L(T)	H	VH1(T)	VH1(T)	N/A
39-0100	M(T)	VH1(T)	VL (T)	N/A	M(T)	M(T)	SP M (OH)	SP H (OH)	VH1(T)	VH(T)	L(T)	L(T)	L(T)	H1	L(T)	VH(T)	VH	H(T)	M(T)	M(T)	L(T)	SP VH (OH)	VH1(T)	SP H(OH1)	SP H (OH)
39-0200	M(T)	VH1(T)	VL (T)	N/A	SP L (OH)	M(T)	SP M (OH)	SP M (OH)	VH1(T)	VH(T)	L(T)	L(T)	L(T)	M	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	SP M(OH)	H	SP H(OH2)	N/A
4-0100	M(T)	VH2	VL (T)	N/A	M(T)	H	H(T)	VH(T)	N/A	N/A	L(T)	SP L (AZ)	L(T)	SP VH (AZ)	L(T)	SP VH (AZ)	VH	N/A	SP H (AZ)	M(T)	N/A	H	VH2	N/A	N/A
4-0200	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	M	N/A	VH1(T)	VH(T)	L(T)	L(T)	L(T)	H2	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	H
42-0600	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	H(T)	N/A	VH2	N/A	L(T)	L(T)	L(T)	H1	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	VH(T)
47-0600	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	M	SP VH (TN)	SP VH (TN)	N/A	L(T)	L(T)	L(T)	H1	L(T)	VH(T)	VH	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	VH(T)
48-0100	M(T)	VH1(T)	VL (T)	N/A	M(T)	M(T)	H(T)	N/A	VH1(T)	N/A	L(T)	L(T)	L(T)	H2	L(T)	VH(T)	VH	N/A	M(T)	M(T)	L(T)	M(T)	H	VH1(T)	VH(T)
5-0200	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	M	VH(T)	VH1(T)	VH(T)	L(T)	L(T)	L(T)	H2	L(T)	VH(T)	VH	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	VH(T)
51-0100	M(T)	VH1(T)	VL (T)	N/A	M(T)	M(T)	M	N/A	VH1(T)	VH(T)	L(T)	L(T)	L(T)	H1	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	VH1(T)	VH1(T)	H
53-0200	M(T)	VH1(T)	VL (T)	N/A	SP L (WA)	M(T)	SP VL (WA)	SP VL (WA)	VH1(T)	N/A	L(T)	L(T)	L(T)	H2	L(T)	VH(T)	H(T)	H(T)	M(T)	M(T)	L(T)	M(T)	H	H	H
55-0100	M(T)	H	VL (T)	VL(T)	M(T)	M(T)	H(T)	n/a	VH1(T)	VH(T)	L(T)	L(T)	L(T)	H1	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	H	VH1(T)	VH(T)
6-0200	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	H(T)	VH(T)	VH1(T)	N/A	L(T)	L(T)	L(T)	H1	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	H	N/A	N/A
8-0200	M(T)	VH1(T)	VL (T)	VL(T)	M(T)	M(T)	H(T)	VH(T)	VH1(T)	N/A	L(T)	L(T)	L(T)	M	L(T)	VH(T)	H(T)	N/A	M(T)	M(T)	L(T)	M(T)	H	VH1(T)	H
Total	**26**	**26**	**26**	**15**	**26**	**26**	**26**	**17**	**23**	**10**	**26**	**26**	**26**	**26**	**26**	**26**	**26**	**3**	**25**	**24**	**22**	**25**	**25**	**22**	**18**

VL = Very light, L = Light, M = Moderate, H = Heavy, VH = Very Heavy, and T = Typical.
N/A = Not applicable.

MEPDG COMPARISON OF NCHRP 1-37A AND LTPP SPS TPF AXLE LOADING DEFAULTS

Analysis Approach

An analysis was used to compare MEPDG outputs using the original defaults and the new alternate defaults. A set of rigid and flexible pavement designs for RI and ROPA roads was developed, and pavement performance was analyzed using the NCHRP 1-37A defaults and the new SPS TPF defaults, as follows:

- NCHRP 1-37A.[(3)]
- SPS TPF tier 1 NALS.
- SPS TPF tier 2 lightest NALS (the lightest available tier 2 NALS cluster was selected for each vehicle class and axle group type, excluding special cases NALS).
- SPS TPF tier 2 typical (the tier 2 NALS cluster identified as "typical" (T) was selected for each vehicle class and axle group type).
- SPS TPF tier 2 heaviest (the heaviest available tier 2 NALS cluster was selected for each vehicle class and axle group type, excluding special cases NALS).

VCDs and AADTT values characteristic to RI and ROPA roads were used for the analyses. MEPDG VCD defaults for TTC1 were used for RI conditions, and TTC6 was used for ROPA. All four LTPP climatic regions were included in the analysis.

Three flexible pavement failure modes were investigated for flexible pavements: rutting, bottom-up cracking, and top-down cracking. For JPCP rigid pavements, slab cracking slab cracking and joint faulting failure modes were investigated. These failure modes were found most critical using MEPDG pavement performance prediction models calibrated to global conditions.

A summary of pavement design inputs is provided in table 44.

Table 44. Pavement structure for NALS defaults comparison.

Road Type and Traffic	Climatic Region			
	Dry-Freeze	Dry-No-Freeze	Wet-Freeze	Wet-No-Freeze
Flexible Design for Top-Down Cracking Investigation				
RI, AADTT = 2,000, TTC 1	AC thickness: 9 inches Binder grade: 76-22	AC thickness: 8.5 inches Binder grade: 82-22	AC thickness: 8.5 inches Binder grade: 76-22	AC thickness: 9 inches Binder grade: 76-22
	Binder content: 10 percent	Binder content: 9 percent	Binder content: 10 percent	Binder content: 10 percent
	Air voids: 5 percent	Air voids: 4 percent	Air voids: 5 percent	Air voids: 5 percent
	Base type/thickness: Crushed stone/16 inches Modulus: 33,300 psi	Base type/thickness: Crushed stone/12 inches Modulus: 28,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 32,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 33,300 psi
	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi
ROPA, AADTT = 500, TTC 6	AC thickness: 7.5 inches Binder grade: 70-22	AC thickness: 7.5 inches Binder grade: 70-22	AC thickness: 7 inches Binder grade: 70-22	AC thickness: 7.5 inches Binder grade: 70-22
	Binder content: 10 percent	Binder content: 10 percent	Binder content: 10 percent	Binder content: 10 percent
	Air voids: 5 percent	Air voids: 5 percent	Air voids: 5 percent	Air voids: 5 percent
	Base type/thickness: Crushed stone/8 inches Modulus: 32,800 psi	Base type/thickness: Crushed stone/8 inches Modulus: 30,400 psi	Base type/thickness: Crushed stone/8 inches Modulus: 31,500 psi	Base type/thickness: Crushed stone/8 inches Modulus: 33,600 psi
	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi
Flexible Design for Bottom-Up Cracking Investigation				
RI, AADTT =2000, TTC 1	AC layer 1: 2 inches Binder grade: 76-22	AC Layer 1: 2 inches Binder grade: 76-22	AC Layer 1: 2 inches Binder grade: 76-22	AC Layer 1: 2 inches Binder grade: 76-22
	Binder content: 11 percent	Binder content: 11 percent	Binder content: 11 percent	Binder content: 11 percent
	Air voids: 5.5 percent	Air voids: 5.5 percent	Air voids: 5.5 percent	Air voids: 5.5 percent
	AC layer 2: 5.5 inches	AC layer 2: 5.5 inches	AC layer 2: 5 inches	AC layer 2: 5.5 inches
	Binder grade: 70-22	Binder grade: 70-22	Binder grade: 64-22	Binder grade: 64-22
	Binder content: 8	Binder content: 8	Binder content: 8	Binder content: 8
	Air voids: 8	Air voids: 8	Air voids: 8	Air voids: 8
	Base type/thickness: Crushed stone/12 inches Modulus: 27,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 26,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 32,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 31,000 psi
	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi
ROPA, AADTT = 500, TTC 6	AC layer 1: 2 inches Binder grade: 76-22	AC layer 1: 2 inches Binder grade: 76-22	AC Layer 1: 2 inches Binder grade: 76-22	AC Layer 1: 2 inches Binder grade: 76-22
	Binder content: 11 percent	Binder content: 11 percent	Binder content: 11 percent	Binder content: 11 percent
	Air voids: 5.5 percent	Air voids: 5.5 percent	Air voids: 5.5 percent	Air voids: 5.5 percent
	AC layer 2: 3.5 inches	AC layer 2: 3.5 inches	AC layer 2: 3 inches	AC layer 2: 3.5 inches
	Binder grade: 64-22	Binder grade: 64-22	Binder grade: 64-22	Binder grade: 64-22
	Binder content: 8	Binder content: 8	Binder content: 8	Binder content: 8
	Air voids: 8	Air voids: 8	Air voids: 8	Air voids: 8
	Base type/thickness: Crushed stone/8 inches Modulus: 26,000 psi	Base type/thickness: Crushed stone/8 inches Modulus: 23,000 psi	Base type/thickness: Crushed stone/8 inches Modulus: 30,000 psi	Base type/thickness: Crushed stone/8 inches Modulus: 26,000 psi
	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi	Subgrade: A-1-b, 26,500 psi

Flexible Design for Rutting Investigation:				
RI, AADTT =2000, TTC 1	AC thickness: 11.5 inches Binder grade: 64-22	AC thickness: 10 inches Binder grade: 76-22	AC thickness: 9 inches Binder grade: 64-22	AC thickness: 11 inches Binder grade: 64-22
	Binder content: 10 percent	Binder content: 10 percent	Binder content: 10 percent	Binder content: 10 percent
	Air voids: 5 percent	Air voids: 5 percent	Air voids: 5 percent	Air voids: 5 percent
	Base type/thickness: Crushed stone/12 inches Modulus: 30,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 30,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 30,000 psi	Base type/thickness: Crushed stone/12 inches Modulus: 34,000 psi
	Subgrade: A-7-6, 12,500 psi	Subgrade: A-7-5, 11,300 psi	Subgrade: A-7-6, 8300 psi	Subgrade: A-7-6, 2,000 psi
Rigid Design for Slab Cracking Investigation:				
RI, AADTT =2000, TTC 1	JPCP thickness: 11 inches	JPCP thickness: 11 inches	JPCP thickness: 10.5 inches	JPCP thickness: 10.5 inches
	28-day PCC modulus of rupture = 650 psi	28-day PCC modulus of rupture = 650 psi	28-day PCC modulus of rupture = 650 psi	28-day PCC modulus of rupture = 650 psi
	Base: Cement stabilized, 6 inches, 800,000 psi	Base: Lean concrete, 6 inches, 2,000,000 psi	Base: Cement stabilized, 6 inches, 1,000,000 psi	Base: Cement stabilized, 6 inches, 100,000 psi
	Subgrade: A-6, 17,000 psi	Subgrade: A-6, 14,000 psi	Subgrade: A-6, 14,000 psi	Subgrade: A-6, 14,000 psi
	Dowels: Yes	Dowels: Yes	Dowels: Yes	Dowels: Yes
	Erodibility Index: Very erosion resistant (2)	Erodibility Index: Very erosion resistant (2)	Erodibility Index: Very erosion resistant (2)	Erodibility Index: Very erosion resistant (2)
Rigid Design for Slab Cracking and Joint Faulting Investigation:				
ROPA, AADTT =700, TTC 2	JPCP thickness: 9.5 inches, 28-day PCC modulus of rupture = 650 psi	JPCP thickness: 10 inches, 28-day PCC modulus of rupture = 650 psi	JPCP thickness: 10 inches, 28-day PCC modulus of rupture = 650 psi	JPCP thickness: 10 inches, 28-day PCC modulus of rupture = 650 psi
	Base: Subgrade cement, 6 inches, 500,000 psi	Base: Subgrade cement, 6 inches, 500,000 psi	Base: Subgrade cement, 6 inches, 1,000,000 psi	Base: Subgrade cement, 6 inches, 500,000 psi
	Subgrade: A-6, 17,000 psi	Subgrade: A-6, 14,000 psi	Subgrade: A-6, 12,000 psi	Subgrade: A-6, 14,000 psi
	Dowels: Yes	Dowels: Yes	Dowels: Yes	Dowels: Yes
	Erodibility Index: Erosion resistant (3)	Erodibility Index: Fairly erodible (4)	Erodibility Index: Erosion resistant (3)	Erodibility Index: Erosion resistant (3)

To compare MEPDG outcomes using different loading defaults, a pavement was first designed using NCHRP 1-37A NALS and APC coefficients, and then that design was reanalyzed using the same inputs, except for NALS and APC coefficients, which were substituted with the SPS TPF default values. Both 15- and 20-year designs were used for flexible and rigid pavements, respectively, based on observed average pavement service life for LTPP sections. MEPDG results computed for 90 percent design reliability (default MEPDG option) were obtained for each default and analyzed.

A summary of MEPDG outcomes based on the most critical design for each failure mode is provided in table 45. The table shows differences in predicted pavement service life and structural thickness using new defaults, compared to values predicted using old defaults. For the majority of defaults and pavement designs, new defaults resulted in longer lives and thinner pavements. The following sections describe in more detail a comparison of MEPDG results using NCHRP 1-37A and results when using LTPP SPS TPF defaults for NALS and APC coefficient for different road types and pavement failure modes.

Table 45. MEPDG results of pavement life and thickness differences using different NALS defaults.

Distress Type	Predicted Life Difference with NCHRP 1-37A NALS Default (Percent)				Predicted Thickness Difference with NCHRP 1-37A NALS Default (Inches)			
	Tier 1	Tier 2 Lightest	Tier 2 Typical	Tier 2 Heaviest	Tier 1	Tier 2 Lightest	Tier 2 Typical	Tier 2 Heaviest
Rigid Pavements								
RI slab cracking	12	41	20	-9	-0.1	-0.4	-0.1	0.1
ROPA slab cracking	23	50	29	-11	-0.2	-0.5	-0.2	0.2
ROPA faulting	-3	5.8	-3	-9.4	0.1	-0.6	0.1	0.3
Flexible Pavements								
RI rutting	14	33	21	5	-0.8	-1.7	-1.2	-0.3
RI top-down cracking	19	52	32	6	-0.3	-0.5	-0.3	0
RI bottom-up cracking	12	33	19	5	-0.2	-0.6	-0.3	-0.1
ROPA top-down cracking	19	51	30	4	-0.3	-0.8	-0.4	0
ROPA bottom-up cracking	13	38	25	6	-0.2	-0.5	-0.3	0

Comparison for Flexible Pavements Designed for RIs

NCHRP 1-37A Versus LTPP SPS TPF Tier 1 NALS Defaults

The results of analyses for flexible pavements designed for RI indicate that an increase in service life prediction close to 3 years (20 percent of service life) is expected if the new tier 1 loading defaults are used instead of the original MEPDG loading defaults. In the case of cracking, this translates up to a 0.3-inch difference in the thickness of the hot mix asphalt (HMA) layer, and in the case of rutting, this could lead to a 1.1-inch thickness difference. The tier 1 loading defaults result in thinner pavements. From a pavement thickness design perspective, HMA thickness differences less than 0.5 inch are not significant. Based on observed thickness differences from MEPDG analysis, use of NCHRP 1-37A or LTPP SPS TPF tier 1 defaults is not likely to result in significant design thickness differences for pavements that are likely to fail in cracking mode but could produce significantly different design outcomes for pavements that are likely to fail in rutting mode. However, rutting isn’t likely to be mitigated just by the increase in AC thickness. As a result, the significance of the different defaults may not be as critical. This conclusion applies to all four climatic zones.

NCHRP 1-37A Versus LTPP SPS TPF Tier 2 NALS Defaults

All tier 2 NALS defaults resulted in longer service life predictions than the NCHRP 1-37A NALS defaults. Service life prediction for the tier 2 Lightest NALS was up to 52 percent longer compared to the NCHRP 1-37A NALS defaults. This difference is considered of practical significance. Service life prediction for the tier 2 typical group was up to 32 percent longer compared to the NCHRP 1-37A NALS defaults. This difference also is considered of practical significance. Service life prediction for the tier 2 heaviest group was just 6 percent longer compared to the NCHRP 1-37A NALS defaults and is not considered of practical significance. All tier 2 loading defaults resulted in thinner pavements. For the tier 2 lightest NALS, AC thickness difference was over 0.5 inch for all distress modes: 1.7 inch for rutting, 0.5 inch for bottom-up cracking, and 0.6 inch for top-down cracking. These differences are considered of practical significance. For the tier 2 typical NALS, AC thickness difference was over 0.5 inch for the rutting distress mode only (1.2 inches); the other distress modes resulted in insignificant differences (0.3 inch or less). For the tier 2 heaviest NALS, all AC thickness differences were between zero and 0.3 inch and are considered insignificant. MEPDG predictions were very similar using the NCHRP 1-37A and SPS TPF tier 2 heaviest NALS defaults.

Comparison for Flexible Pavements Designed for ROPA Roads

NCHRP 1-37A Versus LTPP SPS TPF Tier 1 NALS Defaults

The results of analyses for flexible pavement designed for ROPA roads indicate that an increase in service life prediction close to 3 years (20 percent of service life) is expected if the new tier 1 loading defaults are used instead of the original MEPDG loading defaults. In the case of cracking modes, this translates up to a 0.3-inch HMA thickness difference. The tier 1 loading defaults result in thinner pavements. From a pavement thickness design perspective, HMA thickness differences less than 0.5 inch are not significant. Based on observed thickness differences from MEPDG analysis, use of the NCHRP 1-37A or LTPP SPS TPF tier 1 defaults is not likely to result in significant design thickness differences for pavements that are likely to fail in cracking mode. This conclusion applies to all four climatic zones.

NCHRP 1-37A Versus LTPP SPS TPF Tier 2 NALS Defaults

All tier 2 NALS defaults resulted in longer service life prediction than the NCHRP 1-37A NALS defaults. Service life prediction for the tier 2 lightest NALS was up to 51 percent longer compared to the NCHRP 1-37A NALS defaults. This difference is considered of practical significance. Service life prediction for the tier 2 typical group was up to 30 percent longer compared to the NCHRP 1-37A NALS defaults. This difference also is considered of practical significance. Service life prediction for the tier 2 heaviest group was just 6 percent longer compared to NCHRP 1-37A NALS defaults, which is not considered of practical significance. Tier 2 lightest and typical loading defaults resulted in thinner pavements (up to 0.8 and 0.4 inch difference, respectively). Tier 2 heaviest loading defaults resulted in the same thickness. Only for the tier 2 lightest NALS the AC thickness difference was over 0.5 inch and considered significant from a practical perspective. MEPDG predictions were found very similar using the NCHRP 1-37A and SPS TPF tier 2 heaviest NALS defaults.

Comparison for Rigid Pavements Designed for RIs

NCHRP 1-37A Versus LTPP SPS TPF Tier 1 NALS Defaults

The results of analyses for rigid pavements designed for RI indicate that an increase in service life prediction up to 2.4 years (12 percent) is expected if SPS TPF tier 1 loading defaults are used instead of the original MEPDG loading defaults. This translates into a 0.2-inch PCC slab thickness difference. The tier 1 loading defaults result in thinner pavements. From a pavement thickness design perspective, PCC slab thickness differences less than 0.5 inch are not significant. Based on observed thickness differences from MEPDG analysis, using either the NCHRP 1-37A or LTPP SPS TPF tier 1 defaults is not likely to result in significant design thickness differences for JPCP designed for typical RI conditions. This conclusion applies to all four climatic zones.

NCHRP 1-37A Versus LTPP SPS TPF Tier 2 NALS Defaults

The tier 2 lightest and typical NALS defaults resulted in longer service life predictions, while the tier 2 heaviest NALS defaults resulted in shorter service life prediction compared to the NCHRP 1-37A NALS defaults. Service life prediction for the tier 2 lightest NALS was up to 41 percent longer than the NCHRP 1-37A NALS defaults. This difference is considered of practical significance. Service life prediction for the tier 2 typical group was up to 20 percent longer than the NCHRP 1-37A NALS defaults. This difference also is considered of practical significance. Service life prediction for the tier 2 heaviest group was up to 9 percent shorter than the NCHRP 1-37A NALS defaults, but this difference is not considered of practical significance. The tier 2 lightest and typical loading defaults resulted in thinner pavements (up to 0.4- and 0.1-inch difference, respectively). The tier 2 heaviest loading defaults resulted in a slightly thicker PCC slab (0.1 inch). All PCC thickness differences were less than 0.5 inch and considered insignificant from a practical perspective; however, for the tier 2 lightest NALS defaults, the difference in thickness (0.4 inch) was close to 0.5 inch, and for some designs significant differences are possible. MEPDG predictions were found very similar when using the NCHRP 1-37A and SPS TPF tier 2 heaviest NALS defaults.

Comparison for Rigid Pavements Designed for ROPA Roads

NCHRP 1-37A Versus LTPP SPS TPF Tier 1 NALS Defaults

For designs that fail in faulting mode, the results of analyses indicate a slight decrease in service life prediction if the new tier 1 loading defaults are used instead of the original MEPDG loading defaults—up to 6 months for 20-year design life (2.5 percent). Based on observed differences, using either the NCHRP 1-37A or LTPP SPS TPF tier 1 defaults is not likely to result in significant design differences for pavements that are likely to fail in faulting mode under typical ROPA traffic conditions. This conclusion applies to all four climatic zones.

For designs that fail in cracking mode, the analysis results indicate an increase in service life prediction up to 4.6 years (over 23 percent of service life) is expected if the tier 1 loading defaults are used instead of the original MEPDG loading defaults. This difference in pavement design life could be considered significant from practical perspective. The tier 1 loading defaults result in thinner pavements. However, the PCC slab thickness difference is only 0.3 inch when designed using NCHRP 1-37A and LTPP SPS TPF defaults. From a pavement thickness design perspective, PCC slab thickness differences less than 0.5 inch are not significant. Based on observed thickness differences from MEPDG analysis, using either the NCHRP 1-37A or LTPP SPS TPF tier 1 defaults is not likely to result in significant design thickness differences for pavements that are likely to fail in cracking mode. This conclusion applies to all four climatic zones.

NCHRP 1-37A Versus LTPP SPS TPF Tier 2 NALS Defaults

For slab cracking failure mode, tier 2 lightest and typical NALS defaults resulted in longer service life prediction, while tier 2 heaviest NALS defaults resulted mostly in shorter service life prediction compared to the NCHRP 1-37A NALS defaults. Service life prediction for the tier 2 lightest NALS was up to 49 percent longer than the NCHRP 1-37A NALS defaults. This difference is considered of practical significance. Service life prediction for the tier 2 typical group was up to 28 percent longer than the NCHRP 1-37A NALS defaults. This difference also is considered of practical significance. Service life prediction for the tier 2 heaviest group ranged from 7.5 percent longer up to 11 percent shorter than the NCHRP 1-37A NALS defaults. These differences are not considered of practical significance (20 percent was used as a threshold). The tier 2 lightest and typical loading defaults resulted in thinner pavements (up to 0.5- and 0.2-inch thickness difference, respectively). The tier 2 heaviest loading defaults resulted in a slightly thicker PCC slab (0.2 inch). PCC thickness differences for the tier 2 heaviest and typical loading defaults were less than 0.5 inch and considered insignificant from the practical perspective. However, for the tier 2 lightest NALS defaults, the thickness difference was 0.5 inch and is considered significant. MEPDG predictions were found to be very similar between the NCHRP 1-37A and SPS TPF tier 2 heaviest NALS defaults.

For designs that fail in faulting mode, the tier 2 lightest NALS defaults resulted in longer service life prediction (up to 6 percent), while the tier 2 heaviest and typical NALS defaults resulted in shorter service life prediction (up to 9 percent) compared to the NCHRP 1-37A NALS defaults. These differences are not considered of practical significance (20 percent was used as a threshold). MEPDG predictions were found to be very similar between the NCHRP 1-37A and SPS TPF tier 2 typical NALS defaults.

Comparison of Axles per Class Coefficients

The researchers also ran a scenario in which the new load spectra defaults were used in combination with NCHRP 1-37A and LTPP SPS TPF APC coefficient default values. The results from this analysis did not show significant difference in pavement design life or thickness predictions between the two sets of APC default values.

DEFAULT APC NUMBERS BASED ON SPS TPF DATA

To compute the APC defaults, values were computed for each of the SPS TPF sites and then averaged across the sites using the methodology described in chapter 9. Appendix D includes a database CD that contains these results. APC values are provided for each site by vehicle class and axle group type.

Averaging the APC values for the 26 sites resulted in one set of default values, as shown in table 46.

Table 46. Default axles per class coefficients based on 26 SPS TPF sites (LTPP classification scheme).

Vehicle Class	Single	Tandem	Tridem	Quad
4	1.43	0.57	0.00	0.00
5	2.16	0.02	0.00	0.00
6	1.02	0.99	0.00	0.00
7	1.26	0.20	0.63	0.15
8	2.62	0.49	0.00	0.00
9	1.27	1.86	0.00	0.00
10	1.09	1.15	0.79	0.05
11	4.99	0.00	0.00	0.00
12	3.99	1.00	0.00	0.00
13	1.59	1.26	0.69	0.31

Comparison between NCHRP 1-37A and SPS TPF Default APC Numbers

Figure 50 compares the average number of axles within an axle group type and the total number of axles for each truck class between default values used in the MEPDG version 1.1 software and values computed using SPS TPF data. As shown, there are some differences, but they are relatively small and unlikely to result in any significant difference in terms of required layer thickness or predicted distress for flexible or rigid pavements.

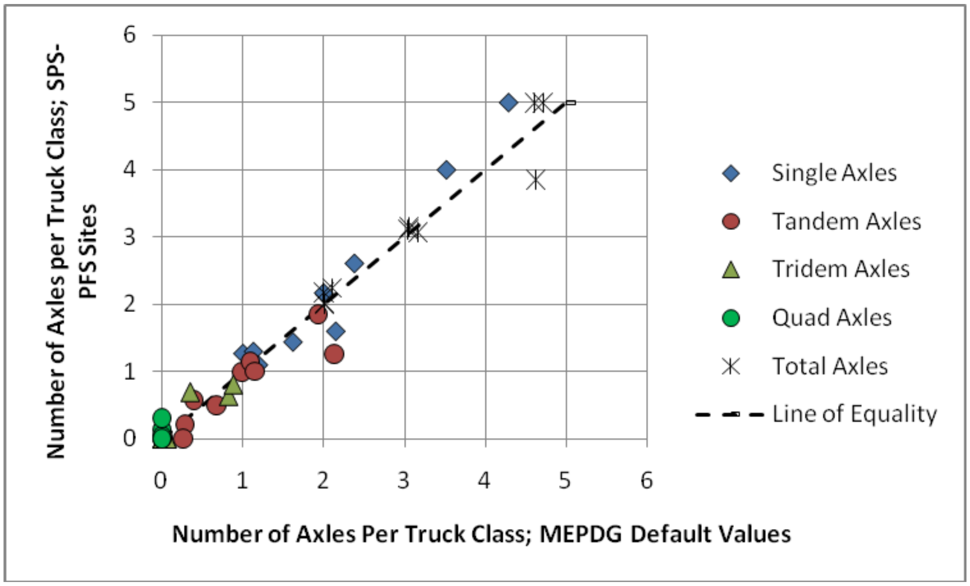

Figure 50. Graph. Comparison of the APC values from all SPS TPF sites to the MEPDG default values.

The comparison of data presented in table 47 indicates that major differences in APC values occurred for classes 11 and 13. However, because these classes are relatively infrequent, improved APC values alone will not have a significant impact on predicted pavement performance.

Table 47. Comparison of SPS TPF and current MEPDG default axles per class.

Vehicle Class	New LTPP Default				MEPDG Default (Version 1.1)				Difference (New LTPP – MEPDG Default)			
	Single	Tandem	Tridem	Quad	Single	Tandem	Tridem	Quad	Single	Tandem	Tridem	Quad
4	1.43	0.57	0.00	0.00	1.62	0.39	0	0	-0.19	0.18	0.00	0.00
5	2.16	0.02	0.00	0.00	2	0	0	0	0.16	0.02	0.00	0.00
6	1.02	0.99	0.00	0.00	1.02	0.99	0.13	0	0.00	0.00	-0.13	0.00
7	1.26	0.20	0.63	0.15	1	0.26	0.83	0	0.26	-0.05	-0.20	0.14
8	2.62	0.49	0.00	0.00	2.38	0.67	0	0	0.22	-0.17	0.00	0.00
9	1.27	1.86	0.00	0.00	1.13	1.93	0	0	0.16	-0.08	0.00	0.00
10	1.09	1.15	0.79	0.05	1.19	1.09	0.89	0	-0.10	0.05	-0.09	0.04
11	4.99	0.00	0.00	0.00	4.29	0.26	0.06	0	0.70	-0.26	-0.06	0.00
12	3.99	1.00	0.00	0.00	3.52	1.14	0.06	0	0.47	-0.14	-0.06	0.00
13	1.59	1.26	0.69	0.31	2.15	2.13	0.35	0	-0.56	-0.87	0.34	0.31

AXLE SPACING AND WHEELBASE DEFAULTS

Average Axle Spacing and Wheelbase

SPS TPF data were used to investigate the distribution of axle spacing (wheelbase) of the tractor unit of tractor-semitrailer combination trucks for FHWA vehicle classes 8 and above. Table 48 shows the results of the axle spacing distribution analysis. Based on these results, users could define their own categories of short, medium, and long axle spacing based on selected slab joint spacing and compute corresponding percentages of axles in the short, medium, and long categories by aggregating the values presented in table 48.

Table 48. Distribution of axle spacing on tractor unit for FHWA vehicle classes 8–13.

Axle Spacing (ft)	Percentage of All Axle Spacing on the Tractor Unit
≤ 7	0.0
> 7 and ≤ 8	0.0
> 8 and ≤ 9	0.0
> 9 and ≤ 10	0.1
> 10 and ≤ 11	0.7
> 11 and ≤ 12	3.5
> 12 and ≤ 13	7.8
> 13 and ≤ 14	5.4
> 14 and ≤ 15	3.0
> 15 and ≤ 16	8.1
> 16 and ≤ 17	12.9

Axle Spacing (ft)	Percentage of All Axle Spacing on the Tractor Unit
> 17 and ≤ 18	32.9
> 18 and ≤ 19	9.8
> 19 and ≤ 20	7.3
> 20 and ≤ 21	6.9
> 21 and ≤ 22	0.9
> 22 and ≤ 23	0.3
> 23 and ≤ 24	0.2
> 24	0.2

Since 15 ft is the most frequently used joint spacing for JPCP joint design, the following axle spacing distribution of the tractor unit of tractor-semitrailer combination trucks for classes 8 and above is recommended based on SPS TPF data:

- **Short** (≤ 12 ft): 4.3 percent.
- **Medium** (>12 and ≤ 15 ft): 16.2 percent.
- **Long** (≥ 15 ft): 79.5 percent.

In addition, the MEPDG states that if other vehicles in the traffic stream also have the axle spacing in the range of the short, medium, and long spacing defined above, the frequency of those vehicles could be added to the axle spacing distribution of truck tractors.(1) For example, if 10 percent of truck traffic is from multiple trailers (class 11 and above) that have a trailer-to-trailer axle spacing in the short range, 10 percent should be added to the percentage of truck tractors for short axles. Thus, the sum of percent trucks in the short, medium, and long categories can be greater than 100.

A sample of axle spacing data from SPS TPF WIM sites was used to estimate percentages of axle spacing that fall in different length categories. The results of the axle spacing distribution analysis are shown in table 49 for vehicle classes 4 through 13 and provide additional insights into what vehicle classes are likely to have axle spacing that could contribute to the development of top-down cracking in JPCP.

Table 49. Distribution of axle spacing by vehicle class using sample of SPS TPF WIM data.

Axle Spacing (ft)	Percentage of All Axle Spacing by Class									
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
≤ 8	37	13	49	66	25	47	62	0	20	50
> 8 and ≤ 9	0	1	0	0	3	0	0	2	6	4
> 9 and ≤ 10	0	1	0	1	1	0	1	17	11	5
> 10 and ≤ 11	0	2	0	3	1	3	1	3	3	3
> 11 and ≤ 12	0	12	1	11	2	1	1	2	5	3
> 12 and ≤ 13	0	7	2	9	8	1	2	12	2	3
> 13 and ≤ 14	0	21	3	3	8	1	2	7	0	2
> 14 and ≤ 15	0	12	3	2	4	1	1	2	0	2
> 15 and ≤ 16	0	4	6	1	2	2	2	2	2	3
> 16 and ≤ 17	0	3	6	0	2	4	2	2	3	3
> 17 and ≤ 18	0	4	9	0	4	9	3	4	6	3
> 18 and ≤ 19	0	3	6	1	4	3	4	2	2	5
> 19 and ≤ 20	0	3	5	0	4	2	2	1	5	4
> 20 and ≤ 21	0	4	6	0	6	2	1	6	13	2
> 21 and ≤ 22	0	5	2	0	5	0	1	24	8	2
> 22 and ≤ 23	1	3	1	0	3	0	0	15	12	1
> 23 and ≤ 24	20	1	0	0	1	0	0	1	1	1
> 24	42	2	0	0	16	25	15	0	0	5

Axle Spacing for Multi-Axle Groups

SPS TPF axle spacing data were used to compute average axle spacing for tandem, tridem, and quad axle groups. These averages were then compared with the current MEPDG defaults. The results are presented in table 50.

Table 50. Average axle spacing for multi-axle groups.

Default Source	Axle Spacing (Inches)		
	Tandem	Tridem	Quads
NCHRP 1-37A	51.6	49.2	49.2
LTPP SPS TPF	49.0	50.8	51.8

As can be seen from the table, the values are very close. SPS TPF-based averages are slightly lower for tandems and higher for tridems and quads compared to the current MEPDG default values.

The values based on SPS TPF WIM sites reported in table 50 are recommended to be used as new MEPDG defaults, as these values are obtained from accurately calibrated WIM sites and are based on the analysis of 4.7 million records from SPS TPF sites.

CHAPTER 11—SUMMARY OF FINDINGS AND RECOMMENDATIONS

SUMMARY OF FINDINGS

Traffic Loading Defaults Based on SPS TPF WIM Data

The focus of this study was to develop MEPDG traffic loading defaults based on the SPS TPF WIM data. The main traffic loading default is NALS. Other defaults that are based on WIM data are axle-per-truck coefficients, axle spacing, and wheelbase.

The researchers assessed available SPS TPF data and found them to be sufficient for developing representative site-specific values and alternate MEPDG axle loading defaults. The primary benefit of these new data is that they are of known acceptable data quality and sufficient quantity to develop representative NALS for each SPS TPF site. The limitation of the SPS TPF data is a limited study scope that includes only 26 WIM sites located in 22 States. Future expansion of the program would expand the applicability of the defaults and, thus, should be considered by FHWA LTPP Program or in conjunction with other programs, like the Long-Term Bridge Performance Program.

The following two tiers of NALS defaults were developed:

- **Tier 1:** Global defaults based on all applicable SPS TPF data. These defaults were based on averaging of NALS computed for the 26 SPS TPF sites by vehicle class and axle group type. One default NALS was computed for each vehicle class and axle group type combination, resulting in 25 unique default NALS. These defaults are fully compatible with the original MEPDG defaults in format and methodology used.

- **Tier 2**: Supplemental defaults based on subsets of SPS TPF data representing several specific loading conditions. These defaults are based on identifying groups of SPS TPF sites representing similar axle loading conditions and averaging of NALS for these sites. Multiple NALS were developed for each vehicle class and axle group type combination. NALS were identified by descriptive loading category. The most frequently observed NALS was labeled as “typical” for each vehicle class and axle group type. If a particular SPS TPF site had loading characteristics significantly different from any other site (usually much lighter or heavier), NALS for these sites were identified as special cases.

In addition to NALS, one set of default axle-per-truck coefficients was developed based on all SPS TPF sites. Representative axle spacing and wheelbase values were also computed.

MEPDG input files for all default NALS were developed in the formats compatible with DARWin-ME™ and NCHRP 1-37A MEPDG software.

LTPP-PLUG

LTPP-PLUG was developed to facilitate the selection and use of axle loading defaults for MEPDG applications.(5) The guide consists of two parts and a software application. The first part of the guide provides guidelines for selecting and using LTPP SPS TPF axle loading defaults within the for MEPDG and DARWin-ME™ software. The purpose of the second part of the guide is to provide practical guidelines for generation of additional MEPDG traffic loading defaults that can be used by States and LTPP users to generate axle loading defaults based on their own WIM data or specific to their analysis purposes. The guide also contains an operator's manual that supports the use of the LTPP-PLUG interactive traffic loading library software application.

The LTPP-PLUG software application provides guidance in the selection of axle loading conditions (the traffic loading library) for pavement designs, and it produces input files for axle load data for use with the AASHTO DARWin-ME™ software. It also allows States to add their own site-specific and default NALS to the PLUG database, which can be used to generate MEPDG input files and compute the new defaults. This software could be used to generate .alf or .xml files for any other NALS added to the LTPP-PLUG database tables.

Comparison of Default Values Based on SPS TPF Data with NCHPR 1-37A Defaults

NALS default values based on SPS TPF data were compared with NCHPR 1-37A defaults. The results of the comparison using tier 1 defaults indicated that significantly different MEPDG outcomes could be expected for some cases (JPCP slab cracking and total rutting of AC pavements). In addition, significantly different MEPDG outcomes are expected when different sets of tier 2 NALS defaults are used (light versus heavy). This conclusion highlights the importance of accurate measurement of the axle load spectra, along with the importance of the local knowledge of the expected axle loading conditions for pavement design and analysis.

The newly computed NALS defaults had fewer very light and fewer very heavy loads. This is most likely due to the fact that the new defaults were collected with more consistently calibrated WIM equipment compared to the dataset used for the development of the original NALS defaults under the NCHRP 1-37A project. The better calibration of the WIM scales used to develop the new defaults means that fewer very light loads (caused by under calibrated scales observing light loads) and fewer very heavy loads (caused by over calibrated scales observing heavy loads) are observed in the new default database.

Assuming that the new defaults are more accurate and representative of typical loading conditions, a conclusion could be made that pavement designs using the new defaults will be thinner than the designs using the original MEPDG defaults. However, from a practical perspective, the difference in the design thickness was significant only for a limited number of pavement scenarios tested.

WIM Data Selection Criteria for Generation of MEPDG Traffic Loading Defaults

WIM data selection criteria used in this study to develop the MEPDG traffic loading defaults addressed data availability, data quality, and data reasonableness. A number of statistical analyses were conducted to evaluate the reliability of computed NALS using different data quality and availability scenarios.

The following conservative minimum data availability criteria were identified to remove any potential DOW and monthly bias from computation of RANALS for individual WIM sites:

- Availability of at least 1 of each 7 DOW per month to avoid potential DOW bias. Days do not need to be consecutive.

- Availability of at least 1 of each 12 calendar months to avoid potential seasonal bias. Months do not need to be consecutive or from the same calendar year.

When more than 7 DOW per month or more than 12 calendar months of acceptable quality data are available, all available data should be used to compute site-specific RANALS.

The following acceptable data quality criteria were identified for this study:

- Data should be from a WIM site conforming to the ASTM E1318-02 specification for type I WIM system accuracy and performance requirements specified in the LTPP Program's internal field operations guide for SPS WIM sites, as evidenced by documented WIM installation reports, and annual or semiannual validation/calibration reports.(6,12)

- Selected data must pass a quality review using the LTPP QC procedures for the SPS TPF study and be identified as Level E data in the LTPP SDR database.

In addition to data availability and data quality, data reasonableness criteria were applied to address cases when data may be valid but atypical. A series of tests were developed to aid in the identification of atypical data.

WIM System Accuracy

The effect of WIM system accuracy on axle weight measurements, NALS estimates, and the associated MEPDG outcomes was also investigated. The MEPDG analysis outcomes indicated that drift in WIM system calibration that leads to over 5 percent bias in mean error between true and WIM-measured axle weight could lead to significant differences in MEPDG design outcomes. Therefore, it is important to keep WIM systems properly calibrated and schedule calibration visits when a consistent drift in axle weight measurement close to 5 percent of the reference dataset (data collected right after previous calibration visit) is observed.

Current SPS TPF WIM performance requirements result in a level of error in WIM data that is insignificant for MEPDG applications, provided that excessive bias values are mitigated in a timely manner through WIM calibration and maintenance activities.

New Summary Statistics to Characterize NALS and to Quantify NALS Reliability

Two new statistical parameters were developed in this study to simplify the description and comparisons of different NALS. Because NALS required for MEPDG analyses include thousands of numbers (considering all load bins, all vehicle classes, and all axle types), comparing or evaluating different NALS is not straightforward. Therefore, the ability to summarize these complex sets of numbers into a single statistic that represents the whole NALS is very helpful. That summary statistic can be used to compare different NALS, characterize the relative size of the loading condition associated with a site or when comparing the likely effects of using different NALS or quantifying NALS accuracy.

Distributions like NALS can be summarized in many ways. For the success of this study, it was critical to define a summary statistic that would account for the following:

- The frequency of load applications, expressed as percentages of the total axle load applications at each load level.
- The impact of different axle load levels on the MEPDG-based pavement performance predictions, accounted for through MEPDG-derived weighting factors.

The following parameters were developed and used in this study:

- **RPPIF**: A summary statistic for the comparison of NALS. This statistic was also used to help group or cluster NALS that represent similar loading characteristics. This statistic converts NALS to a single value, considering both the frequency of load applications and the effect of different load magnitudes on pavement performance.
- **PWLE**: A parameter for quantifying errors associated with using several NALS to compute a single group NALS. The PWLE statistic can also be used to assess the reliability of that summary NALS. PWLE is a single value that provides a representative estimate of the accuracy of a summary NALS, as well as the range of expected errors associated with using that summary. To compute the PWLE statistic, it is necessary to identify the statistical CL at which the reliability of the NALS is to be computed. PWLE takes into consideration both the relative percentage of the traffic at each load level and the impact of each load level on the MEPDG-based pavement performance predictions.

These parameters are applicable for studies involving NALS comparison and grouping and for the evaluation of NALS accuracy. Values for weight factors, W_{ij}, developed in this study were based on generic pavement designs and globally calibrated MEPDG models. These values could be replaced with values developed using different or locally calibrated MEPDG models, or based on different pavement designs that are more applicable to studies being performed, or for local agency use.

RECOMMENDATIONS FOR USING TRAFFIC LOADING DEFAULTS

These recommendations address the selection of default or surrogate NALS based on the data collected at SPS TPF sites if no loading data are available to develop reliable NALS estimates.

Knowledge of Local Traffic Loading Conditions

Before selecting the NALS defaults, it is recommended that every effort is made to understand the expected traffic loading pattern at the site for which the NALS selections are being made. This should include an analysis of site location and likely truck traffic characteristics observed at the site, including the following:

- Dominant heavy vehicle classes observed at the site.
- Percentage of through trucks versus local delivery trucks.
- Dominant commodities being carried by trucks.
- Truck sizes and weight laws of different States (which can result in different truck body/configurations for the same FHWA truck class being utilized within different states).
- Presence and effectiveness of weight enforcement activities.
- Number of roadway lanes.

This information should be used to establish descriptive traffic loading conditions for the dominant heavy vehicle classes observed at the site. An example of axle loading categories by loading condition is provided in table 24.

A special effort should be made to identify loading conditions for class 9 vehicles. For the majority of the LTPP sites (and the majority of U.S. primary roads), class 9 is the dominant heavy vehicle type. Class 5 vehicles are frequently dominant but not heavy enough to make a significant contribution to total traffic loading; thus, they may be excluded from determination of the dominant heavy vehicle classes, unless local knowledge exists of heavier-than-usual class 5 vehicles at the site.

In some instances, historical WIM data or recently collected portable WIM data may be available for the site. These data may not be accurate enough to compute NALS for the site but may be useful in establishing a descriptive loading condition, including evaluation of loading conditions by direction and for identifying loading condition for the design lane.

Default Selection

Once descriptive loading categories are determined for the dominant vehicle classes expected at the site, tier 2 default NALS corresponding to the identified loading categories could be selected from the database (see appendix D). If no local knowledge exists, either tier 1 NALS defaults or tier 2 NALS defaults representing typical conditions could be used. For a more conservative analysis, tier 2 NALS defaults representing heavy conditions could be used. Chapter 10 provides decision tree to aid in the default selection process.

If a State's truck sizes and weight laws allow loads exceeding Federal regulations 23 U.S.C. 127 and 23 CFR 658, and the site has a low percentage of interstate traffic, there is a higher likelihood of heavier-than-typical NALS, especially if there is local knowledge of heavy commodities being transported by certain vehicle classes using road facilities that include the site of interest.[19,20]

MEPDG Testing of NALS Alternatives

Not all pavement designs have the same sensitivity to NALS; therefore, analysis of MEPDG outcomes from different NALS inputs may be beneficial to determine if using alternative NALS will result in differences in MEPDG outcomes that have practical significance. In this study, for example, MEPDG analysis considering different single axle NALS did not result in outcomes that carry practical significance for any vehicle classes, except class 11, while for tandem axles results were significantly different for all classes, except classes 5 (due to low weight) and 12 (due to low volume). NALS for tridem and quad axles may lead to significantly different outcomes if these axles carry a significant percentage of the total load for the site.

Applicability and Limitations of LTPP SPS TPF Defaults

The new defaults are based on high-quality WIM data from 26 sites primarily located on RI and ROPA roadways. These are the road types for which State agencies are likely to use the MEPDG design method. The sites were located throughout the U.S. and provide reasonable estimates of expected axle loading condition for these types of roads, in the absence of site-specific loading information.

However, based on the limited number of sites, it was not possible to determine if these defaults would be applicable to roadways in other functional categories or in jurisdictions that utilize types of trucks or serve industrial or agricultural facilities significantly different from the ones observed in the LTPP SPS TPF study. For example, only two SPS TPF sites were located on roads classified as "urban." Usability and applicability of the defaults developed in this study should be determined at the State level by comparing these defaults with the available site-specific data. Special care should be taken to assure that the data collected by the State are based on data selection criteria similar to the ones described in this report to assure data accuracy and data completeness for generation of representative NALS.

It is highly recommended that some local knowledge of loading conditions be applied when judging the applicability of the SPS TPF defaults, especially for roads that are likely to carry a large percentage of local truck traffic.

Use of LTPP SPS TPF Defaults with MEPDG or DARWin-ME™ Software

The SPS TPF default NALS were developed to follow the formats established for the NCHRP 1-37A MEPDG and DARWin-ME™ software. Defaults for axle spacing and APC coefficients could be uploaded to these software products as direct user inputs, while NALS could be imported as *.alf or *.xml files. This could be accomplished using the LTPP-PLUG software.

FUTURE RESEARCH RECOMMENDATIONS

Future research recommendations include the following:

- Axle loading defaults developed in this study are based on the data from 26 LTPP SPS TPF sites. It is recommended that as more sources (additional WIM sites) of the research-quality WIM data are identified, these data should be included in development of the updated NALS defaults.

- NALS defaults developed in this study were based on clustering of NALS representing axle loading conditions that are likely to produce significantly different MEPDG outcomes based on globally calibrated models. As MEPDG pavement performance prediction models and design criteria evolve, these clusters may change. Therefore, the defaults should be reviewed and updated when major revisions are made to the MEPDG models.

- NALS defaults were developed for single, tandem, tridem, and quad axle groups. However, heavy trucks that have axle groups with five or more axles could be found in some States. It is recommended that the effect of the axle loads and the frequency of occurrence of such trucks on pavement design should be evaluated to determine if the MEPDG should consider these trucks (with five or more axle group types) in routine pavement design.

- All NALS defaults were developed based on data collected using the LTPP vehicle classification scheme. In summer 2012, additional rules were introduced to that scheme, resulting in changes how vehicle classes 7, 10, and 13 are identified. It is recommended that NALS developed for these vehicle classes are revised once the new data become available.

- Since truck traffic characteristics, pavement design criteria, and pavement design philosophy (considering pavement thickness, frequency of maintenance/rehabilitation activities, and pavement design reliability) differ from State to State, it is recommended that States evaluate the applicability of the defaults developed in this study to their local conditions through comparison of the default and State-specific NALS, as well as MEPDG outcomes using these NALS.

APPENDIX A—RESULTS OF MONTHLY AXLE LOAD TEMPORAL CONSISTENCY AND OUTLIER ANALYSIS

Data available in LTPP SDR 24 LTAS database table MM_AX were used to construct monthly NALS and conduct temporal consistency and outlier analysis. Results of this analysis, including the automated and manual checks, are presented in the following two tables.

Table 51. Results of automated QA checks.

State Code	SHRP ID	Year	Month	Automatic Filtering of Potential Outliers (Statistical Checks)									
				Excessive Cumulative Absolute Difference in NALS					Significant Shift in Monthly Peak Loads				
				Single 9	Single 9 Heavy	Tandem 9	Tandem 9 Heavy	Number of Failed Tests	Single 9	Single 9 Heavy	Tandem 9 Light	Tandem 9 Heavy	Number of Failed Tests
4	0100	2007	10	Y				1					
4	0100	2007	11				Y	1					
4	0100	2007	12	Y	Y	Y	Y	4					
4	0100	2008	1	Y	Y		Y	3					
5	0200	2008	6			Y		1			Y		1
5	0200	2008	8	Y		Y		2		Y			1
5	0200	2008	10	Y		Y		2			Y		1
5	0200	2008	11	Y		Y		2	Y		Y		2
5	0200	2008	12	Y		Y		2	Y		Y		2
8	0200	2006	4	Y				1					
8	0200	2006	5		Y			1					
8	0200	2006	6		Y			1					
8	0200	2007	11	Y	Y	Y		3					
8	0200	2007	12	Y	Y	Y	Y	4					
8	0200	2008	1	Y	Y	Y	Y	4					
8	0200	2008	2	Y	Y	Y	Y	4					
8	0200	2008	3		Y		Y	2					
8	0200	2008	4	Y	Y			2					
8	0200	2009	5				Y	1					
12	0100	2004	1		Y	Y		2					
12	0500	2004	4		Y			1					
12	0500	2004	12		Y			1					
12	0500	2005	1						Y				1
12	0500	2005	7		Y			1	Y			Y	2
12	0500	2005	8						Y				1
12	0500	2005	9						Y				1
12	0500	2005	10		Y			1					
12	0500	2005	11						Y				1
12	0500	2005	12						Y				1
12	0500	2006	1						Y				1
12	0500	2006	2						Y				1
12	0500	2006	3						Y				1
12	0500	2006	4			Y		1	Y		Y		2
12	0500	2006	5						Y				1
12	0500	2006	6						Y				1
12	0500	2006	7						Y				1
12	0500	2006	8						Y				1
2	0500	2006	12									Y	1
12	0500	2007	2		Y			1			Y	Y	2
12	0500	2007	3		Y			1				Y	1
12	0500	2007	4		Y			1					
22	0100	2008	1	Y				1					
23	0500	2008	12	Y				1					
23	0500	2009*	1	Y		Y		2					
24	0500	2008	6	Y				1					

				Automatic Filtering of Potential Outliers (Statistical Checks)									
				Excessive Cumulative Absolute Difference in NALS					Significant Shift in Monthly Peak Loads				
State Code	**SHRP ID**	**Year**	**Month**	**Single 9**	**Single 9 Heavy**	**Tandem 9**	**Tandem 9 Heavy**	**Number of Failed Tests**	**Single 9**	**Single 9 Heavy**	**Tandem 9 Light**	**Tandem 9 Heavy**	**Number of Failed Tests**
24	0500	2008	7	Y				1					
26	0100	2007	8	Y				1					
26	0100	2007	9	Y				1					
26	0100	2008	2	Y	Y			2					
26	0100	2008	4	Y				1					
26	0100	2009	1	Y	Y	Y	Y	4					
26	0100	2009	2	Y	Y	Y	Y	4					
26	0100	2009	3	Y	Y	Y	Y	4					
26	0100	2009	4	Y	Y	Y	Y	4					
27	0500	2006	11		Y			1					
27	0500	2008	5	Y	Y	Y	Y	4					
27	0500	2008	6		Y			1					
27	0500	2009	2		Y			1					
27	0500	2009	3		Y			1					
27	0500	2009	4		Y			1					
35	0100	2008	6	Y	Y			2					
35	0100	2008	7	Y	Y			2					
35	0100	2008	8	Y	Y			2					
35	0500	2008	6	Y				1					
35	0500	2008	7		Y			1					
39	0100	2004	5	Y	Y			2					
39	0100	2004	6	Y				1					
39	0100	2004	7	Y	Y			2					
39	0100	2004	8	Y				1					
39	0100	2004	9	Y				1					
39	0100	2004	10	Y				1					
39	0100	2004	11	Y				1					
39	0100	2004	12	Y				1					
39	0200	2004	10	Y				1					
39	0200	2004	11	Y	Y	Y	Y	4					
39	0200	2004	12	Y	Y	Y	Y	4					
48	0100	2006	1	Y	Y	Y	Y	4					
48	0100	2006	2	Y	Y	Y	Y	4					
48	0100	2006	3	Y	Y	Y	Y	4					
48	0100	2006	4	Y	Y	Y	Y	4					
48	0100	2008	2	Y	Y	Y	Y	4					
55	0100	2008	4		Y			1					
55	0100	2008**	12	Y				1					
Number of Months Excluded								**70**					**22**
Percentage of Months Excluded								**9**					**3**

*Class 10 tridems have very high percentage of lightly loaded trucks (34 percent for 0–11,999 lb and 39 percent for 12,000–14,999 lb). This could be evidence for possible misclassification. Tridems will not be used for defaults.
**There is a peak shift in winter months for single and tandem axles class 9 load spectra. Sensor temperature sensitivity or calibration issues should be checked. December 2008, February 2008, January 2008, and January 2009 have a shifted peak (9,000 lb) in the single axle class 9 plot.
Note: Blank cells indicate no instances were identified.

Table 52. Results of manual QA checks.

State Code	SHRP ID	Year	Month	Manual Review for Reasonableness and Consistency (Manual Checks)								
				Load Peaks Outside Typical Range for the Site			Load Peaks Outside Typical Range for Class 9			Cumulative Percent of Overloads > Typical Upper Range for a Site		Cumulative Percent of Overloads > Typical Upper Range for Class 9
				Single 9 (Steering)	Tandem 9 Heavy	Number of Failed Tests	Typical Peak for Single 9 (9,000–13,000 lb)	Typical Peak for Tandem 9 (26,000–34,000 lb)	Number of Failed Tests	Single 9	Tandem 9	Single 9
4	0100	2007	10	Y		1						
4	0100	2007	11	Y		1						
4	0100	2007	12	Y	Y	2						
4	0100	2008	1	Y		1						Y
5	0200	2008	6	Y	Y	2		Y	1			
5	0200	2008	8	Y	Y	2						
5	0200	2008	10	Y	Y	2		Y	1			
5	0200	2008	11	Y	Y	2	Y	Y	2			
5	0200	2008	12	Y	Y	2	Y	Y	2			
8	0200	2006	4	Y	Y	2						
8	0200	2006	5	Y		1						
8	0200	2006	6	Y		1						
8	0200	2007	11	Y		1						
8	0200	2007	12	Y		1						
8	0200	2008	1	Y		1						Y
8	0200	2008	2	Y		1						
8	0200	2008	3	Y		1						
8	0200	2008	4	Y		1						
8	0200	2009	5	Y		1						
12	0100	2004	1	Y		1						
12	0500	2004	4		Y	1		Y	1			
12	0500	2004	12		Y	1		Y				
12	0500	2005	1	Y		1	Y					
12	0500	2005	7	Y		1	Y					
12	0500	2005	8	Y		1	Y					
12	0500	2005	9	Y		1	Y					
12	0500	2005	10	Y		1	Y					
12	0500	2005	11	Y		1	Y					
12	0500	2005	12	Y		1	Y					
12	0500	2006	1	Y		1	Y					
12	0500	2006	2	Y		1	Y					
12	0500	2006	3	Y		1	Y					
12	0500	2006	4	Y		1	Y					
12	0500	2006	5	Y		1	Y					
12	0500	2006	6	Y		1	Y					
12	0500	2006	7	Y		1	Y					
12	0500	2006	8	Y		1	Y					
12	0500	2006	12	Y		1	Y					
12	0500	2007	2	Y		1	Y					
12	0500	2007	3		Y	1		Y				
12	0500	2007	4	Y		1	Y					
22	0100	2008	1									
23	0500	2008	12	Y	Y	2						
23	0500	2009*	1	Y	Y	2						
24	0500	2008	6	Y		1						Y
24	0500	2008	7									Y

State Code	SHRP ID	Year	Month	Manual Review for Reasonableness and Consistency (Manual Checks)								
				Load Peaks Outside Typical Range for the Site			Load Peaks Outside Typical Range for Class 9			Cumulative Percent of Overloads > Typical Upper Range for a Site		Cumulative Percent of Overloads > Typical Upper Range for Class 9
				Single 9 (Steering)	Tandem 9 Heavy	Number of Failed Tests	Typical Peak for Single 9 (9,000–13,000 lb)	Typical Peak for Tandem 9 (26,000–34,000 lb)	Number of Failed Tests	Single 9	Tandem 9	Single 9
26	0100	2007	8	Y	Y	2						
26	0100	2007	9	Y	Y	2						
26	0100	2008	2	Y	Y	2	Y	Y	2			
26	0100	2008	4	Y	Y	2						
26	0100	2009	1	Y	Y	2	Y	Y	2			
26	0100	2009	2	Y	Y	2	Y	Y	2			
26	0100	2009	3	Y	Y	2	Y	Y	2			
26	0100	2009	4	Y	Y	2	Y	Y	2			
27	0500	2006	11	Y	Y	2						
27	0500	2008	5	Y	Y	2						
27	0500	2008	6	Y	Y	2						
27	0500	2009	2	Y	Y	2						Y
27	0500	2009	3	Y	Y	2						
27	0500	2009	4	Y	Y	2						
35	0100	2008	6	Y	Y	2						
35	0100	2008	7	Y	Y	2						
35	0100	2008	8	Y	Y	2						
35	0500	2008	6	Y	Y	2						
35	0500	2008	7	Y	Y	2						
39	0100	2004	5	Y		1						
39	0100	2004	6	Y		1						
39	0100	2004	7	Y		1						
39	0100	2004	8	Y	Y	2						
39	0100	2004	9	Y		1						
39	0100	2004	10	Y		1						
39	0100	2004	11	Y		1						
39	0100	2004	12	Y		1						
39	0200	2004	10	Y	Y	2						
39	0200	2004	11	Y	Y	2						
39	0200	2004	12	Y		1						
48	0100	2006	1	Y	Y	2		Y	1			
48	0100	2006	2	Y	Y	2		Y	1			
48	0100	2006	3	Y	Y	2		Y	1			
48	0100	2006	4	Y	Y	2		Y	1			Y
48	0100	2008	2	Y	Y	2		Y	1			
55	0100	2008	4	Y	Y	2						
55	0100	2008**	12	Y	Y	2						
No Months Excluded						**81**			**35**			**14**
Percent Months Excluded						**11%**			**5%**			**1%**

* Class 10 tridems have very high percentage of lightly loaded trucks (34 percent for 0–11,999 lb and 39 percent for 12,000–14,999 lb). This could be evidence for possible misclassification. Tridems will not be used for defaults.

**There is a peak shift in winter months for single and tandem axles class 9 load spectra. Sensor temperature sensitivity or calibration issues should be checked. December 2008, February 2008, January 2008, and January 2009 have a shifted peak (9,000 lb) in the single axle class 9 plot.

Note: Blank cells indicate that no instances were identified.

APPENDIX B—EVALUATION OF ATYPICAL APC COEFFICIENTS

Axle group types reported for individual vehicle classes 4 through 13 were reviewed to identify atypical axle group types for each class using the LTPP vehicle classification scheme. Atypical axle group types identified as a result of this review were reported to FHWA using feedback reports. A summary of the evaluation is presented in the following table.

Table 53. Summary of atypical axle group types.

State Code	SHRP ID	Class	Reason(s) for Flag	Comments
39	0100	4	Small number of tridems reported for buses. Possible misclassification.	Tridems reported in buses for June 2005, February 2007, and March 2007 only. Only 3 of 22 months had significant tridems reported (with APC at least 0.01). From monthly NALS, 9 months have 100 percent in first load bin; none of the other SPS TPF sites had tridems reported for buses.
39	0200	6	High single APC, lower than expected tandem APC.	Single APC values are higher and tandem APC values are lower in 2005 (May–August). Single axle class 6 RANALS peak is in the first bin (average 18 percent overall and 26 percent in May–August 2005). Tandem class 6 peak is in the third bin (average 30 percent at 8,000–9,999 lb) for all months.
53	0200	6	Highest single APC and lowest tandem APC among SPS TPF sites.	Single and tandem APC are high for many months. Class 6 single axle plot has high percentage (average 9 percent) in the first load bin. Tandem class 6 peak is in the third bin (average 28 percent at 8,000–9,999 lb) for all months.
4	0100	7	High single and tandem APC.	Single and tandem APC values are high for most months. No light weights observed in class 7 single and tandem RANALS.
6	0200	7	High single and tandem APC.	Single and tandem APC values are high for most months. Some low weights (6.6 percent) observed in the 8,000–9,999-lb load bin in class 7 tandem RANALS plot. No light weights observed in single axle class 7 RANALS plots.
12	0100	7	Average total number of axles less than four. Possible misclassification.	Single APC values are okay. Tandem APC values are higher than usual, and tridem APC values are lower than usual for outlier months. Outlier months are random. Also, there are no light weights observed in class 7 single and tandem RANALS.
12	0500	7	Average total number of axles less than four. Possible misclassification.	Single APC values are okay. Tandem APC values are higher than usual, and tridem APC values are lower than usual for outlier months. Maximum outlier months are in 2004. Total APC value is low for these months in 2004 (January, April, and May). Low total APC is always associated with higher tandem APC. Also, there are no light weights observed in class 7 single and tandem RANALS.
35	0100	7	High single and tandem APC.	Single and tandem APC values are high for most months. No light weights observed in class 7 single and tandem RANALS;
39	0100	7	High single APC.	Single APC values are high for most months. Light weights observed in class 7 single RANALS in both second and third load bins (~14 percent in 3,000–3,999-lb and 4,000–4,999-lb bins). These light weights are observed in all months.
39	0200	7	High single APC.	Single APC values are high for most months (> 1.5) and even higher for months in 2005 (> 2). Light weights observed in May–November 2005 (average 40 percent).

State Code	SHRP ID	Class	Reason(s) for Flag	Comments
53	0200	7	Average total number of axles less than four. High tandem APC and low tridem APC. Possible misclassification.	Low APC in 5 of 30 months (December 2006 to April 2007), primarily single axles. Possible misclassification. Tandem RANALS peak is at 0–5999 lb; tridems are okay.
4	0100	9	Highest single and lowest tandem APC among SPS TPF sites.	Single APC consistently high and tandem APC consistently low. There is a secondary peak (8.32 percent at 16,000–16,999 lb) after legal limit in class 9 single axle plot in all months. It could be because of the presence of split tandem axle.
53	0200	11	Highest number of tandem among SPS TPF sites. Also, tridems are reported.	Tandems and tridems reported for many months. Tandem class 11 peak is at fourth bin (average 27 percent at 10,000–11,999 lb). Very few tridems reported at level E for class 11.
53	0200	12	Only SPS TPF site that has tridems.	Low percentage of tridems reported in most of the months, with January 2009 having the highest tridem APC = 0.18. Low weight tridems in first load bin (0–11,999 lb) for 4 of 26 months. January 2009 has the highest percentage in first load bin (~42 percent at 0–11,999 lb).
24	0500	13	Average total number of axles less than FHWA scheme. Possible misclassification.	Misclassification possible. There are many months with total APC less than seven.

APPENDIX C—STATISTICAL CLUSTER ASSIGNMENTS FOR LTPP SPS TPF SITES USED FOR MEPDG SENSITIVITY ANALYSIS

The following table shows axle load spectra cluster assignments for each SPS TPF site. SPS TPF site ID is shown in the first column. Axle load spectra were developed for 25 class-axle combinations listed in the first row and analyzed using statistical clustering technique. Based on the results of the analysis, these load spectra were assigned to different statistical clusters. Each of the 25 class-axle combinations had 3 to 6 clusters representing different axle loading conditions. These clusters are identified in the cells by a number from 1 to 6. For each class-axle, the cluster that had the largest number of SPS TPF sites was called “typical.” To identify which cluster is typical in the table, “typical” is included after the cluster number. In addition, when a cluster was formed by a single axle load spectrum, SPS TPF site ID was used to identify the cluster in the table instead of a number.

Table 54. List of SPS TPF sites with load spectra cluster assignments.

State-Site	Class 4 Single	Class 5 Single	Class 6 Single	Class 7 Single	Class 8 Single	Class 9 Single	Class 10 Single	Class 11 Single	Class 12 Single	Class 13 Single	Class 4 Tandem	Class 5 Tandem	Class 6 Tandem	Class 7 Tandem
04-0100	3 - Typical	1 - Typical	3	3 - Typical	2 - Typical	4	1 - Typical	5	4 - Typical	3	4	1 - Typical	2	1 - Typical
04-0200	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	4 - Typical	1 - Typical	3 - Typical	1 - Typical	1 - Typical	1 - Typical
05-0200	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	4 - Typical	1 - Typical	3 - Typical	1 - Typical	1 - Typical	1 - Typical
06-0200	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	4 - Typical	1 - Typical	3 - Typical	1 - Typical	1 - Typical	1 - Typical
08-0200	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	3	1 - Typical	3 - Typical	2	1 - Typical	1 - Typical
10-0100	3 - Typical	2	4	3 - Typical	3	2 - Typical	1 - Typical	2	3	2	4	1 - Typical	4	2
12-0100	2	4	3	3 - Typical	4	2 - Typical	1 - Typical	3 - Typical	3	1 - Typical	2	1 - Typical	5	4
12-0500	1	3	5	3 - Typical	2 - Typical	1	1 - Typical	2	1	5	1	1 - Typical	2	3
17-0600	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	4 - Typical	1 - Typical	3 - Typical	2	1 - Typical	1 - Typical
18-0600	3 - Typical	2	2	3 - Typical	2 - Typical	2 - Typical	3	3 - Typical	3	2	3 - Typical	1 - Typical	2	1 - Typical
20-0200	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	4 - Typical	1 - Typical	3 - Typical	2	1 - Typical	1 - Typical
22-0100	3 - Typical	3	3	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	2	1 - Typical	3 - Typical	1 - Typical	3	1 - Typical
23-0500	3 - Typical	1 - Typical	1 - Typical	5	3	2 - Typical	1 - Typical	4	5	2	3 - Typical	1 - Typical	1 - Typical	1 - Typical
24-0500	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	2	3	2	3 - Typical	1 - Typical	1 - Typical	1 - Typical
26-0100	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	4	3 - Typical	4 - Typical	2	3 - Typical	1 - Typical	1 - Typical	1 - Typical
27-0500	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	1	3	1 - Typical	3 - Typical	2	1 - Typical	1 - Typical
35-0100	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	2	2	1 - Typical	2	1 - Typical	1 - Typical	1 - Typical
35-0500	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	2	3 - Typical	4 - Typical	3	3 - Typical	3	1 - Typical	1 - Typical
39-0100	3 - Typical	2	1 - Typical	3 - Typical	2 - Typical	2 - Typical	3	3 - Typical	3	4	3 - Typical	1 - Typical	1 - Typical	1 - Typical
39-0200	3 - Typical	1 - Typical	1 - Typical	2	1	2 - Typical	3	3 - Typical	4 - Typical	1 - Typical	2	1 - Typical	1 - Typical	1 - Typical
42-0600	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	3	1 - Typical	3 - Typical	1 - Typical	1 - Typical	1 - Typical
47-0600	3 - Typical	1 - Typical	1 - Typical	2	2 - Typical	2 - Typical	1 - Typical	3 - Typical	4 - Typical	1 - Typical	3 - Typical	1 - Typical	1 - Typical	5
48-0100	3 - Typical	1 - Typical	1 - Typical	3 - Typical	1	2 - Typical	2	3 - Typical	4 - Typical	1 - Typical	3 - Typical	1 - Typical	1 - Typical	1 - Typical
51-0100	3 - Typical	1 - Typical	1 - Typical	3 - Typical	2 - Typical	2 - Typical	1 - Typical	3 - Typical	3	1 - Typical	3 - Typical	1 - Typical	1 - Typical	1 - Typical
53-0200	3 - Typical	2	1 - Typical	1	2 - Typical	3	1 - Typical	3 - Typical	4 - Typical	1 - Typical	3 - Typical	1 - Typical	1 - Typical	1 - Typical
55-0100	3 - Typical	1 - Typical	1 - Typical	4	2 - Typical	2 - Typical	3	3 - Typical	3	1 - Typical	2	1 - Typical	1 - Typical	1 - Typical
04-0100	3	4	5	4 - Typical	4	1 - Typical	4	1	1 – Typical	1 - Typical	3	04-0100	3	4
04-0200	4 - Typical	2 - Typical	2 - Typical	4	2 - Typical	1 - Typical	3 - Typical	3 - Typical	2	1 - Typical	3	04-0200	4 - Typical	2 - Typical

State-Site	Class 4 Single	Class 5 Single	Class 6 Single	Class 7 Single	Class 8 Single	Class 9 Single	Class 10 Single	Class 11 Single	Class 12 Single	Class 13 Single	Class 4 Tandem	Class 5 Tandem	Class 6 Tandem	Class 7 Tandem
05-0200	4 - Typical	2 - Typical	3	4	3	1 - Typical	4	3 - Typical	3	1 - Typical	5 - Typical	05-0200	4 - Typical	2 - Typical
06-0200	4 - Typical	2 - Typical	2 - Typical	4 - Typical	2 - Typical	1 - Typical	3 - Typical	3 - Typical	1 - Typical	1 - Typical	5 - Typical	06-0200	4 - Typical	2 - Typical
08-0200	3	1	2 - Typical	4 - Typical	1	1 - Typical	3 - Typical	3 - Typical	1 - Typical	1 - Typical	4	08-0200	3	1
10-0100	4 - Typical	2 - Typical	4	4 - Typical	2 - Typical	4	5	4	1 - Typical	1 - Typical	2	10-0100	4 - Typical	2 - Typical
12-0100	6	3	3	4 - Typical	2 - Typical	2	5	3 - Typical	1 - Typical	1 - Typical	3	12-0100	6	3
12-0500	4 - Typical	1	2 - Typical	1	5	4	3 - Typical	1	1 - Typical	1 - Typical	1	12-0500	4 - Typical	1
17-0600	3	2 - Typical	2 - Typical	4 - Typical	2 - Typical	1 - Typical	3 - Typical	3 - Typical	2	1 - Typical	5 - Typical	17-0600	3	2 - Typical
18-0600	2	1	2 - Typical	4 - Typical	2 - Typical	3	4	3 - Typical	3	1 - Typical	5 - Typical	18-0600	2	1
20-0200	4 - Typical	2 - Typical	2 - Typical	4 - Typical	2 - Typical	1 - Typical	3 - Typical	3 - Typical	2	1 - Typical	5 - Typical	20-0200	4 - Typical	2 - Typical
22-0100	2	1	3	4 - Typical	3	1 - Typical	4	4	1 - Typical	1 - Typical	5 - Typical	22-0100	2	1
23-0500	4 - Typical	1	1	5	4	1 - Typical	1	5	1 - Typical	1 - Typical	5 - Typical	23-0500	4 - Typical	1
24-0500	3	1	2 - Typical	4 - Typical	2 - Typical	1 - Typical	3 - Typical	3 - Typical	2	1 - Typical	4	24-0500	3	1
26-0100	1	1	2 - Typical	4 - Typical	2 - Typical	1 - Typical	3 - Typical	2	2	2	5 - Typical	26-0100	1	1
27-0500	2	1	1	1	2 - Typical	1 - Typical	2	3 - Typical	2	1 - Typical	4	27-0500	2	1
35-0100	3	1	2 - Typical	2	2 - Typical	1 - Typical	3 - Typical	3 - Typical	1 - Typical	1 - Typical	3	35-0100	3	1
35-0500	4 - Typical	3	3	4 - Typical	3	1 - Typical	4	3 - Typical	1 - Typical	1 - Typical	5 - Typical	35-0500	4 - Typical	3
39-0100	4 - Typical	2 - Typical	3	4 - Typical	2 - Typical	1 - Typical	4	2	2	3	3	39-0100	4 - Typical	2 - Typical
39-0200	4 - Typical	1	2 - Typical	4 - Typical	1	1 - Typical	3 - Typical	2	2	3	5 - Typical	39-0200	4 - Typical	1
42-0600	4 - Typical	2 - Typical	2 - Typical	4 - Typical	2 - Typical	3	3 - Typical	3 - Typical	1 - Typical	1 - Typical	5 - Typical	42-0600	4 - Typical	2 - Typical
47-0600	4 - Typical	2 - Typical	2 - Typical	4 - Typical	2 - Typical	5	4	3 - Typical	1 - Typical	1 - Typical	5 - Typical	47-0600	4 - Typical	2 - Typical
48-0100	5	2 - Typical	4	4 - Typical	2 - Typical	1 - Typical	5	3 - Typical	1 - Typical	1 - Typical	5 - Typical	48-0100	5	2 - Typical
51-0100	4 - Typical	2 - Typical	2 - Typical	4 - Typical	2 - Typical	1 - Typical	3 - Typical	3 - Typical	2	1 - Typical	4	51-0100	4 - Typical	2 - Typical
53-0200	3	2 - Typical	2 - Typical	4 - Typical	1	1 - Typical	3 - Typical	2	1 - Typical	3	3	53-0200	3	2 - Typical
55-0100	3	1	2 - Typical	4 - Typical	2 - Typical	1 - Typical	3 - Typical	3 - Typical	2	1 - Typical	4	55-0100	3	1

APPENDIX D—DATABASE CD AND DATA DICTIONARY

DATA DICTIONARY

This data dictionary contains descriptions for the tables and field names included in the appendix.

The following list contains brief descriptions of the tables present in the database:

- **DEFAULT_AxlesPerTruck:** This table contains default APC coefficients based on all applicable SPS TPF data. Table 53 contains the field names and descriptions.

- **DEFAULT_NALS**: This table contains tier 1 or tier 2 based on all applicable SPS TPF data or user defined defaults. Table 54 contains the field names and descriptions.

- **SITE_SPECIFIC_AxlesPerTruck**: This table contains APC for each site. Table 55 contains the field names and descriptions.

- **SITE_SPECIFIC_NALS**: This table contains representative annual NALS for each SPS TPF or user-supplied site. Table 56 contains the field names and descriptions.

Table 55. Field names and descriptions for tables "DEFAULT_AxlesPerTruck."

Field Name	Data Type	Description
classNumber	NUMBER(2,0)	Code indicating the 13-bin classification into which trucks have been grouped.
numberAxle	NUMBER(1,0)	Type of axle for which the values in the field "truckAxleConfig" apply.
truckAxleConfig	NUMBER(2,2)	Number of this type of axle for a vehicle in this class.

Table 56. Field names and descriptions for table "DEFAULT_NALS."

Field Name	Data Type	Description
VEH_CLASS	NUMBER(2,0)	Code indicating the 13-bin classification into which trucks have been grouped.
AXLE_GROUP	NUMBER(1,0)	Type of axle for which these percentage of axles apply.
NALS_CLUSTERS	VARCHAR2(255)	Code indicating the type of default NALS.
MEPDG_LG01	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 0–2,999 lb for single axles, 0–5,999 lb for tandem axles, and 0–11,999 lb for tridem and quad axles.
MEPDG_LG02	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 3,000–3,999 lb for single axles, 6,000–7,999 lb for tandem axles, and 12,000–14,999 lb for tridem and quad axles.
MEPDG_LG03	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 4,000–4,999 lb for single axles, 8,000–9,999 lb for tandem axles, and 15,000–17,999 lv for tridem and quad axles.

Field Name	Data Type	Description
MEPDG_LG04	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 5,000–5,999 lb for single axles, 10,000–11,999 lb for tandem axles, and 18,000–20,999 lb for tridem and quad axles.
MEPDG_LG05	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 6,000–6,999 lb for single axles, 12,000–13,999 lb for tandem axles, and 21,000–23,999 lb for tridem and quad axles.
MEPDG_LG06	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 7,000–7,999 lb for single axles, 14,000–15,999 lb for tandem axles, and 24,000–26,999 lb for tridem and quad axles.
MEPDG_LG07	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 8,000–8,999 lb for single axles, 16,000–17,999 lb for tandem axles, and 27,000–29,999 lb for tridem and quad axles.
MEPDG_LG08	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 9,000–9,999 lb for single axles, 18,000–19,999 lb for tandem axles, and 300,00–32,999 lb for tridem and quad axles.
MEPDG_LG09	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 10,000–10,999 lb for single axles, 20,000–21,999 lb for tandem axles, and 33,000–35,999 lb for tridem and quad axles.
MEPDG_LG10	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 11,000–11,999 lb for single axles, 22,000–23,999 lb for tandem axles, and 36,000–38,999 lb for tridem and quad axles.
MEPDG_LG11	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 12,000–12,999 lb for single axles, 24,000–25,999 lb for tandem axles, and 39,000–41,999 lb for tridem and quad axles.
MEPDG_LG12	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 13,000–13,999 lb for single axles, 26,000–27,999 lb for tandem axles, and 42,000–44,999 lb for tridem and quad axles.
MEPDG_LG13	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 14,000–14,999 lb for single axles, 28,000–29,999 lb for tandem axles, and 45,000–47,999 lb for tridem and quad axles.
MEPDG_LG14	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 15,000–15,999 lb for single axles, 30,000–31,999 lb for tandem axles, and 48,000–50,999 lb for tridem and quad axles.
MEPDG_LG15	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 16,000–16,999 lb for single axles, 32,000–33,999 lb for tandem axles, and 51,000–53,999 lb for tridem and quad axles.
MEPDG_LG16	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 17,000–17,999 lb for single axles, 34,000–35,999 lb for tandem axles, and 54,000–56,999 lb for tridem and quad axles.
MEPDG_LG17	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 18,000–18,999 lb for single axles, 36,000–37,999 lb for tandem axles, and 57,000–59,999 lb for tridem and quad axles.
MEPDG_LG18	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 19,000–19,999 lb for single axles, 38,000–39,999 lb for tandem axles, and 60,000–62,999 lb for tridem and quad axles.

Field Name	Data Type	Description
MEPDG_LG19	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 20,000–20,999 lb for single axles, 40,000–41,999 lb for tandem axles, and 63,000–65,999 lb for tridem and quad axles.
MEPDG_LG20	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 21,000–21,999 lb for single axles, 42,000–43,999 lb for tandem axles, and 66,000–68,999 lb for tridem and quad axles.
MEPDG_LG21	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 22,000–22,999 lb for single axles, 44,000–45,999 lb for tandem axles, and 69,000–71,999 lb for tridem and quad axles.
MEPDG_LG22	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 23,000–23,999 lb for single axles, 46,000–47,999 lb for tandem axles, and 72,000–74,999 lb for tridem and quad axles.
MEPDG_LG23	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 24,000–24,999 lb for single axles, 48,000–49,999 lb for tandem axles, and 75,000–77,999 lb for tridem and quad axles.
MEPDG_LG24	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 25,000–25,999 lb for single axles, 50,000–51,999 lb for tandem axles, and 78,000–80,999 lb for tridem and quad axles.
MEPDG_LG25	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 26,000–26,999 lb for single axles, 52,000–53,999 lb for tandem axles, and 81,000–83,999 lb for tridem and quad axles.
MEPDG_LG26	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 27,000–27,999 lb for single axles, 54,000–55,999 lb for tandem axles, and 84,000–86,999 lb for tridem and quad axles.
MEPDG_LG27	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 28,000–28,999 lb for single axles, 56,000–57,999 lb for tandem axles, and 87,000–89,999 lb for tridem and quad axles.
MEPDG_LG28	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 29,000–29,999 lb for single axles, 58,000–59,999 lb for tandem axles, and 90,000–92,999 lb for tridem and quad axles.
MEPDG_LG29	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 30,000–30,999 lb for single axles, 60,000–61,999 lb for tandem axles, and 93,000–95,999 lb for tridem and quad axles.
MEPDG_LG30	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 3,1000–31,999 lb for single axles, 62,000–63,999 lb for tandem axles, and 96,000–98,999 lb for tridem and quad axles.
MEPDG_LG31	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 32,000–32,999 lb for single axles, 64,000–65,999 lb for tandem axles, and 99,000–101,999 lb for tridem and quad axles.
MEPDG_LG32	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 33,000–33,999 lb for single axles and 66,000–67,999 lb for tandem axles.
MEPDG_LG33	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 34,000–34,999 lb for single axles and 68,000–69,999 lb for tandem axles.
MEPDG_LG34	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 35,000–35,999 lb for single axles and 70,000–71,999 lb for tandem axles.

Field Name	Data Type	Description
MEPDG_LG35	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 36,000–36,999 lb for single axles and 72000–73999 lb for tandem axles.
MEPDG_LG36	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 37,000–37,999 lb for single axles and 74,000–75,999 lb for tandem axles.
MEPDG_LG37	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 38,000–38,999 lb for single axles and 76,000–77,999 lb for tandem axles.
MEPDG_LG38	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 39,000–39,999 lb for single axles and 78,000–79,999 lb for tandem axles.
MEPDG_LG39	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 40,000–40,999 lb for single axles and 80,000–81,999 lb for tandem axles.
Description	VARCHAR2(255)	Description for codes used in NALS_CLUSTERS field.
Recommended_ Road_Usage	VARCHAR2(255)	Description indicating the recommended road usage for each default NALS.

Table 57. Field names and descriptions for table "SITE_SPECIFIC_AxlesPerTruck."

Field Name	Data Type	Description
STATE_CODE	NUMBER(2,0)	Numerical code for state or province. U.S. codes are consistent with Federal Information Processing Standards.
SHRP_ID	VARCHAR2(255)	Test section identification number assigned by the LTPP Program. Must be combined with STATE_CODE to be unique.
classNumber	NUMBER(2,0)	Code indicating the 13-bin classification into which trucks have been grouped.
numberAxle	NUMBER(1,0)	Type of axle for which the values in the field "truckAxleConfig" apply.
truckAxleConfig	NUMBER(1,2)	Number of this type of axle for a vehicle in this class.

Table 58. Field names and descriptions for table "SITE_SPECIFIC_NALS."

Field Name	Data Type	Description
STATE_CODE	NUMBER(2,0)	Numerical code for state or province. U.S. codes are consistent with Federal Information Processing Standards.
SHRP_ID	VARCHAR2(25 5)	Test section identification number assigned by the LTPP Program. Must be combined with STATE_CODE to be unique.
VEH_CLASS	NUMBER(2,0)	Code indicating the 13-bin classification into which trucks have been grouped.
AXLE_GROUP	NUMBER(1,0)	Type of axle for which these percentages of axles apply.
MEPDG_LG01	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 0–2,999 lb for single axles, 0–5,999 lb for tandem axles, and 0–11,999 lb for tridem and quad axles.
MEPDG_LG02	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 3,000–3,999 lb for single axles, 6,000–7,999 lb for tandem axles, and 12,000–14,999 lb for tridem and quad axles.
MEPDG_LG03	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 4,000–4,999 lb for single axles, 8,000–9,999 lb for tandem axles, and 15,000–17,999 lb for tridem and quad axles.

Field Name	Data Type	Description
MEPDG_LG04	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 5,000–5,999 lb for single axles, 10,000–11,999 lb for tandem axles, and 18,000–20,999 lb for tridem and quad axles.
MEPDG_LG05	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 6,000–6,999 lb for single axles, 12,000–13,999 lb for tandem axles, and 21,000–23,999 lb for tridem and quad axles.
MEPDG_LG06	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 7,000–7,999 lb for single axles, 14,000–15,999 lb for tandem axles, and 24,000–26,999 lb for tridem and quad axles.
MEPDG_LG07	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 8,000–8,999 lb for single axles, 16,000–17,999 lb for tandem axles, and 27,000–29,999 lb for tridem and quad axles.
MEPDG_LG08	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 9,000–9,999 lb for single axles, 18,000–19,999 lb for tandem axles, and 30,000–32,999 lb for tridem and quad axles.
MEPDG_LG09	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 10,000–10,999 lb for single axles, 20,000–21,999 lb for tandem axles, and 33,000–35,999 lb for tridem and quad axles.
MEPDG_LG10	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 11,000–11,999 lb for single axles, 22,000–23,999 lb for tandem axles, and 36,000–38,999 lb for tridem and quad axles.
MEPDG_LG11	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 12,000–12,999 lb for single axles, 24,000–25,999 lb for tandem axles, and 39,000–41,999 lb for tridem and quad axles.
MEPDG_LG12	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 13,000–13,999 lb for single axles, 26,000–27,999 lb for tandem axles, and 42,000–44,999 lb for tridem and quad axles.
MEPDG_LG13	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 14,000–14,999 lb for single axles, 28,000–29,999 lb for tandem axles, and 45,000–47,999 lb for tridem and quad axles.
MEPDG_LG14	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 15,000–15,999 lb for single axles, 30,000–31,999 lb for tandem axles, and 48,000–50,999 lb for tridem and quad axles.
MEPDG_LG15	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 16,000–16,999 lb for single axles, 32,000–33,999 lb for tandem axles, and 51,000–53,999 lb for tridem and quad axles.
MEPDG_LG16	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 17,000–17,999 lb for single axles, 34,000–35,999 lb for tandem axles, and 54,000–56,999 lb for tridem and quad axles.
MEPDG_LG17	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 18,000–18,999 lb for single axles, 36,000–37,999 lb for tandem axles, and 57,000–59,999 lb for tridem and quad axles.
MEPDG_LG18	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 19,000–19,999 lb for single axles, 38,000–39,999 lb for tandem axles, and 60,000–62,999 lb for tridem and quad axles.

Field Name	Data Type	Description
MEPDG_LG19	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 20,000–20,999 lb for single axles, 40,000–41,999 lb for tandem axles, and 63,000–65,999 lb for tridem and quad axles.
MEPDG_LG20	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 21,000–21,999 lb for single axles, 42,000–43,999 lb for tandem axles, and 66,000–68,999 lb for tridem and quad axles.
MEPDG_LG21	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 22,000–22,999 lb for single axles, 44,000–45,999 lb for tandem axles, and 69,000–71,999 lb for tridem and quad axles.
MEPDG_LG22	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 23,000–23,999 lb for single axles, 46,000–47,999 lb for tandem axles, and 72,000–74,999 lb for tridem and quad axles.
MEPDG_LG23	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 24,000–24,999 lb for single axles, 48,000–49,999 lb for tandem axles, and 75,000–77,999 lb for tridem and quad axles.
MEPDG_LG24	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 25,000–25,999 lb for single axles, 50,000–51,999 lb for tandem axles, and 78,000–80,999 lb for tridem and quad axles.
MEPDG_LG25	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 26,000–26,999 lb for single axles, 52,000–53,999 lb for tandem axles, and 81,000–83,999 lb for tridem and quad axles.
MEPDG_LG26	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 27,000–27,999 lb for single axles, 54,000–55,999 lb for tandem axles, and 84,000–86,999 lb for tridem and quad axles.
MEPDG_LG27	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 28,000–28,999 lb for single axles, 56,000–57,999 lb for tandem axles, and 87,000–89,999 lb for tridem and quad axles.
MEPDG_LG28	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 29,000–29,999 lb for single axles, 58,000–59,999 lb for tandem axles, and 90,000–92,999 lb for tridem and quad axles.
MEPDG_LG29	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 30,000–30,999 lb for single axles, 60,000–61,999 lb for tandem axles, and 93,000–95,999 lb for tridem and quad axles.
MEPDG_LG30	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 31,000–31,999 lb for single axles, 62,000–63,999 lb for tandem axles, and 96,000–98,999 lb for tridem and quad axles.
MEPDG_LG31	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 32,000–32,999 lb for single axles, 64,000–65,999 lb for tandem axles, and 99,000–101,999 lb for tridem and quad axles.
MEPDG_LG32	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 33,000–33,999 lb for single axles and 66,000–67,999 lb for tandem axles.
MEPDG_LG33	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 34,000–34,999 lb for single axles and 68,000–69,999 lb for tandem axles.
MEPDG_LG34	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 35,000–35,999 lb for single axles and 70,000–71,999 lb for tandem axles.

Field Name	Data Type	Description
MEPDG_LG35	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 36,000–36,999 lb for single axles and 72,000–73,999 lb for tandem axles.
MEPDG_LG36	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 37,000–37,999 lb for single axles and 74,000–75,999 lb for tandem axles.
MEPDG_LG37	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 38,000–38,999 lb for single axles and 76,000–77,999 lb for tandem axles.
MEPDG_LG38	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 39,000–39,999 lb for single axles and 78,000–79,999 lb for tandem axles.
MEPDG_LG39	NUMBER(3,14)	Percentage of axles whose weight falls in the bin 40,000–40,999 lb for single axles and 80,000–81,999 lb for tandem axles.

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