Title
Updating Weigh-in-Motion (WIM) Spectra in PaveM

Authors
Kim, Changmo
Lea, Jeremy D
Kannekanti, Venkata
et al.

Publication Date
2022-07-01

DOI
10.7922/G2JD4V3M

July 2022
Technical Memorandum: UCPRC-TM-2018-01

Updating Weigh-in-Motion (WIM) Spectra in PaveM

Authors:
Changmo Kim, Jeremy D. Lea, Venkata Kannekanti,
and John T. Harvey

Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) Numbers 3.28 and 5.08
(DRISI Tasks 2354 and 2706): Document PaveM Traffic Updating Processes

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation, and System Information
Office of Materials and Infrastructure

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NUMBER UCPRC-TM-2018-01	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE Updating Weigh-in-Motion (WIM) Spectra in PaveM	5. REPORT PUBLICATION DATE July 2022 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Changmo Kim (ORCID 0000-0001-9652-8675), Jeremy D. Lea (ORCID 0000-0003-3445-8661), Venkata Kannekanti (ORCID 0000-0001-6411-1760), and John T. Harvey (ORCID 0000-0002-8924-6212)	8. PERFORMING ORGANIZATION REPORT NO. UCPRC-TM-2018-01 UCD-ITS-RR-22-70
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California Pavement Research Center Department of Civil and Environmental Engineering, UC Davis 1 Shields Avenue Davis, CA 95616	10. WORK UNIT NUMBER 11. CONTRACT OR GRANT NUMBER
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Division of Research, Innovation, and System Information P.O. Box 942873 Sacramento, CA 94273-0001	13. TYPE OF REPORT AND PERIOD COVERED Technical Memorandum November 2014 to October 2017 14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES
doi:10.7922/G2JD4V3M

16. ABSTRACT

Weigh-in-motion (WIM) devices measure and record highway vehicle axle loads. The data they collect include axle loads and spacing, vehicle classification and gross weights, and travel speed. These WIM data are used for pavement design, management, and performance studies. In 2016, there were 123 WIM devices operating on sites throughout the California state-owned highway network, one of the densest and best maintained in the United States. The University of California Pavement Research Center (UCPRC) has studied California's WIM data with the California Department of Transportation (Caltrans) since 2007 to advance mechanistic-empirical (ME) pavement design procedures. Previously, the UCPRC completed the first analysis of the WIM data collected from 1998 to 2003 to discover similarities in axle load distributions at the WIM sites and then grouped them using cluster analysis to generate default traffic inputs for pavement design software. For this research, the UCPRC processed WIM data collected from 80 California WIM-measuring sites from 2004 to 2015, identified the axle load distribution for each site, and updated the earlier grouping using hierarchical cluster analysis. A decision tree was developed to classify WIM data into five WIM axle load spectra, which have been implemented in the Caltrans pavement management system database, *PaveM*, to generate truck traffic inputs in the *CalME* and *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*) pavement design software tools used by Caltrans for asphalt and concrete pavement design, respectively.

17. KEY WORDS weigh-in-motion, WIM, axle load spectra, axle load distribution, truck traffic, PaveM	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. SECURITY CLASSIFICATION (of this report) Unclassified	20. NUMBER OF PAGES 63	21. PRICE None

Reproduction of completed page authorized

UCPRC ADDITIONAL INFORMATION

1. DRAFT STAGE Final	2. VERSION NUMBER 1
3. PARTNERED PAVEMENT RESEARCH CENTER STRATEGIC PLAN ELEMENT NUMBER 3.28 and 5.08	4. DRISI TASK NUMBER 2354 and 2706
5. CALTRANS TECHNICAL LEAD AND REVIEWER Imad Basheer	6. FHWA NUMBER CA222706A
7. PROPOSALS FOR IMPLEMENTATION	
8. RELATED DOCUMENTS	
9. LABORATORY ACCREDITATION The UCPRC laboratory is accredited by AASHTO re:source for the tests listed in this report	AASHTO ACCREDITED

10. SIGNATURES

C. Kim **FIRST AUTHOR**	J.T. Harvey **TECHNICAL REVIEW**	C. Fink **EDITOR**	J.T. Harvey **PRINCIPAL INVESTIGATOR**	I. Basheer **CALTRANS TECH. LEADS**	T.J. Holland **CALTRANS CONTRACT MANAGER**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

ACKNOWLEDGMENTS

This technical memorandum describes research activities requested and sponsored by the California Department of Transportation (Caltrans) Division of Research, Innovation, and System Information. Caltrans sponsorship is gratefully acknowledged. The contents of this technical memorandum reflect the views of the authors and do not reflect the official views or policies of the State of California or the Federal Highway Administration.

LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AADTT	Annual average daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
ASCII	American Standard Code for Information Interchange
EMD	Earth Mover's Distance
ESAL	Equivalent single-axle load
LCA	Life cycle assessment
LRS	Linear referencing system
ME	Mechanistic-empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
PeMS	Performance Measurement System
TSN	Transportation Systems Network
UCPRC	University of California Pavement Research Center
WIM	Weigh-in-motion

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
		MASS		
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
		AREA		
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised April 2021)

PROJECT OBJECTIVES

The objectives of this project, part of Partnered Pavement Research Center Strategic Plan Elements 3.28 and 5.8, were to analyze recent weigh-in-motion (WIM) data collected on California state-owned highways and to develop a set of representative axle load spectra that can be used in pavement mechanistic-empirical (ME) design, pavement management performance modeling, and life cycle assessment. These objectives were accomplished by performing the following set of tasks:

- Obtain recent Caltrans WIM data (binary files), clean them, and then convert them into a relational database that makes them accessible and ready for computations.
- Develop axle load spectra for the various axle groups of each truck type, and compare these with spectra from varied locations and time periods.
- Characterize past truck traffic loading patterns, including truck speeds and gross weights.
- Extrapolate the WIM spectra to highway segments where no WIM devices are installed.
- Develop a traffic calculation tool that generates traffic input files for the *AASHTOWare Pavement ME Design* software (previously known as the *Mechanistic-Empirical Pavement Design Guide* [*MEPDG*]).

1 INTRODUCTION

1.1 Background

Highway pavements deteriorate from the environment and traffic, and the interaction of the two, and nearly all the traffic-related damage is due to heavy trucks. Historically, truck traffic data used for pavement design were typically aggregated into equivalent repetitions of a standard axle load (equivalent single-axle load [ESAL]). However, starting in 2000, the California Department of Transportation (Caltrans) and the University of California Pavement Research Center (UCPRC) began development and evaluation of mechanistic-empirical (ME) pavement design procedures for both rigid and flexible pavement types *(1)*.

The UCPRC also undertook development of pavement analysis and design models for the Caltrans ME pavement design software, *CalME*, for flexible pavement *(1)*. The UCPRC ME procedure uses axle load spectra for specific cases where a particular level of detail is required. An *axle load spectra* is defined as the load distribution of an axle group during a specific time period *(2),* and these spectra can be calculated using weigh-in-motion (WIM) data. These data are gathered by a WIM system that continuously measures and stores axle load and spacing data about each truck that passes through a WIM site *(3)*.

1.2 Weigh-in-Motion

Since 1987, Caltrans has operated 123 WIM sites at key highway locations to collect, process, and store truck traffic data *(1)*. Caltrans also maintains a detailed collection of historical truck traffic data from highway sites statewide. The WIM system types currently used in California fall into two categories: (1) regular data collection sites (107 sites) and (2) weigh station bypass sites (16 sites). The former collects truck traffic data on California highways, and the latter is used in the PrePass™ operation that enables registered heavy vehicles to legally bypass weigh stations after electronic verification *(3)*. The bypass WIM system only stores data to be used for performance checks on the regular data collection sites. As a result, the data analyzed in this study were collected from the regular WIM sites only.

1.2.1 How WIM Works

California's WIM system operates by using bending plate scales that determine the wheel load estimates and inductive loop detectors that determine when a vehicle is present, vehicle speeds, and overall vehicle lengths. The scale's steel bending plates are typically 2 in. to 3 in. thick, 20 in. to 24 in. wide, and 6 ft. long, and they are secured in frames anchored and epoxy-bonded into the pavement (Figure 1.1). Caltrans typically uses an "in-line" configuration, where two bending plates are installed side by side in each lane with one plate for each wheelpath.

Figure 1.1: Example WIM site (*4*).

As a vehicle passes over the WIM system sensors, the sensors instantaneously record dynamic axle loads and axle spaces, the number of axles, vehicle speed, overall vehicle length, lane and direction of travel, and the date and time. Each WIM system is calibrated to produce the best possible estimate of static gross weight and the portion of that gross weight carried by each wheel for the majority of the vehicles passing through the WIM site. WIM system accuracy depends primarily on vehicle dynamics and the inherent variances of the technology used within the system. A structurally sound and extremely smooth pavement is also critical for a WIM system to generate accurate wheel load estimates.

1.2.2 Literature Review

Many researchers have used various approaches to analyze WIM data for truck traffic studies and for traffic input generation for *Mechanical-Empirical Pavement Design Guide* (*MEPDG*) tools, including the *AASHTOWare Pavement ME Design* software. States where research has been undertaken include California, Louisiana, North Carolina, and Virginia *(2,5-9)*.

In Louisiana, researchers grouped portable WIM sites based on the degree of similarity between two distributions of a pair of WIM sites *(6)*. They calculated the degree of similarity using the sum of squares of the difference between the two-axle load distributions at corresponding intervals and further analyzed the axle load spectra per truck classification group. However, they were unable to determine seasonal and long-term variation because the study only used 48 hours of data collected at the portable sites, which was too small an amount to determine those variations.

Researchers in North Carolina conducted a hierarchical clustering analysis and a post-clustering analysis for each axle load with four traffic parameters: truck volume, truck percentage, the ratio of Class 5 to Class 9 (5/9) vehicles, and the ratio of Class 4 to 7 (4/7) to Class 8 to 13 (8/13) vehicles *(7)*. Researchers analyzed 15 Virginia WIM sites to develop site-specific traffic data inputs for the *MEPDG* pavement design method *(8)*. They compared site-specific axle load spectra with the *MEPDG* defaults by comparing WIM-based and non-WIM-based parameters and showing the differences between the two. In another study, researchers conducted a sensitivity analysis of the predicted pavement performances for the *MEPDG* software's default traffic input parameters and site-specific parameters in Ontario, Canada, and found differences in the axle load spectra *(9)*.

These research findings demonstrate that rather than using the default axle load spectra in the *MEPDG*, axle load spectra for use with the ME design method should be developed with site-specific traffic parameters by region to obtain a more accurate performance analysis.

1.3 Objectives

The objectives of this project, part of Partnered Pavement Research Center Strategic Plan Elements 3.28 and 5.8, were to analyze recent WIM data collected on California highways and to develop a set of representative axle load spectra that can be used in pavement ME design, pavement performance models, and life cycle assessment. These objectives were to be accomplished by performing the following set of tasks:

- Obtain recent Caltrans WIM data (binary files), clean them, and then convert them into a relational database that makes them accessible and ready for computations.
- Develop axle load spectra for the various axle groups of each truck type, and compare these with spectra from varied locations and time periods.
- Characterize past truck traffic loading patterns, including truck speeds and gross weights.
- Extrapolate the WIM spectra to highway segments where no WIM devices are installed.
- Develop a traffic calculation tool that generates traffic input files for the *AASHTOWare Pavement* software (previously known as the *Mechanistic-Empirical Pavement Design Guide* [*MEPDG*]).

1.4 Overall Approach

The overall approach taken in this project was to analyze newer WIM data with a statistical method (cluster analysis using the Earth Mover's Distance [EMD]) to develop representative axle load spectra per WIM group. First, raw binary data files for 2004 to 2015 were obtained from the WIM sites. Using the tool *iAnalyze*,[1] these files were converted into files with a readable format (American Standard Code for Information Interchange [ASCII]) that included Caltrans vehicle classifications and were then imported into the WIM database. Sampled ASCII files in the database were then subjected to a cluster analysis that aggregated data from 80 of the WIM sites into seven WIM groups based on their axle load spectra similarities. A decision tree using explanatory variables from the other database in *PaveM* (highway log and traffic information) then categorized the seven groups into five WIM axle load spectra. These final five WIM axle load spectra were used to determine the axle load spectra of each segment in the California state-owned highway network. These results were then used to develop a traffic calculation tool to generate traffic input files for the *AASHTOWare Pavement ME Design* software.

It should be noted that this process used axle load spectra based on updated WIM data collected from 2004 to 2015. These newer data are used in *AASHTOWare*, *CalME*, *PaveM*, and the *eLCAP* life cycle assessment (LCA) application tool.

The study's overall approach for updating the WIM spectra and developing the applications is shown in the flow chart in Figure 1.2. The dotted outlined boxes indicate the data sources required for this study, and the dashed outlined boxes show each step for grouping axle load spectra. The solid outlined box indicates the procedure performed in the *PaveM* database, and the ovals show the application tools that use WIM spectra.

1.5 WIM Data Uses in Caltrans Tools

Caltrans has developed a number of software applications that use multiple databases and models for pavement design and management, construction analysis, LCA, and life cycle cost analysis. Figure 1.3 illustrates the interactions among the databases, models, and software/applications for pavement engineering. As the figure shows, the *PaveM* traffic database, *PaveM* network performance models, and the *AASHTOWare*/*CalME* traffic generator programs all use these data, and the data are subsequently used by the *PaveM* pavement management software, the *CalME* design program, and the *eLCAP* LCA program.

---

[1] Developed by International Road Dynamics, Inc. irdinc.com/public/uploads/downloads/1452713024_iAnalyze5.12_manual.pdf.

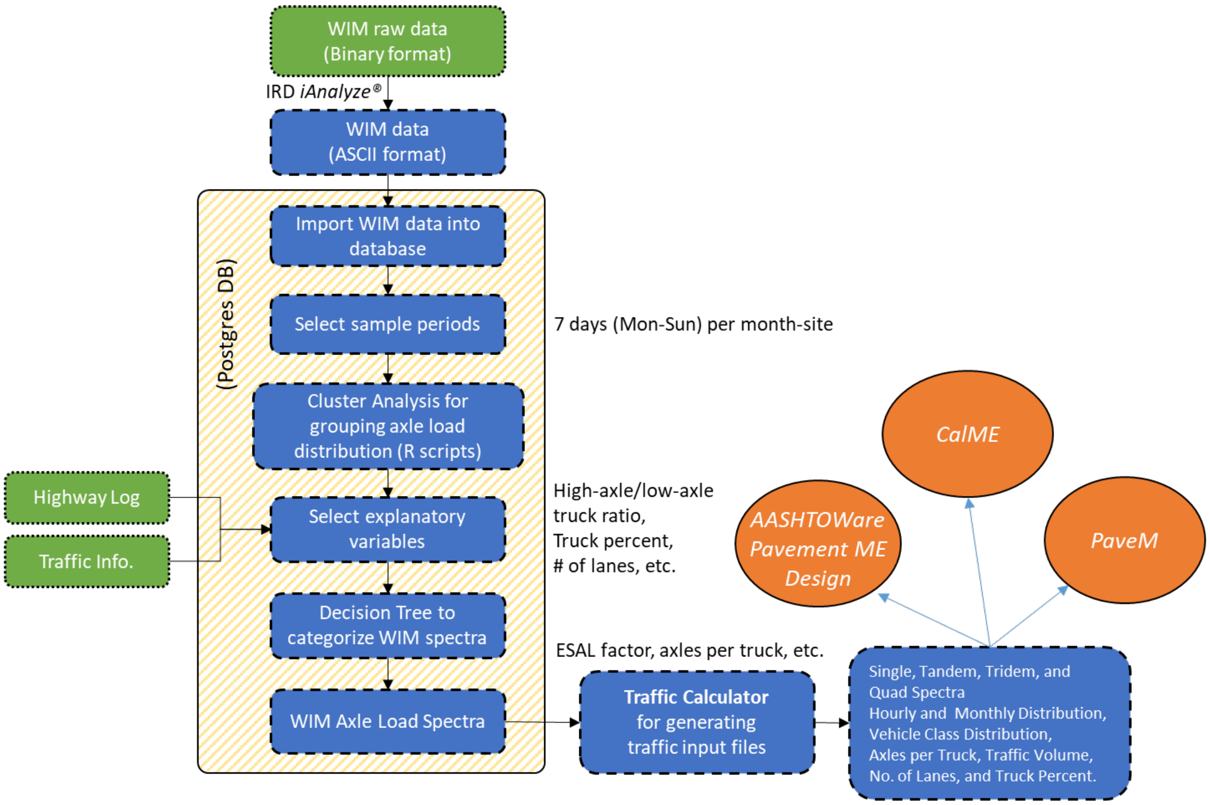


Figure 1.2: Study flow for updating WIM spectra and implementation.

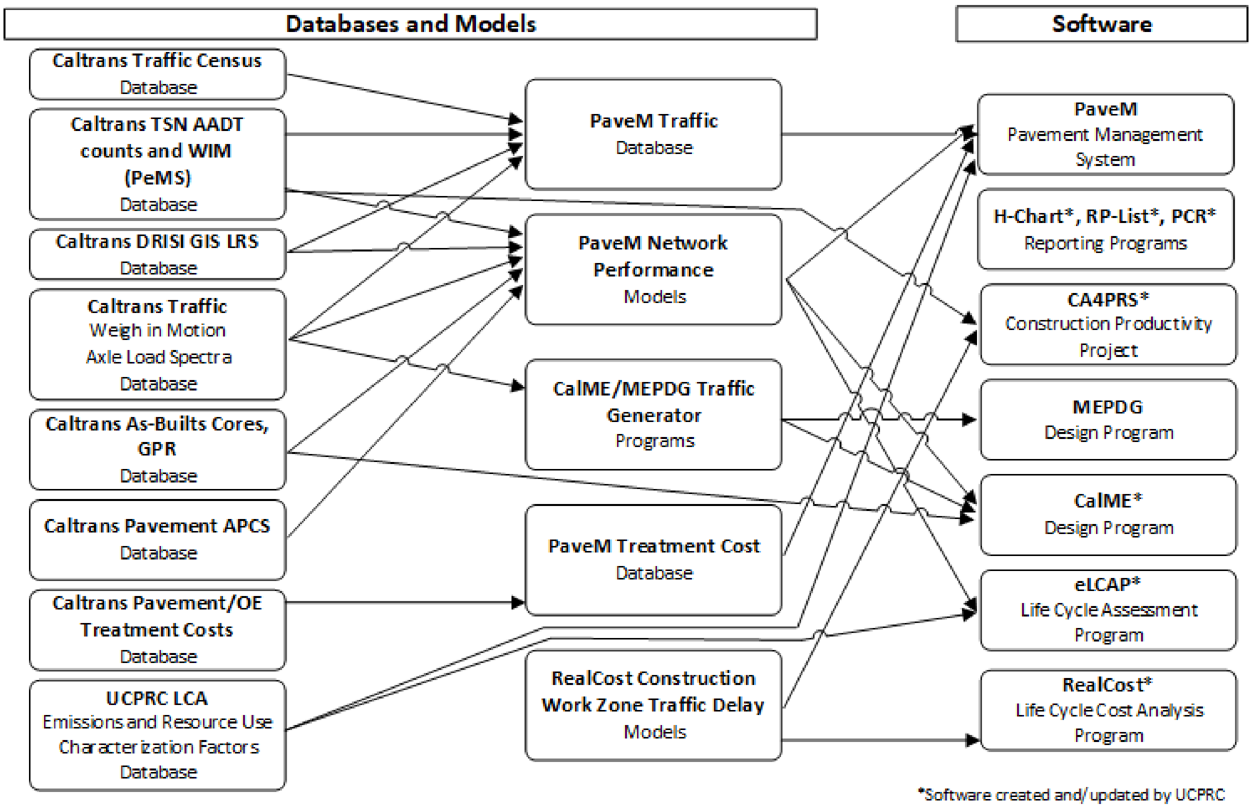


Figure 1.3: Caltrans pavement engineering and database/software interactions.

One component of the Caltrans pavement management system, *PaveM*, is the optimization system, *Pavement Analyst*. The *Pavement Analyst* application uses WIM axle load spectra in its pavement performance calculations. The *CalME/MEPDG* traffic generator also utilizes WIM axle load spectra to generate a set of traffic inputs for running *AASHTOWare Pavement* software for rigid pavements. The program *CalME,* which is used for ME flexible pavement design, takes the WIM axle load spectra from the *CalME/MEPDG* traffic generator to determine traffic loads in its calculations. The LCA application tool *eLCAP* uses WIM axle load spectra as the input parameters in the LCA procedure.

2 DATA DESCRIPTION

WIM devices collected data for one direction at 53 sites and data for two directions at 27 sites. The resulting data available for this study therefore included one-direction WIM data on 107 locations. (No data from 16 pre-pass sites were included in the analysis due to a lack of specific information on lane numbering.) These data, collected from 2004 to 2015, were provided by the Caltrans Office of Commercial Vehicle Operations, which is under the Division of Traffic Operations. Each month Caltrans performs a data quality check on each WIM site to ensure that WIM devices are operating properly, to adjust for calibration drift, and to ensure the proper coding of vehicle records containing questionable data elements. All the WIM devices selected for this study were reported by Caltrans to be in good condition after routine monthly checks.

Previous UCPRC research includes an overview of the California WIM system (*2*). It should be noted that Caltrans implemented a revised vehicle classification definition that was a slight modification of the Federal Highway Administration (FHWA) vehicle classification system with two truck classes added: Class 14 (five-axle truck trailers) and Class 15 (irregular trucks and trucks unclassified due to system error).

Before September 2012, Caltrans WIM sites had two types of WIM devices, one manufactured by PAT Traffic Control Corporation and one by International Road Dynamics, Inc. PAT Traffic Control had provided three models of its device type—the DAW 100, DAW 190, and DAW 200—and International Road Dynamics had provided a single model, the IRD. The two vendors used different data formats and software. In September 2012, Caltrans replaced all the PAT devices with IRD devices, and the IRD devices have been used in all California WIM sites since then.

2.1 List of WIM Sites

At the end of 2015, Caltrans operated 123 WIM sites on California's highway network (Table 2.1). Caltrans districts with larger networks had a greater number of WIM sites than smaller districts. District 4 operated the largest number of WIM sites (22 sites), and District 8 operated the second largest number (19 sites). District 1 (3 sites) and District 2 (4 sites) were among those with the fewest sites. Appendix A shows the list of WIM sites with district, county, route, direction, and post mile information.

Table 2.1: Number of WIM Sites in Each District (Excluding Pre-Pass Sites)

District	Number of Existing WIM Sites
District 1	3
District 2	4
District 3	10
District 4	22
District 5	6
District 6	7
District 7	16
District 8	19
District 9	5
District 10	8
District 11	14
District 12	9
Total	123

2.2 WIM Data Quality

California WIM site data quality has improved significantly due to recently enhanced communication and calibration technologies. The percent of days with good quality data in 2004 was only 31%, but by 2015 that had risen to 85% for the data used in this study (Table 2.2). Appendix B shows the percentage of good quality data per year on each WIM site from 2004 to 2015.

Table 2.2: Quality Summary of WIM Collection Days (2004 to 2015)

Year	Number of Days					Percentage Good (%)
	Good[a]	Partial Good[b]	Bad	Missing	All	
2004	13,531	0	7,066	22,925	43,522	31
2005	15,989	0	4,051	23,794	43,834	36
2006	12,647	0	8,142	23,107	43,896	29
2007	13,941	178	3,748	26,025	43,892	32
2008	26,520	252	6,170	10,954	43,896	60
2009	30,336	0	5,696	8,413	44,175	69
2010	27,587	0	10,335	6,290	44,268	62
2011	25,713	825	10,273	7,306	44,268	58
2012	29,726	1,756	1,366	7,639	40,578	73
2013	34,517	0	0	9,007	43,524	79
2014	36,202	0	5	7,317	43,524	83
2015	36,942	0	1	6,581	43,524	85
Average	25,304	251	4,738	13,280	43,575	58

[a] "Good" indicates that the WIM device provided high quality data for 90% of the day it operated.
[b] "Partial Good" indicates that the WIM device provided high quality data for 75% of the day it operated.

2.3 Sample Data Selection

A total of 481,000 binary raw files (185 gigabytes) stored from 123 WIM sites from 2004 to 2015 were converted to two ASCII file formats. Using *iAnalyze*, the files were made readable and imported into the WIM database (2.5 terabytes) stored on a UCPRC server. One of the ASCII formats is used for vehicle classification by the Federal Highway Administration (FHWA) and the other by Caltrans. The WIM spectra analysis in this study used the Caltrans format.

Computation time for analyzing the data was extremely long so the process was expedited by having the query only include data for the first seven consecutive days (Monday to Sunday) of each month at each site in the analysis. This data selection query included data reflecting yearly and seasonal variations and variations of day of week (Monday to Sunday). The variation within a month (week to week) was small and neglectable. When a missing day was identified during this period, it was replaced with data for the same day in the next week for which good quality data were available.

3 ANALYSIS AND RESULTS

3.1 WIM Axle Load and Gross Vehicle Weight Summary

This chapter discusses WIM axle load distribution and gross vehicle weight trends over the 11 years from 2005 to 2015. The averages of single-axle and tandem-axle load distributions and gross vehicle weights were analyzed per year during the analysis period.

3.1.1 WIM Axle Load

Axle load spectra for all the single axles from the 80 WIM sites were compared for 2005, 2010, and 2015. As shown in Figure 3.1, the three single-axle load spectra follow similar patterns and do not show any significant differences. The axle load at 20 kN is the largest proportion, between 25% and 30%, and the axle load at 30 kN is the second largest proportion, 15%. The 2015 axle load spectra shows a slightly higher 20 kN proportion and lower 70 kN and 80 kN proportions than the 2005 axle load spectra. This indicates that a single-axle load was typically slightly lighter in 2015 than in 2005. (Note: The standard single-axle load of 18 kips is equivalent to 80 kN.)

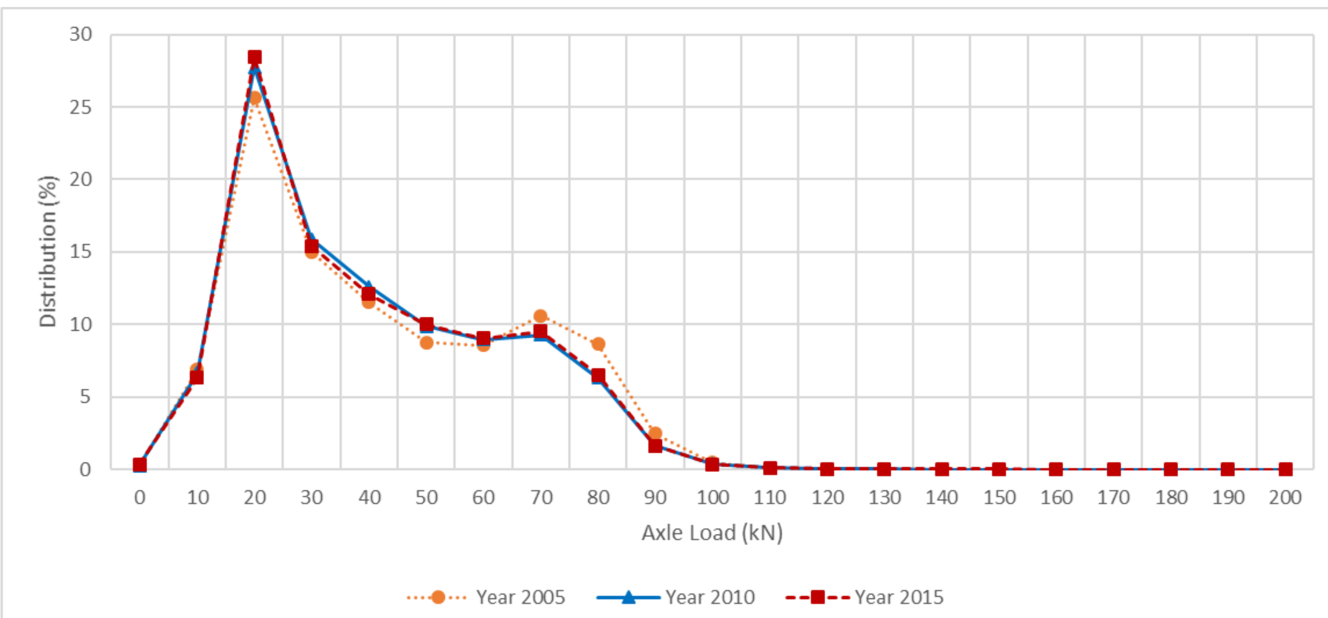


Figure 3.1: WIM axle load spectra of single axles for 2005, 2010, and 2015.

Figure 3.2 shows the tandem-axle load spectra trend for 2005, 2010, and 2015. Similar to the single-axle load spectra, the tandem-axle load spectra also show that tandem-axle loads were slightly lighter in 2015 compared to 2005. The heavy axle loads (140 kN and 160 kN) decreased slightly over those years, but in 2015 the light (60 kN) and medium axle loads (80 kN and 120 kN) increased.

The axle load spectra trends shown in Figure 3.1 and Figure 3.2 reveal that the truck axle loads for single and tandem axles over the 11-year span did not change significantly.

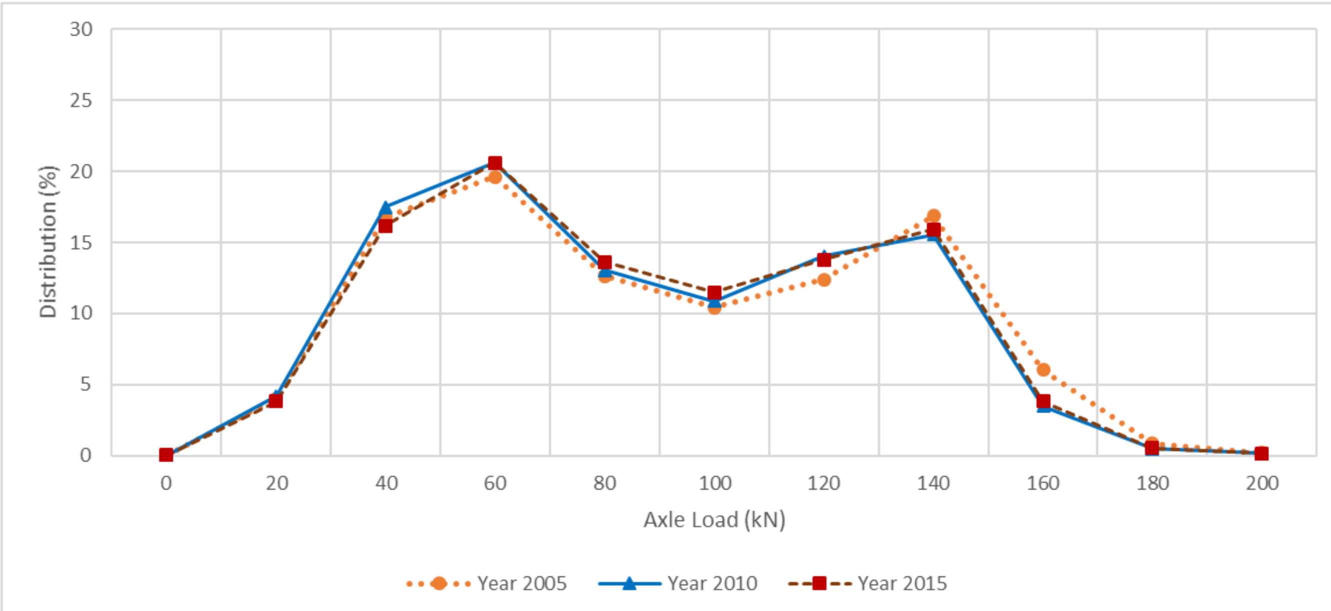


Figure 3.2: WIM axle load spectra of tandem axles for 2005, 2010, and 2015.

3.1.2 Average Gross Vehicle Weight

Average gross vehicle weights for each vehicle class over the 11-year period from 2005 to 2015 were also extracted from the WIM database and analyzed to identify any changes over time. Figure 3.3 shows the average gross vehicle weights of Vehicle Class 13, vehicles with seven or more axles (Figure 3.4), were the heaviest each year, ranging between 90 and 100 kips. The average gross vehicle weight increased from 94.85 kips in 2005 to 98.81 kips in 2010 and decreased to 91.39 kips in 2015. The lightest gross vehicle weights were observed in Vehicle Class 5, vehicles with two axles; these weights showed a narrow range, from 13.40 to 13.86 kips, meaning there was almost no change over time. The average gross vehicle weights of Vehicle Classes 6, 7, and 8 slightly increased in 2015 compared to 2005. The average gross vehicle weights for the heavy vehicles decreased by 3% to 4%, while the average gross vehicle weights for light and medium vehicles increased by 1% to 4% over the 11 years.

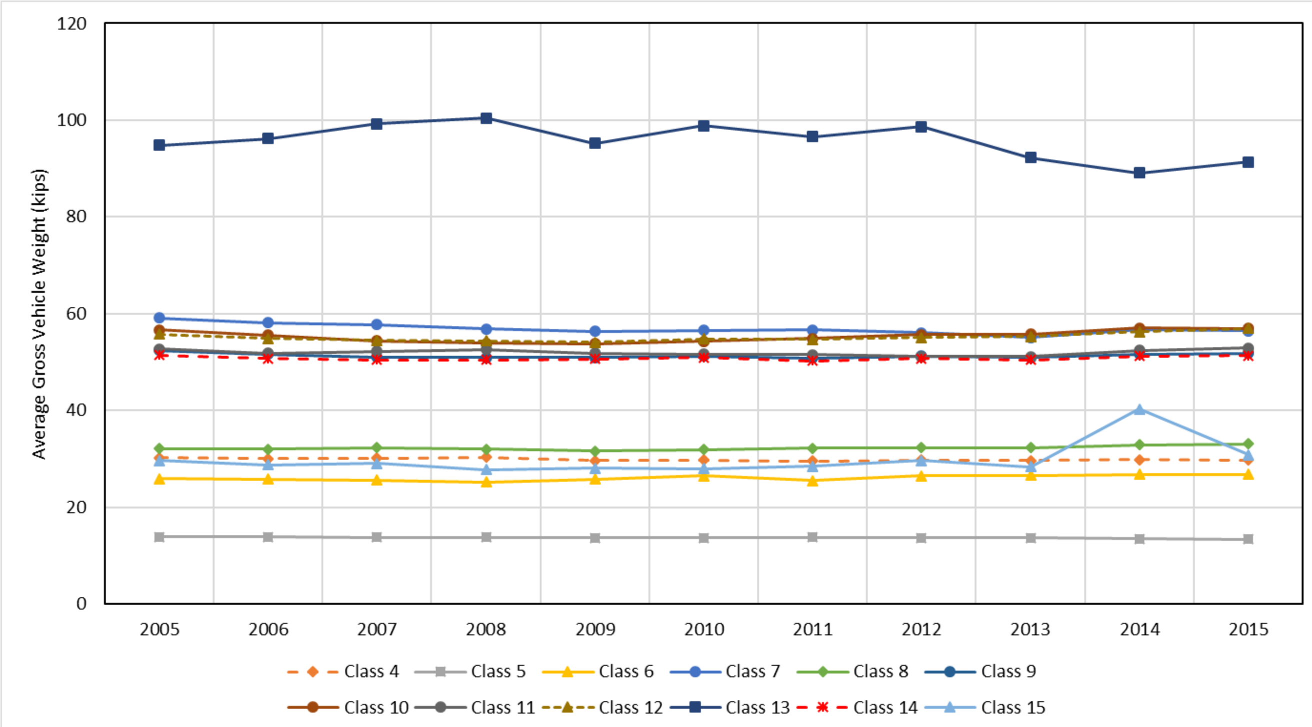


Figure 3.3: Annual average gross vehicle weight per vehicle class from 2005 to 2015.

The weighted average gross vehicle weights of Vehicle Classes 8 through 14, which all contain semi-tractor trailers, was 50.18 kips for the analysis period (2005 to 2015). About 80% of the heavy vehicles (semi-tractor trailers, Vehicle Class 8 to Vehicle Class 14) were found in Vehicle Class 9, and its average gross vehicle weight was 51.26 kips, shown in Table 3.1. The average gross vehicle weight trend over time was consistent with the WIM axle load spectra trend over that same time.

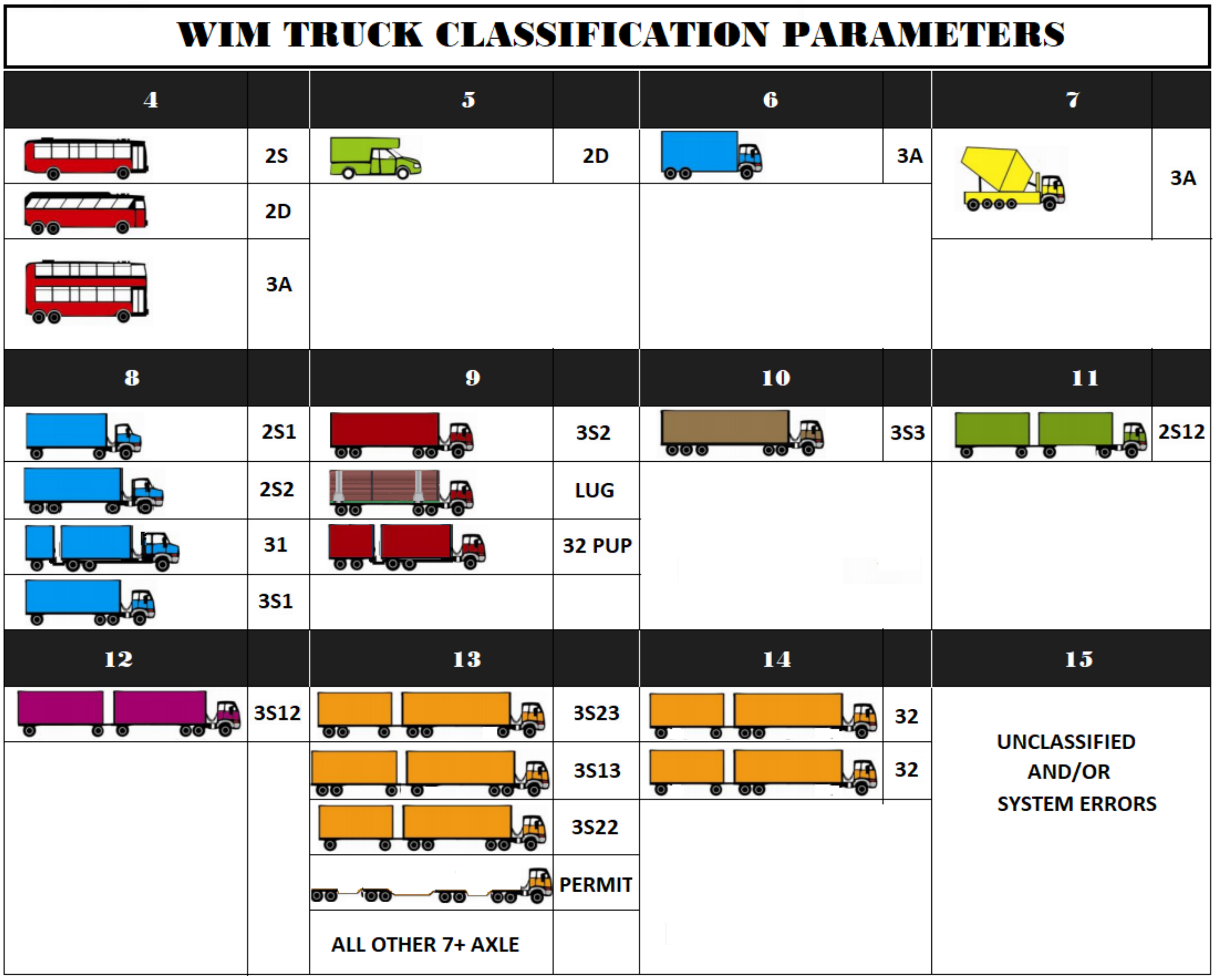


Figure 3.4: Typical vehicle profiles for Caltrans truck types.

Table 3.1: 2015 Proportion and Average Gross Vehicle Weight (Heavy Vehicles) Proportions from 2005 to 2015 by Vehicle Class

Vehicle Class	Proportion (2015) (%)	Average Gross Vehicle Weight (2005 to 2015) (kips)
Class 8	6.6	32.29
Class 9	81.7	51.26
Class 10	0.5	55.56
Class 11	7.0	52.12
Class 12	1.5	55.21
Class 13	0.1	90.23
Class 14	2.6	50.93
Total	100	50.18

3.1.3 Average Vehicle Speed

Heavy vehicle speed information is also useful in pavement design and analysis. The average speeds of heavy vehicles by vehicle class were calculated for each year from the 2004 to 2015 WIM data. Figure 3.5 shows the average speed change for each vehicle class at all WIM sites for that 12-year analysis period. The overall average speed of Vehicle Classes 5 through 14 decreased by 11.0%, from 55.8 mph in 2004 to 49.7 mph in 2015. The average speed for each vehicle class (Vehicle Classes 5 through 15) gradually decreased over these years. From 2004 to 2015, Vehicle Class 10 showed the largest average speed decrease, 16.7%, and Vehicle Class 12 showed the smallest average speed decrease, 4.5%.

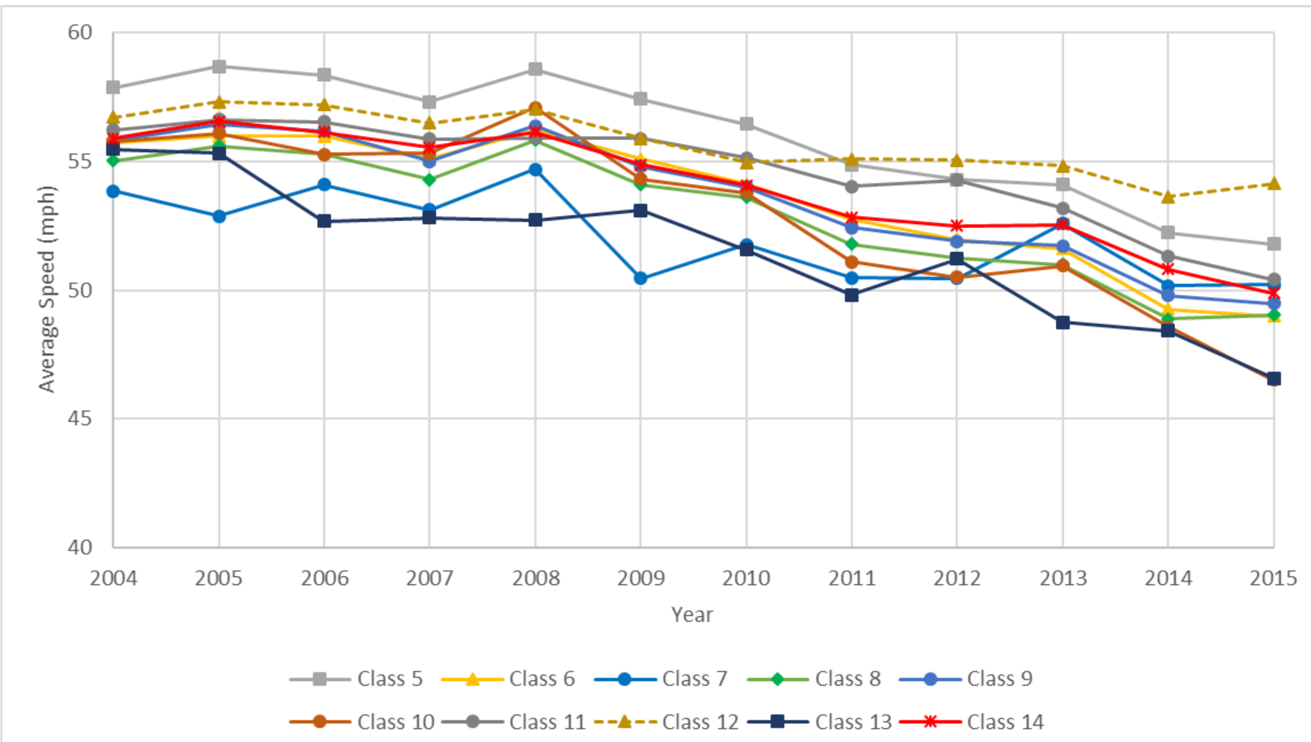


Figure 3.5: Average speed per vehicle class from 2004 to 2015.

Figure 3.6 shows the average speeds of Vehicle Classes 5, 9, and 13, and Vehicle Classes 5 through 15 at each WIM site in 2015. For Vehicle Classes 5 through 15, 1% of the WIM sites showed average speeds under 45 mph and 3% of the sites showed average speeds in the 45 to 50 mph range, 60% showed average speeds in the 55 to 60 mph range, and 20% showed average speeds over 60 mph. The overall weighted average speed of all the WIM sites was 57 mph for Vehicle Classes 5 through 15. The average speed for each vehicle class at each WIM site is shown in Appendix C.

Figure 3.6 shows that of all the WIM sites in 2015, Vehicle Class 5 showed the highest average speed, 62 mph, and Vehicle Class 13 showed the lowest average speed, 55 mph. While no reason could be determined for the overall decrease in speeds, it was suspected that increased congestion is a likely explanation.

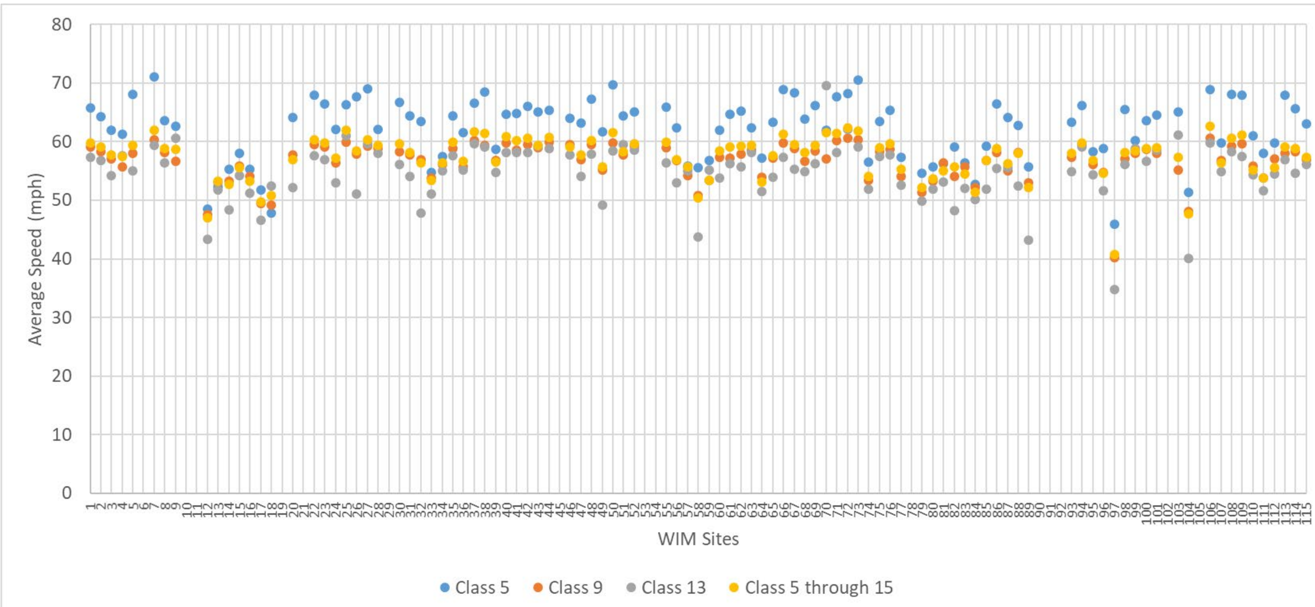


Figure 3.6: Average speeds of Vehicle Classes 5, 9, 13, and all vehicles at each WIM site in 2015.

3.2 Cluster Analysis

3.2.1 Analysis Approach

The 80 WIM sites were grouped by their axle load distribution similarities using cluster analysis in *R*, the statistical program.[2] The Earth Mover's Distance (EMD) method, a hierarchical clustering algorithm, was applied to group the individual WIM sites into clusters by the weighted axle load (squared axle load) distribution. The EMD is a method for evaluating dissimilarity between two multidimensional distributions in a feature space with a measurable distance between the features, which is called the *group distance* (*10*). The EMD method's basic approach is to calculate the number of cuts and fills in a civil engineering earthwork by using the elevation difference between the land profile and the elevation of the vertical alignment at each survey station. The *minimum balance* of the total earthwork takes the shortest time and lowest cost to complete the job. The EMD method is used predominantly in the field of data science. Equation (3.1) shows an EMD algorithm.

[2] The R Project for Statistical Computing. r-project.org.

Given two signatures P and Q,

$$EMD(P,Q) = \min_{F=\{f_{i,j}\}} \frac{\sum_{i,j} f_{i,j} d_{i,j}}{\sum_{i,j} f_{i\,j}} \tag{3.1}$$

with the following constraints:

$$\sum_j f_{i,j} \leq p_i, \sum_j f_{i,j} \leq q_j, \sum_{i,\,j} f_{i,j} = min\ \{\sum_i p_i, \sum_j q_j\}, f_{i,j} \geq 0$$

Where:

$F = \{f_{i,j}\}$ denotes a set of flows. Each flow $f_{i,j}$ represent the amount of transported from the i^{th} supply to the j^{th} demand *(10)*.

In the hierarchical cluster analysis, the distance between each pair of WIM stations was computed by taking the square of the axle loads as the horizontal distance and the cumulative axle load distribution as the land surface profile. However, before this could be done, the tandem and tridem axles had to be converted to single axles by dividing the loads into halves or thirds, and doubling or tripling the number of axles. This step allowed for comparison of single equivalent axle load spectra for all three types of axles (single, tandem, and triple axles) on loads (kN) at each WIM site. These are referred to as *single equivalent axle loads* in the remainder of this technical memorandum.

The full distance matrix is passed to the hierarchical clustering algorithm, which recursively finds the nearest pair of distinct clusters and merges them into one group. This process is repeated until the number of clusters is reduced to a single one and the hierarchy of clusters is returned as a tree structure.

3.2.2 Analysis Results

Using this cluster analysis, the 80 WIM sites were grouped into seven groups, Groups A to G. Group A included the WIM site that showed the lightest axle load distribution, and Group G included the WIM sites that showed the heaviest axle load distribution, shown in Figure 3.7. The y-axis shows the distance between a pair of properties, with a larger distance indicating a larger dissimilarity between the two properties (groups).

Group A has one WIM site (WIM ID 049 on Route 49 in District 3), and Group C has 21 sites. Group G contains five WIM sites that were located in Districts 2, 3, 6, and 8.

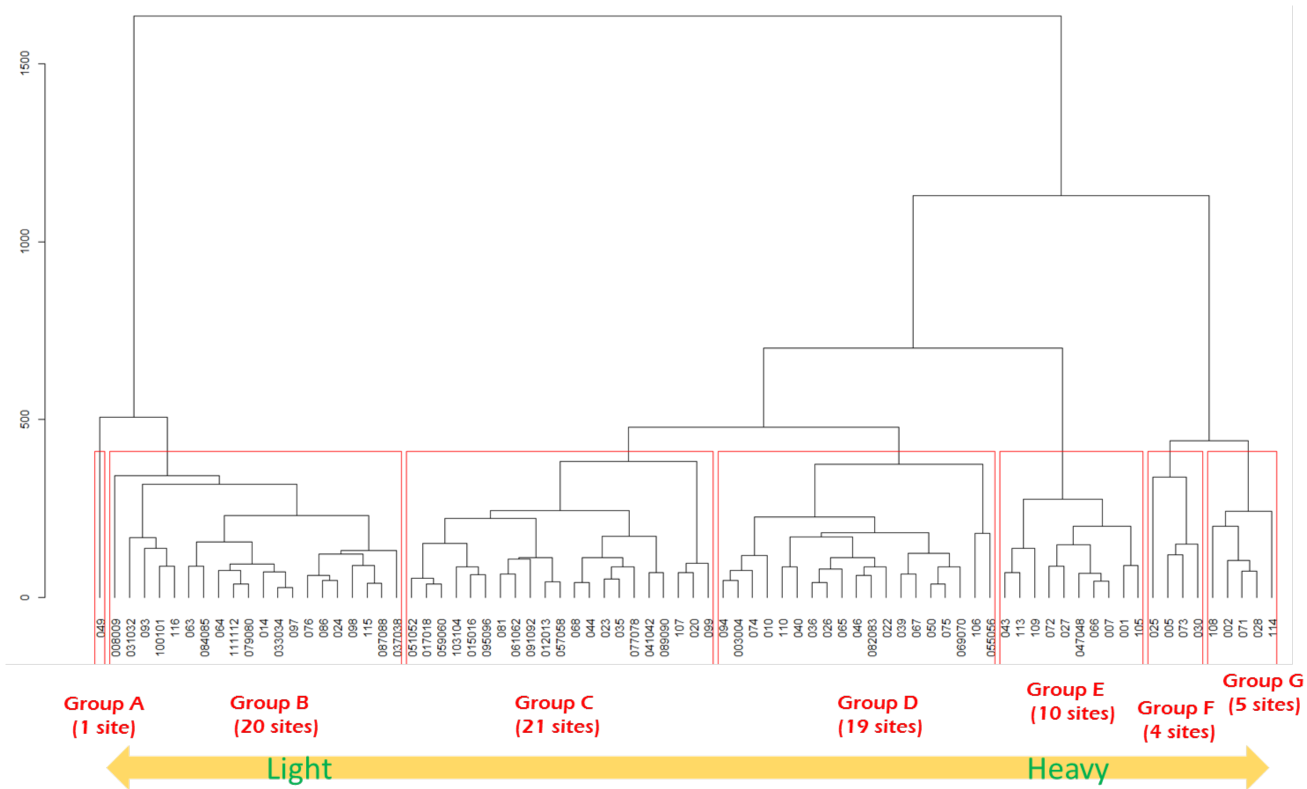


Figure 3.7: Cluster analysis result: Group A through Group G.

Figure 3.8 shows the distribution of WIM site Groups A to G from the lowest number of equivalent single-axle loads (ESALs) per 1,000 axles to the highest number. Groups A and B, which contain the lightest axle load spectra, are mostly under 200 ESALs per 1,000 axles, and Groups F and G, which contain the heaviest axle load spectra, are mostly over 330 ESALs per 1,000 axles. This plot shows the consistency of the WIM grouping results. Although it is possible to group WIM spectra using number of ESALs for the WIM sites, the EMD method actually compares axle load distributions of two sites and not just their axle loads.

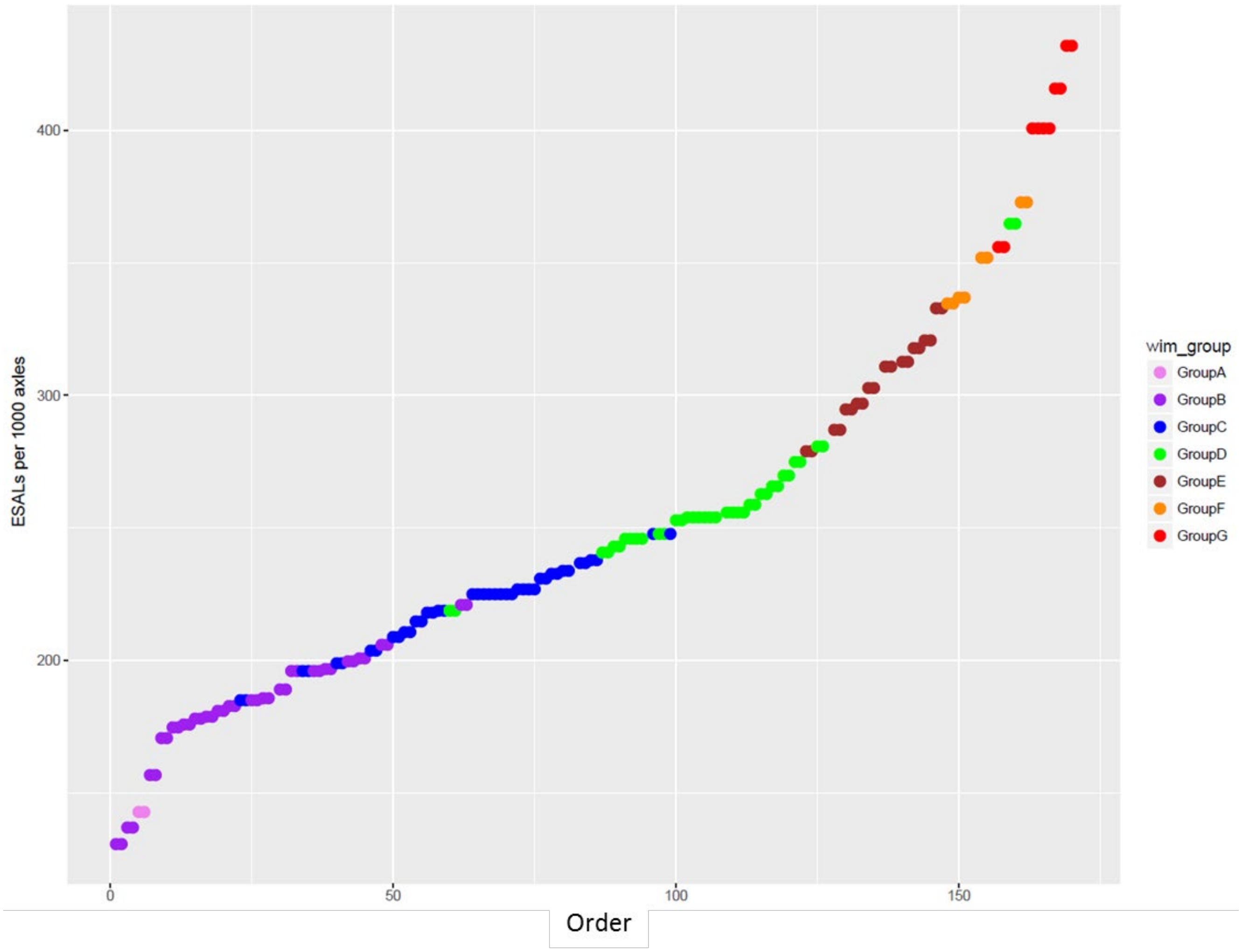


Figure 3.8: Distribution of WIM site Groups A through G based on number of equivalent single-axle loads (ESALs) per 1,000 axles.

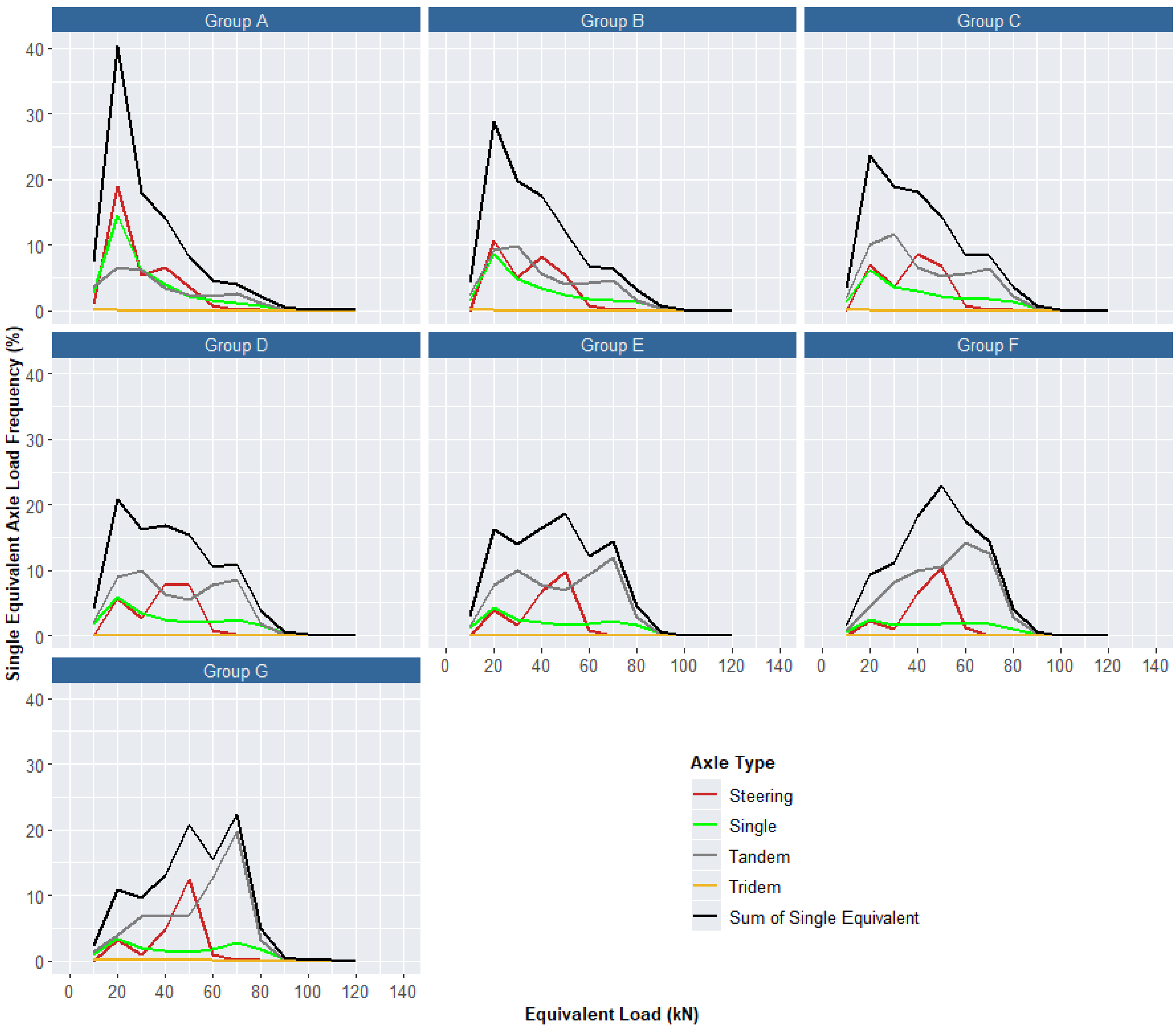
Table 3.2 lists the WIM site locations for each WIM group. One WIM site (in District 3, Route 49, a mountainous two-lane highway) fell into Group A and 20 WIM sites (in Districts 1, 4, 5, 6, 7, 8, 10, 11, and 12) fell into Group B. The WIM sites on urban highway routes mostly belonged to Groups B, C, and D, which have the medium axle load spectra. The WIM sites on the intercity sections of Interstate 5 fell into Groups F and G, which have the heaviest axle load spectra. The intercity sections of Interstate 5 are known as routes for long-haul heavy freight trucks, and the WIM grouping results show consistency. About 50% of the WIM sites fell into Groups C and D, with the medium axle load spectra. This indicates that medium axle load spectra were observed mostly on urban highway sections. In the axle load analysis, it was assumed that a tandem-axle load is half of a single-axle load because a tandem axle transfers load to pavement through two axles whereas a single-axle transfers load to pavement through a single axle.

Table 3.2: WIM Site Locations for Each Group

No.	WIM Sites																				
	Group A (1 site)			Group B (20 sites)			Group C (21 sites)			Group D (19 sites)			Group E (10 sites)			Group F (4 sites)			Group G (5 sites)		
	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID
1	3	49	049	1	29	093	1	101	020	2	395	110	3	5	105	2	5	030	2	5	002
2				1	101	086	3	50	051*	3	80	003*	3	80	072	6	5	073	2	97	028
3				4	12	024	3	99	107	3	99	046	5	46	043	8	10	005	3	5	108
4				4	92	064	4	80	041*	3	99	106	7	5	047*	8	40	025	6	58	114
5				4	101	033*	4	80	057*	4	505	050	8	15	066				8	58	071
6				4	280	031*	4	101	068	4	680	055*	9	395	109						
7				5	101	076	4	152	035	4	680	065	10	5	001						
8				6	65	115	4	880	017*	5	101	094	10	5	007						
9				7	47	116	5	101	081	6	99	010	10	5	027						
10				7	91	079*	7	405	012*	6	99	074	10	580	113						
11				7	101	008*	7	710	059*	7	210	082*									
12				8	15	037*	8	10	077*	8	15	069*									
13				8	71	098	8	60	095*	8	30	039									
14				8	83	097	10	120	099	8	86	040									
15				8	215	063	10	205	044	8	215	067									
16				11	5	084*	11	8	023	10	99	075									
17				11	15	087*	11	805	089*	10	152	036									
18				11	78	014	11	805	091*	11	8	022									
19				11	163	100*	12	5	015*	11	8	026									
20				12	405	111*	12	57	103*												
21							12	91	061*												

Note: * indicates a WIM site measuring both directions. The order was sorted by districts and routes in each group.

Figure 3.9 shows the axle load distribution per axle type and the sum of single equivalent axle loads for the seven WIM groups determined from the cluster analysis. The x-axis represents values for equivalent load (kN), which were converted from steering-, single-, tandem-, and tridem-axle data, and the y-axis represents the single equivalent load frequency (percent) of the equivalent loads. The figure shows that the highest sum of single equivalent axle load frequency (40%) for a low equivalent load (20 kN) appears in Group A, the lightest WIM group. The figure also shows that the highest sum of single equivalent axle load frequency (23%) for a high equivalent load (70 kN) appears in Group G, the heaviest WIM group.



Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

Figure 3.9: WIM sites cluster analysis results.

3.3 Decision Tree to Determine WIM Spectra

3.3.1 Decision Tree Model

The decision tree model was developed using the program *R* to group the 80 WIM sites into five WIM spectra categorized by axle load distribution similarity. In developing the decision tree model, traffic information extracted from the California highway log database were added to the WIM database in *PaveM* and considered to be explanatory variables. Table 3.3 shows the selected explanatory variables and their descriptions. According to the decision tree model, only the following two explanatory variables from the *PaveM* traffic database were statistically significant:

1. *truck percent*
2. *low-axle/high-axle truck ratio*, defined for this study as the ratio of the total number of two-, three-, and four-axle trucks to the total number of trucks with five axles or more

The variables from the California highway log were not significant. The final decision tree model used only those two significant variables to group the WIM sites into five WIM spectra, shown in Figure 3.10.

Table 3.3: The Explanatory Variables in the Decision Tree Analysis

Variable Name	Variable Type	Variable Source	Significance
Ratio of the total number of two-, three-, and four-axle trucks to the total number of trucks with five axles or more (low-axle/high-axle truck ratio)	Continuous	*PaveM* traffic	Yes
Truck percent	Continuous	*PaveM* traffic	Yes
Road type (rural/urban)	Discrete	Highway log	No
National truck route	Discrete (Yes or No)	Highway log	No
Divided highway	Discrete (Yes or No)	Highway log	No
Number of lanes	Discrete (Integer)	Highway log	No
Freight network tier	Discrete (Integer)	Highway log	No
Pavement classification	Discrete (Integer)	Highway log	No
City	Discrete (Yes or No)	Highway log	No
Interregional road system (IRRS)	Discrete	Highway log	No

In the decision tree model, the variable *low-axle/high-axle truck ratio* was used to make the first decision. The decision tree model separated WIM sites where this ratio was larger than 1.955 from the other WIM sites and grouped them into Spectra 1. Thus, Spectra 1 is the axle load spectra that shows the lightest axle load distribution. In the second decision, the variable *truck percent* was used to separate some WIM sites from the rest. The WIM sites where *truck percent* was larger than 20.378% were placed into Spectra 5, which shows the heaviest axle load distribution. The third decision tree method discernment used the variable *truck percent* again, separated WIM sites where *truck percent* fell between 15.906% and 20.378% from the other sites, and placed them into Spectra 4. The final decision was made using the *low-axle/high-*

axle truck ratio again, and WIM sites where this ratio was between 0.805 and 1.955 were grouped into Spectra 2. The remaining WIM sites were grouped into Spectra 3. The numbers included in the spectra names were determined using the axle load distribution pattern of each spectra (with 1 being the lightest axle load distribution and 5 the heaviest).

WIM Spectra 1, the lightest axle load spectra, consists of one, twelve, and three WIM sites from Groups A, B, and C, respectively (16 sites total), while WIM Spectra 5, the heaviest axle load spectra, consists of one, two, two, four, and five WIM sites from Groups B, D, E, F, and G, respectively (14 sites total). WIM Spectra 3, the medium axle load spectra observed most often on California highways, consists of ten, twelve, and one site from Groups C, D, and E, respectively (23 sites total), shown in Figure 3.11.

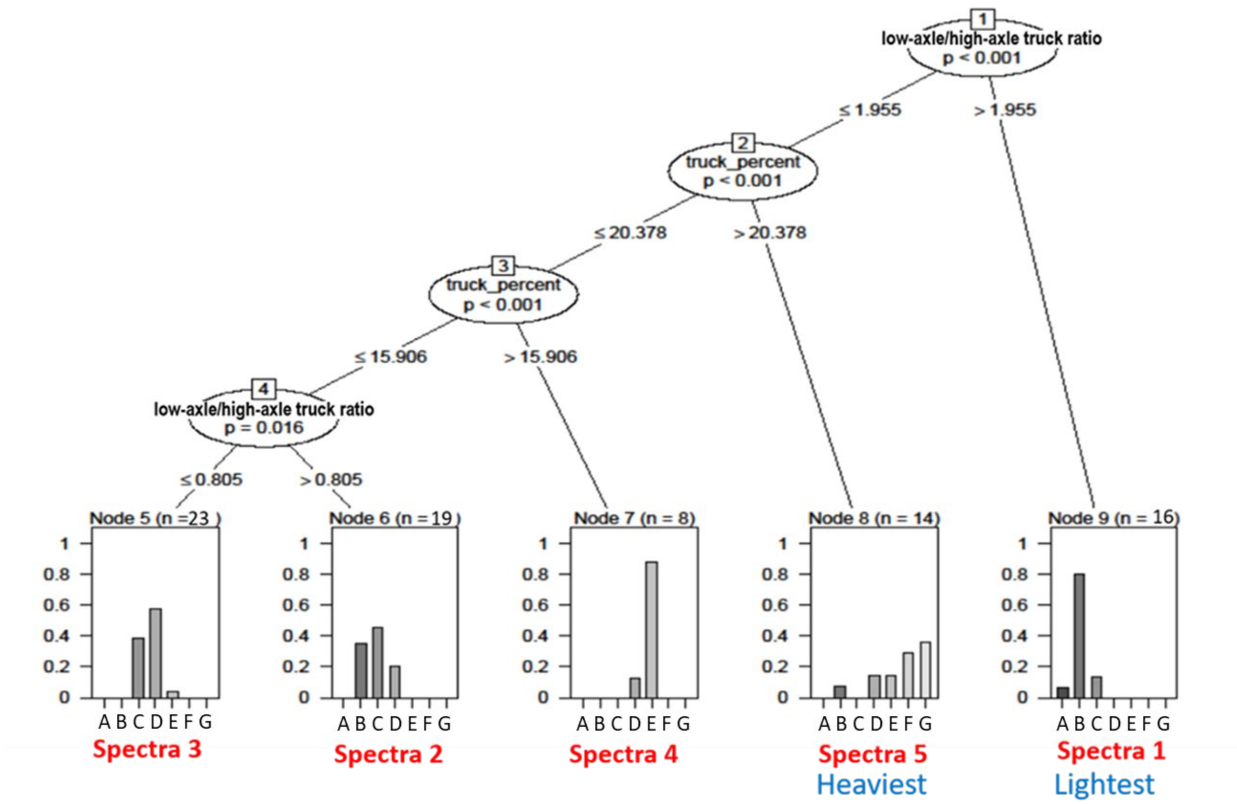


Figure 3.10: The result of the decision tree analysis of WIM spectra.

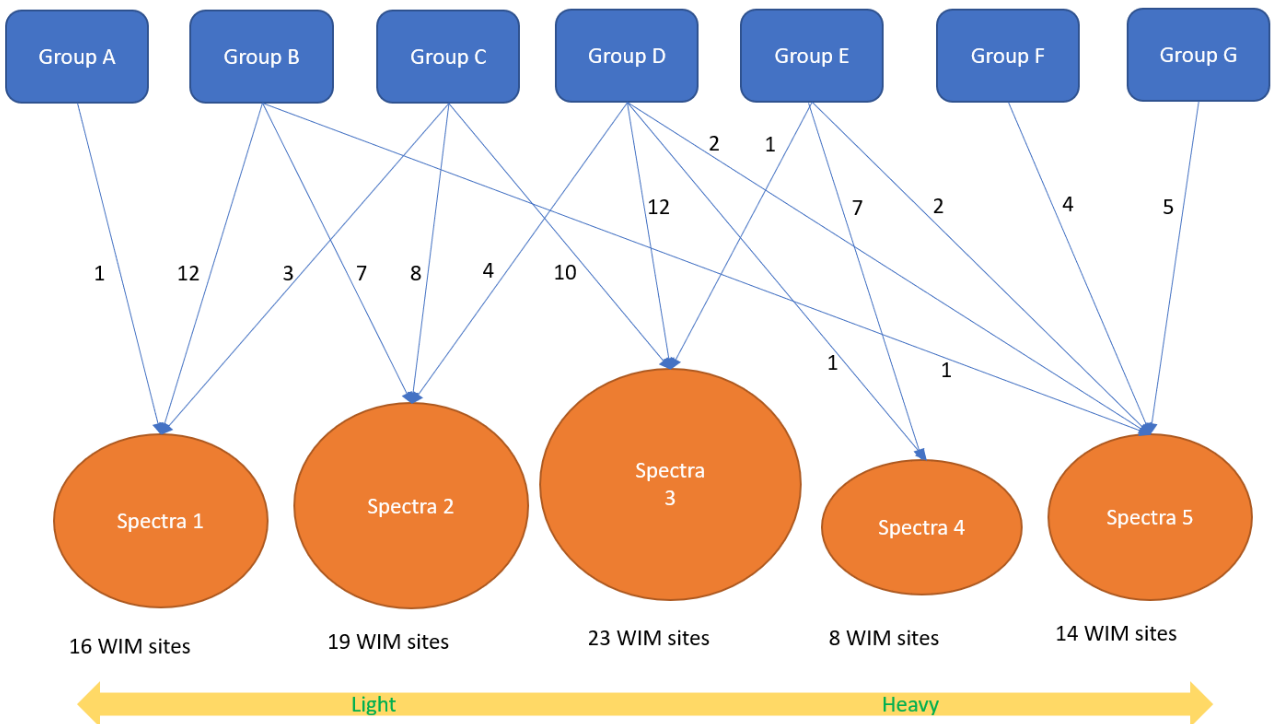


Figure 3.11: The WIM spectra in the decision tree model result.

Table 3.4 lists the WIM sites for each WIM spectra. The following are descriptions of each spectra:

- Spectra 1: This is the lightest axle load spectra and includes WIM sites on rural and interregional highway sections in Districts 1, 3, 4, 5, 6, 7, 8, 10, and 11. (Note: When this project was carried out, there were no WIM sites in District 9.)
- Spectra 2 and 3: These are the medium axle load spectra, which include WIM sites on urban and intraregional highway sections in Districts 3, 4, 5, 6, 7, 8, 10, 11, and 12. Interestingly, none of the 19 WIM sites included in Spectra 2 were located in Districts 1, 2, 6, or 9, and 22 of the 23 WIM sites in Spectra 3 were located on urban highway sections in Districts 3, 4, 5, 6, 7, 8, 10, 11, and 12 (except one WIM site in District 6). This implies that Spectra 2 and Spectra 3 are the typical axle load spectra found only on urban highway sections.
- Spectra 4: This spectra is the second heaviest axle load spectra observed on Interstate 5 and Interstate 99 in Districts 3, 6, 7, and 10.
- Spectra 5: This is the heaviest axle load spectra and was often found on Interstate 5 in Districts 2, 3, 6, and 10, and Interstates 10 and 40 in District 8, the routes that function as major interregional freight corridors.

Table 3.4: WIM Sites for Each WIM Spectra

No.	WIM Spectra														
	Spectra 1 (16 sites)			Spectra 2 (19 sites)			Spectra 3 (23 sites)			Spectra 4 (8 sites)			Spectra 5 (14 sites)		
	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID	District	Route	WIM ID
1	1	29	093	3	50	051*	3	80	003*	3	5	105	2	5	002
2	1	101	020	3	99	106	3	80	072	5	46	043	2	5	030
3	1	101	086	4	12	024	3	99	046	6	99	074	2	97	028
4	3	49	049	4	92	064	4	80	041*	7	5	047*	2	395	110
5	3	99	107	4	680	055*	4	80	057	8	15	066	3	5	108
6	4	101	033*	4	880	017*	4	101	068	9	395	109	6	5	073
7	4	280	031*	5	101	081	4	152	035	10	5	001	6	58	114
8	5	101	076	7	101	008	4	505	050	10	580	113	7	47	116
9	6	65	115	7	405	012*	4	680	065				8	10	005
10	7	91	079*	8	15	037*	5	101	094				8	40	025
11	8	71	098	8	83	097	6	99	010				8	58	071
12	8	215	063	8	215	067	7	210	082*				8	86	040
13	10	120	099	11	5	084*	7	710	059				10	5	007
14	11	15	087*	11	8	026	8	10	077*				10	5	027
15	11	78	014	11	805	089*	8	15	069*						
16	11	163	100*	11	805	091*	8	30	039						
17				12	5	015*	8	60	095*						
18				12	91	061*	10	99	075						
19				12	405	111	10	152	036						
20							10	205	044						
21							11	8	022						
22							11	8	023						
23							12	57	103*						

Note: * indicates a WIM site measuring both directions. The order was sorted by districts and routes in each group.

Figure 3.12 shows the WIM sites ordered by their *low-axle/high-axle truck ratio* (log-scaled). The color of each WIM site indicates its WIM group. The WIM groups that contain lighter axle load spectra show higher *low-axle/high-axle truck ratios,* and the WIM groups that contain heavier axle load spectra show lower ratios. The decision tree model found two values (1.96 and 0.85) of the *low-axle/high-axle truck ratio* that separate the WIM sites. Most WIM sites in Groups A and B show a *low-axle/high-axle truck ratio* higher than 1.96, and the WIM sites in Group C show ratios between 1.96 and 0.85. The remaining WIM sites (Groups D, E, F, and G) show *low-axle/high-axle truck ratios* less than 0.80.

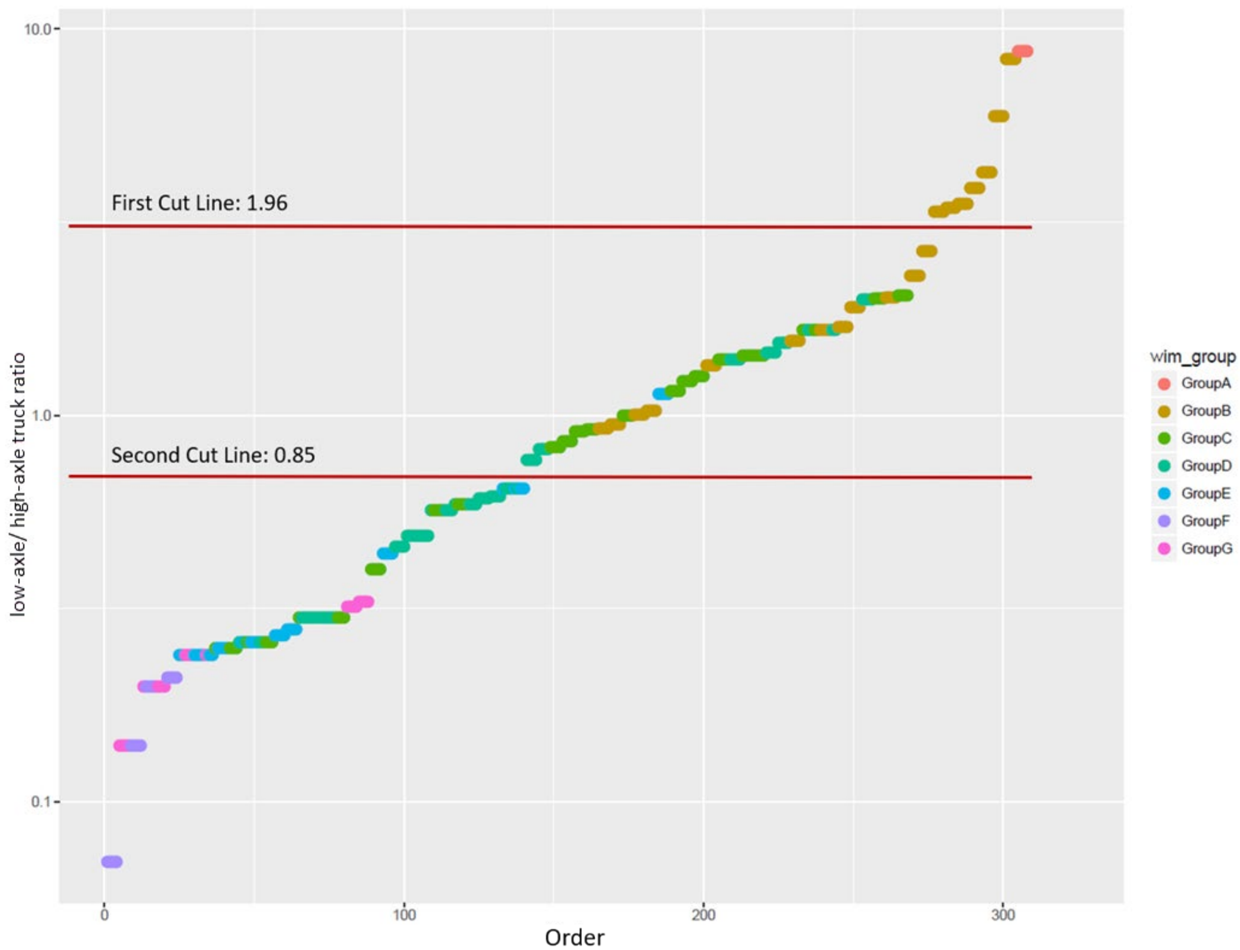
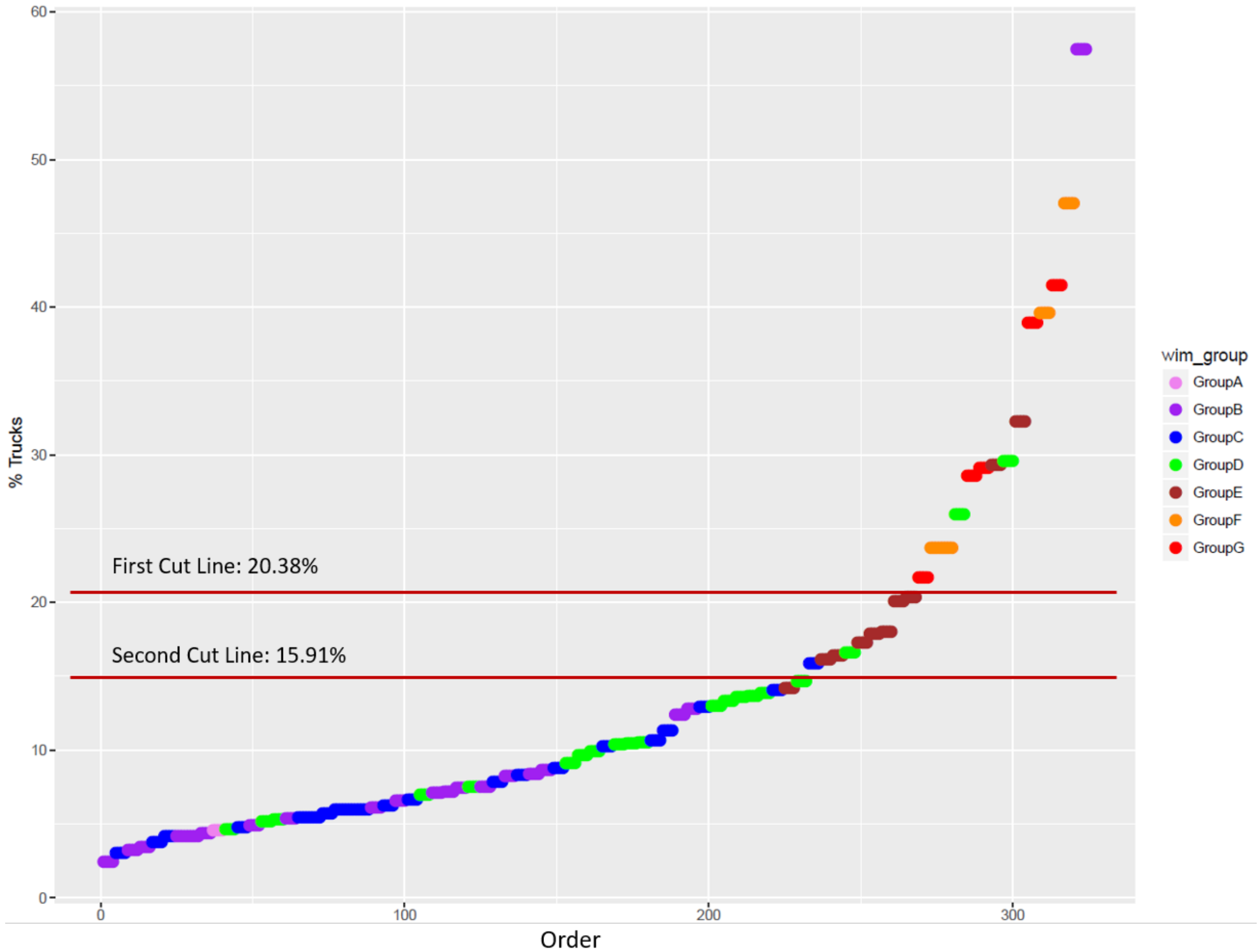


Figure 3.12: Explanatory variable: *low-axle/high-axle truck* ratio per group.

Figure 3.13 shows the WIM sites ordered by *truck percent,* and the color of each WIM site indicates its WIM group. The decision tree model found two *truck percent* boundary values (15.91 and 20.38) as the explanatory variable. Most of the WIM sites in Groups A, B, and C and some in Group D show *truck percent* values less than 15.91, and these WIM sites are light axle load spectra. Most of the WIM sites in Group E, medium axle load spectra, have *truck percent* values between 15.91 and 20.38. The WIM sites in Groups F and G, heavy axle load spectra, have *truck percent* values higher than 20.38.



Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

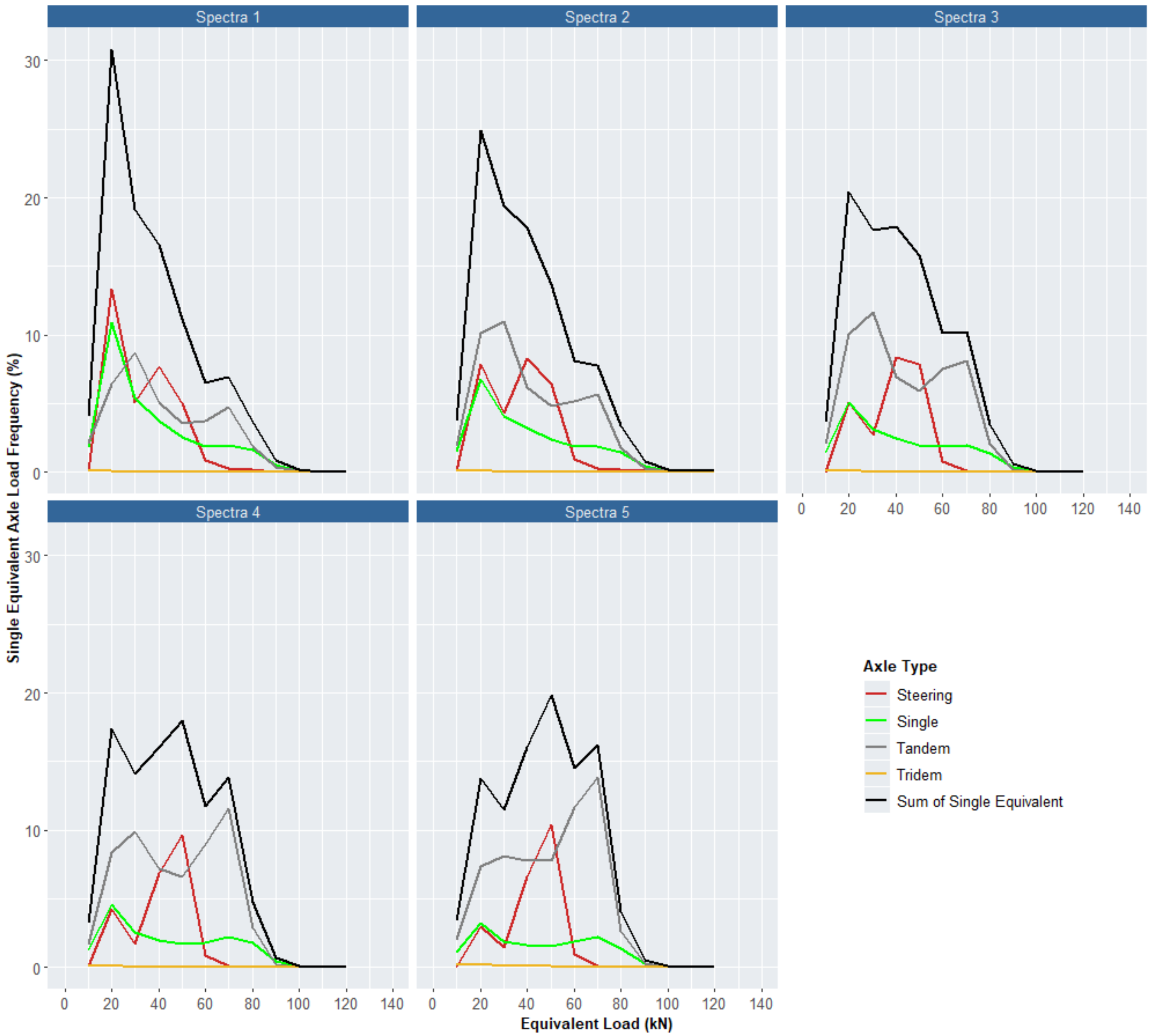
Figure 3.13: Explanatory variable *truck percent* by group.

3.3.2 WIM Spectra Results

Using the EMD method resulted in a decision tree model that yielded five typical WIM spectra:

- Spectra 1 is the lightest *axle load distribution,* so-called because it has the highest load percentage (50%) of *single-counted axles* (that is, the sum of the number of single axles derived by adding up the number of single axles and each axle in a tandem axle [see Section 3.2.1]) between 20 and 30 kN.
- Spectra 2 is the second lightest axle load distribution, with the largest percentage (about 65%) of single-counted axles concentrated between 20 and 40 kN.

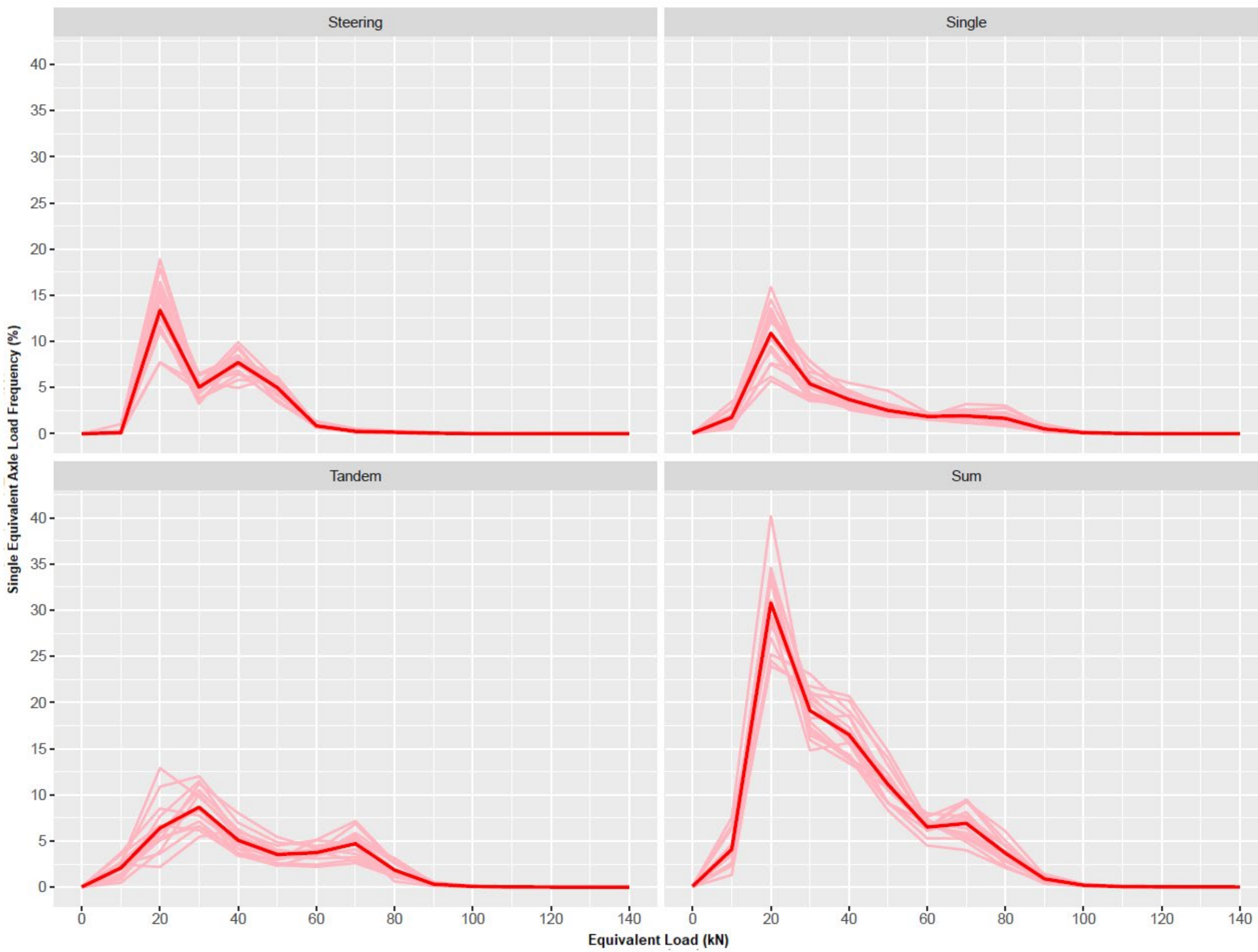
- Spectra 3 is the medium axle load distribution, with its largest single-counted axle load proportion (70%) widely distributed between 20 and 50 kN, but with a light axle load proportion (20 kN) still slightly higher than the proportion of the heavy axle loads (60 kN).
- Spectra 4 is the second heaviest axle load distribution, with its single-counted axle loads fairly well distributed from 15 to 70 kN (between 10% and 20%); its proportion of single-counted axle loads at 20 kN is about the same as the proportion of single-counted axle loads at 50 kN.
- Spectra 5 is the heaviest axle load distribution, with its single-counted axle loads distributed more toward heavy axle loads (over 50 kN) than to light axle loads (under 40 kN).



Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

Figure 3.14: Five-axle load spectra resulting from the decision tree model.

Figure 3.15 shows the steering-, single-, tandem-, and single-counted axle load distributions of 16 the WIM sites in Spectra 1. The steering and single-axle loads are concentrated at 20 kN, and the tandem-axle load is concentrated at 30 kN and 70 kN. Of the average of the single-counted (sum) axle load distribution, 30% is observed at 20 kN.

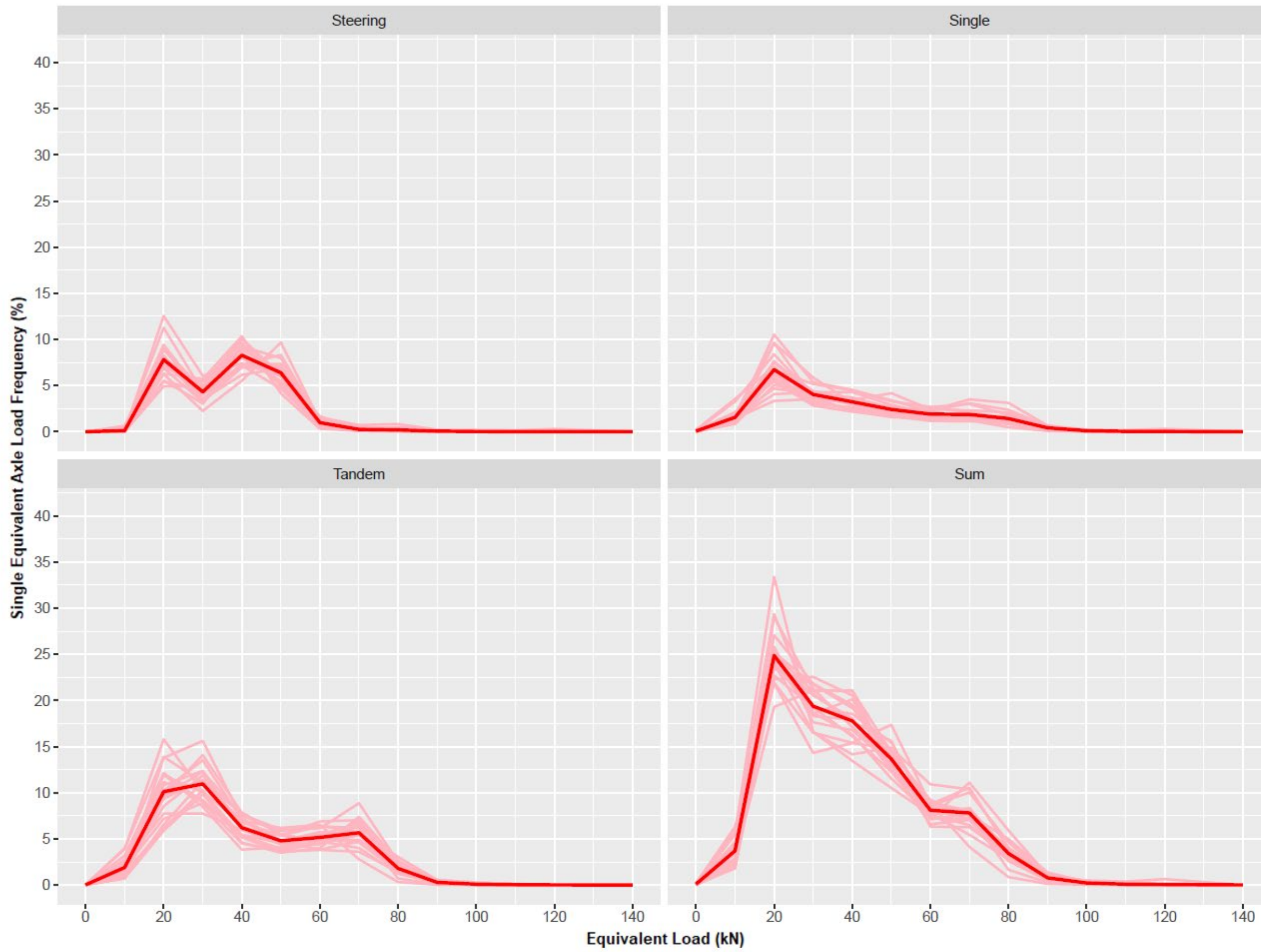


Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

Figure 3.15: Axle loads Spectra 1.

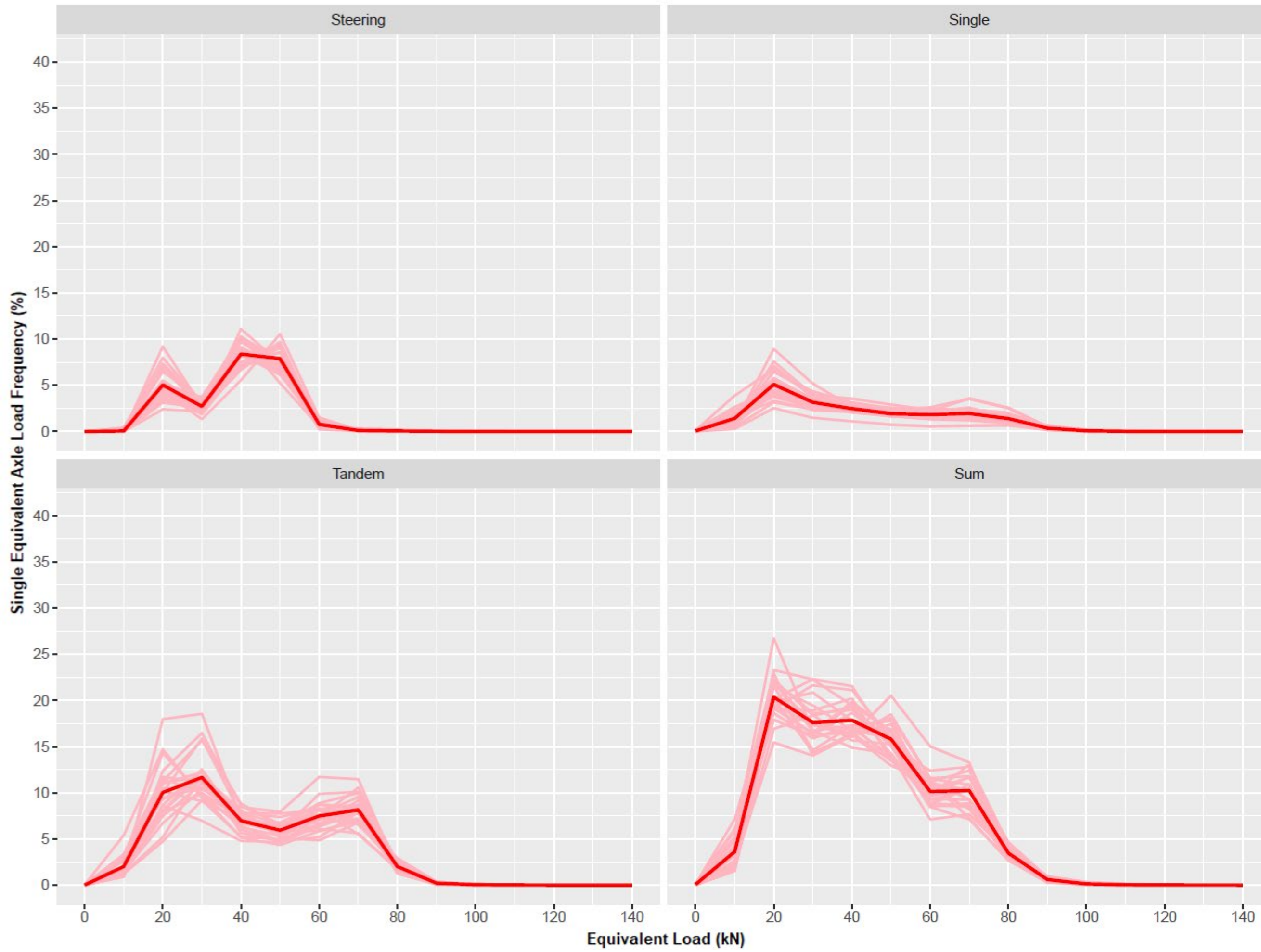
Figure 3.16 shows the steering, single-, tandem-, and single-counted axle load distributions of the 19 WIM sites in Spectra 2. The steering axle loads are concentrated at 20 kN and 40 kN, and the highest proportion of single-axle loads are observed at 20 kN. The tandem-axle loads are concentrated at 20 kN and 30 kN. Of the average of the single-counted (sum) axle load distributions, 25% and 20% are observed at 20 kN and 30 kN, respectively. The average axle load distribution of Spectra 2 in Figure 3.16 shows a higher axle load distribution than Spectra 1 in Figure 3.15.

For Spectra 3, in Figure 3.17, the steering axle load distributions of the 23 WIM sites are spread between 20 and 50 kN, with the highest proportion observed at 40 kN. The single-axle load distributions are more widely spread between 10 and 60 kN than in Spectra 1 and Spectra 2. Figure 3.17 shows that axle loads are widely distributed between light loads (under 20 kN) and heavy loads (over 60 kN).



Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

Figure 3.16: Axle loads Spectra 2.

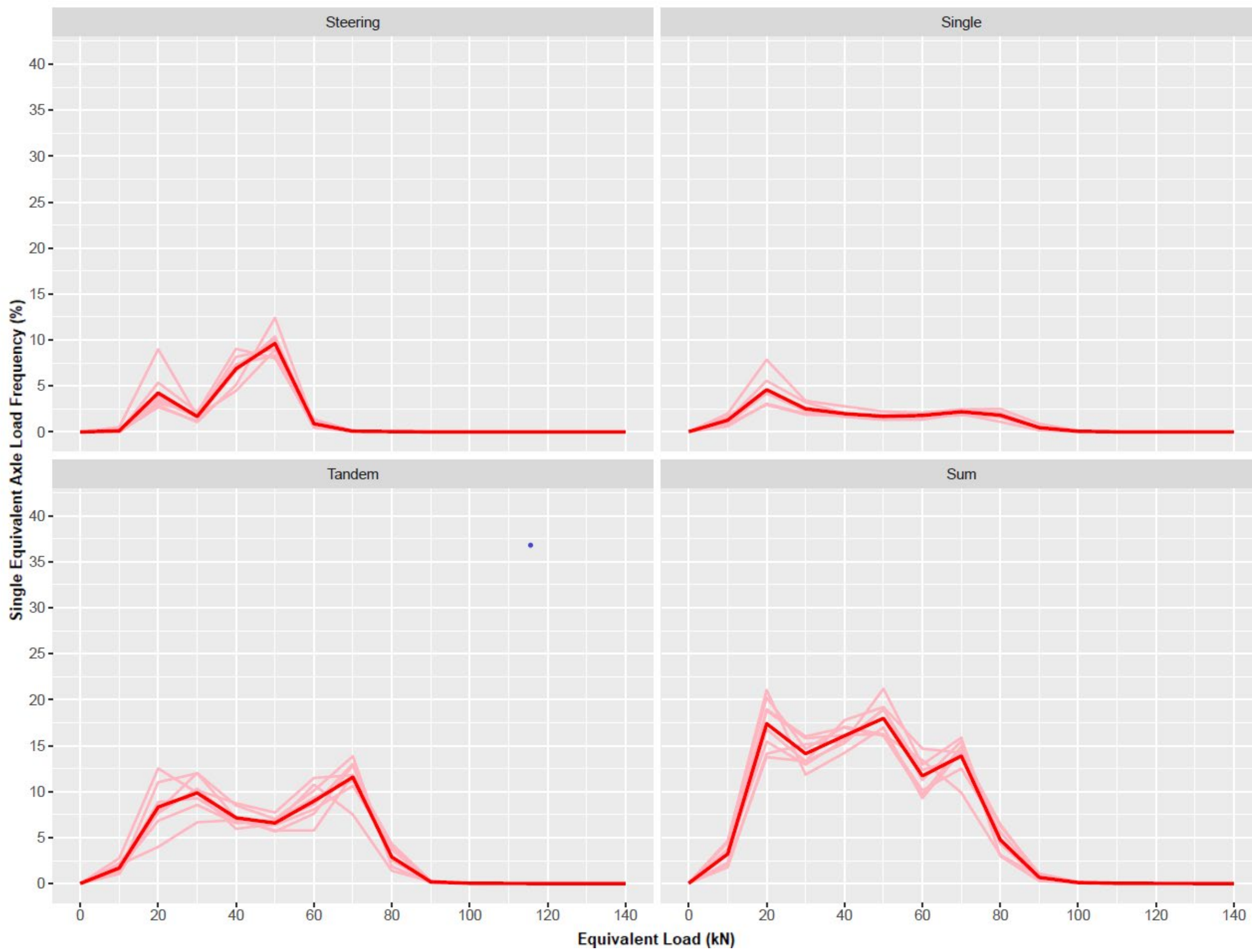


Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

Figure 3.17: Axle loads Spectra 3.

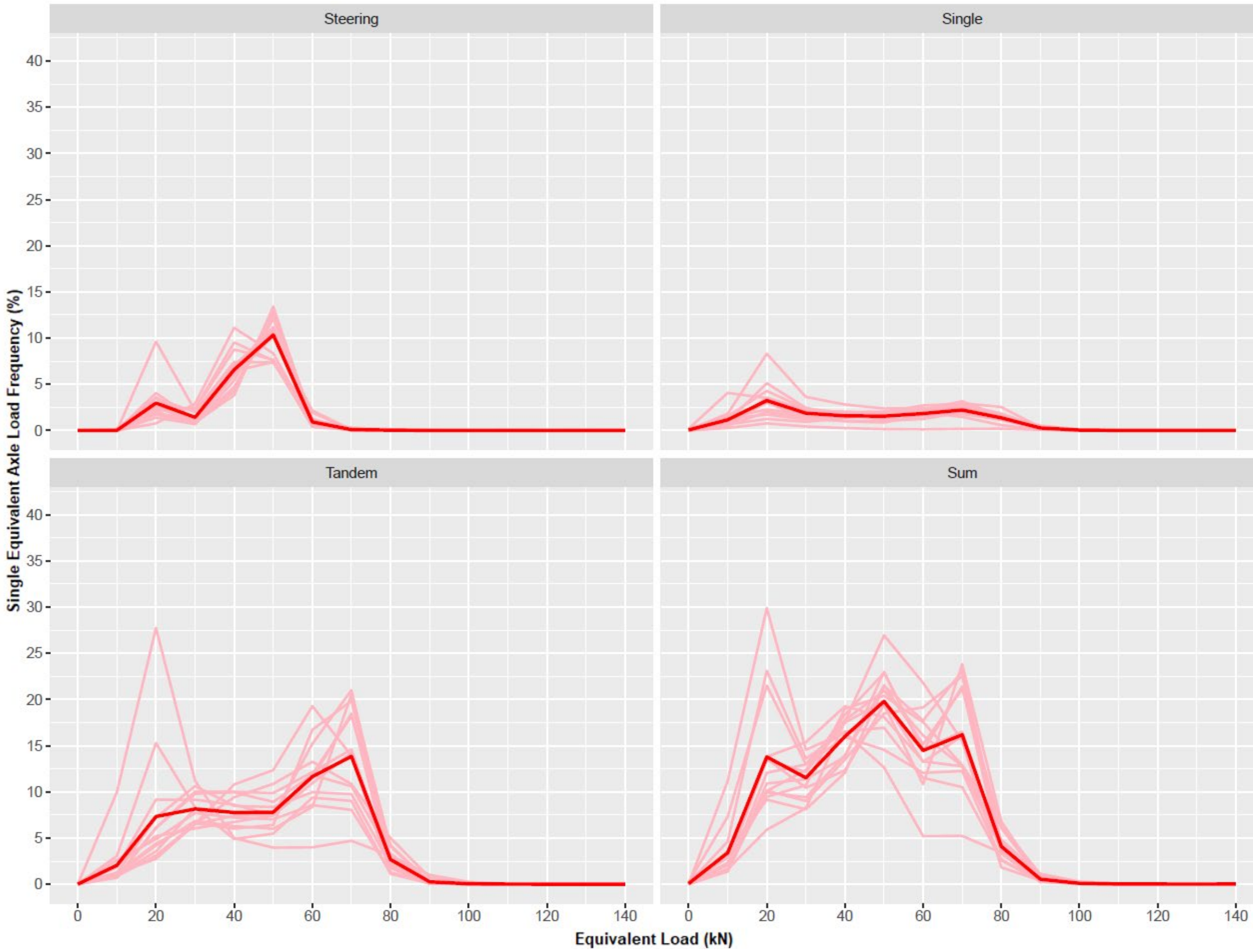
Figure 3.18 shows the axle load distributions of the eight WIM sites in Spectra 4. The steering axle loads (10%) are more concentrated at the heavier load (50 kN) than the steering axle loads (7%) of Spectra 3, and the tandem-axle loads (12%) are more concentrated at the heavier load (70 kN) than the tandem-axle loads (8%) of Spectra 3. The single-counted axle loads are fairly well distributed between 20 and 70 kN.

The axle load distributions of the 14 WIM sites in Spectra 5 are skewed toward the heavier loads for the steering-, tandem-, and single-counted axles, shown in Figure 3.19. Most of the steering axle loads are observed at 50 kN and most of the tandem-axle loads are observed at 70 kN, while the single-axle loads are fairly well distributed between 20 and 80 kN. The single-counted axle load distributions are skewed toward the heavy loads (over 50 kN) compared to the other axle load distributions of Spectra 1, 2, 3, and 4.



Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

Figure 3.18: Axle loads Spectra 4.



Note: Tandem and tridem axles were converted to single equivalent axles by counting each axle in the tandem or tridem group as one axle and dividing the group load by two or three, respectively.

Figure 3.19: Axle loads Spectra 5.

3.4 Extension to the Entire Caltrans Network

With the decision tree to determine the spectra in hand, the methodology needed to be extended to another location on the highway network. This required determining the *truck percent* and *low-axle/high-axle truck ratio* for the entire network. In addition to being useful for predicting design ESALs and other traffic parameters for design and management, the annual average daily traffic (AADT) at all locations on the network needed to be determined. Three sets of data were available for this task: (1) Performance Measurement System (PeMS) data, (2) CalTrucks data, and (3) Transportation Systems Network (TSN) AADT data. The PeMS data, which only has AADT, is based on raw detector counts at various locations on the network and does not have full coverage. However, they are raw data, so the data were assumed to be close to the actual field values measured at the detectors. The *CalTrucks* and TSN AADT data were actual outputs from a single source known as the Traffic Census Program, which is not well documented.

The *CalTrucks* data, which are published annually in an Excel spreadsheet *(1),* consist of AADT, average annual daily truck traffic (AADTT), and the percentages of the various two-, three-, four-, and five-axle trucks. These data consist of a set of points on the network with back and forward counts at each point. The spreadsheet has almost full coverage of the Caltrans highway network and lacks only some very small segments and suffixed routes. If a traffic measurement point location was not at the start or end of a continuously drivable segment of a route, the data were extrapolated backward or forward to cover the route. If a traffic measurement point location was at the start or end, the data were extrapolated linearly between the ahead values from one point to the back values at the following point.

The TSN AADT data are also produced by the Traffic Census Program, but they are stored annually in the TSN database. The data consist of bidirectional AADT counts on small segments of the network, ostensibly on the first of January at each location. The TSN database also stores historical data on the Caltrans highway network and is used for extracting a snapshot of the network on a particular date. This snapshot serves as a "highway log" that is used to manage the network; it is also used by the Caltrans Geographic Information Systems group to determine the linear reference system (LRS) for a particular year. The log is updated annually, allowing for translation between map coordinates, distances driven, and Caltrans post miles (the official position measures on the network). Because the LRS provides a snapshot of the network at a given time, it is always possible to determine which records in the TSN data were used to develop the LRS.

All AADT values are the total for both directions, except when the road is unidirectional. As a result, most need to be halved to determine the AADT in only one direction, and this process was performed first. Because the TSN AADT values are produced by a process and are not raw data, they include full coverage of the network. However, because of what appear to be some bugs in the process, some locations have received AADT counts that are zero or otherwise unrealistic and therefore cannot be used directly. To compensate, the AADT counts from the PeMS data and the full historical AADT counts from the TSN data are imported for every TSN segment in the LRS. A weighted average AADT for every center point of every segment in the LRS is determined from the PeMS data (which is at a point) and all the historical TSN data both for the segment and the adjacent segments. The weight is based on the formula shown in Equation (3.2):

$$w_{jt}^{i} = \exp\left(-\sqrt{\left(\frac{T_{jt} - T_i}{2}\right)^2 + \left(\frac{P_j - P_i}{3}\right)^2}\right) \quad \textbf{(3.2)}$$

Where:

w_{jt}^{i}: the weight for the the j^{th} segment at time t in the computation for segment i

T_{jt}: the time of the AADT for the j^{th} segment at time t (in years)

T_i: the time of the AADT for the i^{th} segment in the LRS

P_{jt} the center position of the j^{th} segment (in miles)

P_i the center position of the i^{th} segment in the LRS (in miles)

The weight is thus based on the "distance" of the AADT measurements both in space and time from the segment in question. The weighted mean and weighted standard deviation for the data at each segment were computed and compared to the TSN AADT for the segment at the time of the LRS. If the TSN AADT was zero or was more than two standard deviations from the weighted average, it was replaced with the weighted mean. The value was also rounded using the formula shown in Equation (3.3):

$$AADT = \frac{round\left(200\frac{AADT}{10^{\text{floor}\left(\log_{10}\left(AADT\right)\right)+1}}\right)}{200}10^{\text{floor}\left(\log_{10}\left(AADT\right)\right)+1} \quad \textbf{(3.3)}$$

Where the floor function rounds down to the nearest integer.

This effectively rounds to the nearest two-hundredth, but with only three significant digits (so 196,235 rounds to 195,000). This is the formula used by the Traffic Census Program to round the AADT data.

This process identified approximately 50 locations on the network where the TSN AADT data in the LRS snapshot were incorrect. These data were replaced with the average. The percentage of trucks and percentage of each of the different axle count trucks were linearly interpolated or, if these data were missing in the *CalTrucks* data, they were replaced with suitable values based on expert judgment. With these data, it was then possible to determine the appropriate WIM spectrum, and, with the AADT, any other traffic information for design or management can be determined for every segment on the network.

3.5 Final Results for the Entire Caltrans Network

The new WIM spectra developed in the decision tree model were applied to the California highway network, with the results shown in Figure 3.20 (North Region), Figure 3.21 (Central Region and District 4), and Figure 3.22 (Districts 7, 8, 11, and 12). Each pavement segment was classified into one of the five WIM spectra based on its *low-axle/high-axle truck ratio* and *truck percent.* The *R* script used the two variables to determine the WIM spectra for each pavement segment. The pavement segments were divided by highway characteristics, such as lane add/drop, on-ramp/off-ramp, and bridge begin/end. Most segments on the Interstate 5 corridor were classified into Spectra 5, the heaviest axle load distribution, and most segments on Highway 1 fell into Spectra 1, the lightest axle load distribution. Urban highways in Districts 3, 4, 7, 8, 12, and 11 turned out to have light or medium axle load distributions, which are shown in Spectra 1, 2, and 3, while rural highways in Districts 2, 3, 4, and 8 fell into Spectra 4 and 5.

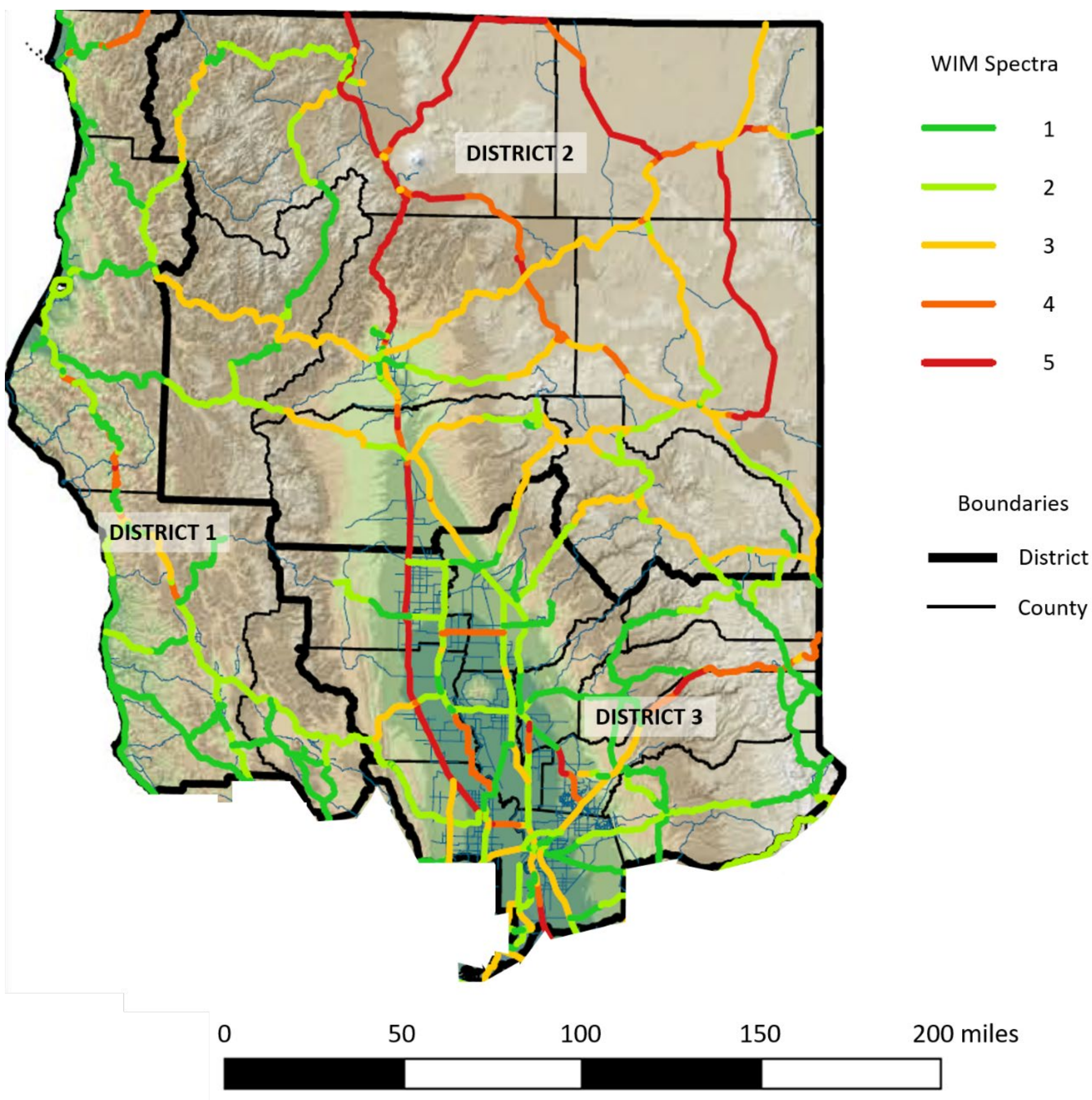


Figure 3.20: Display of WIM spectra on the California highway network: North Region.

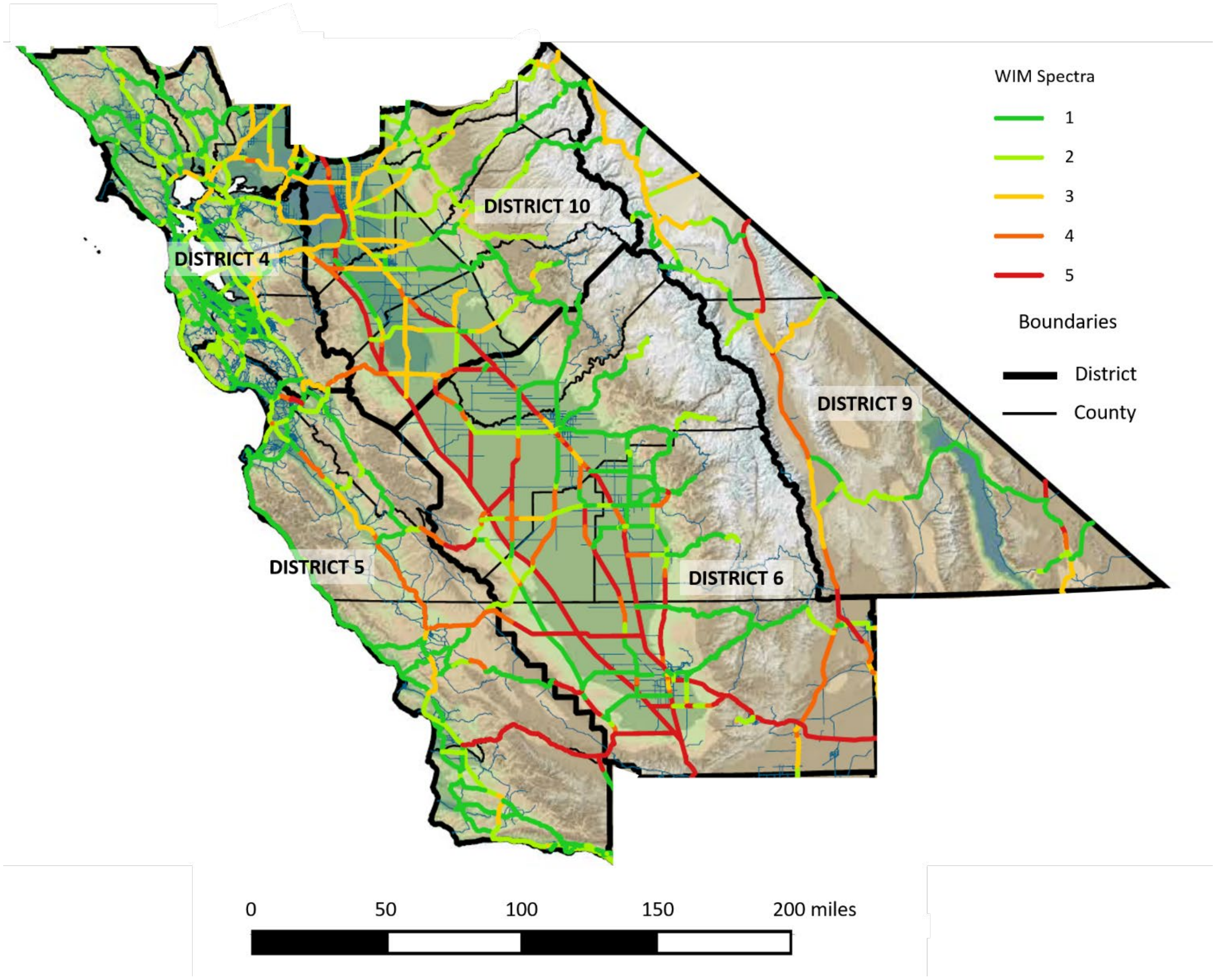


Figure 3.21: Display of WIM spectra on the California highway network: Central Region and District 4.

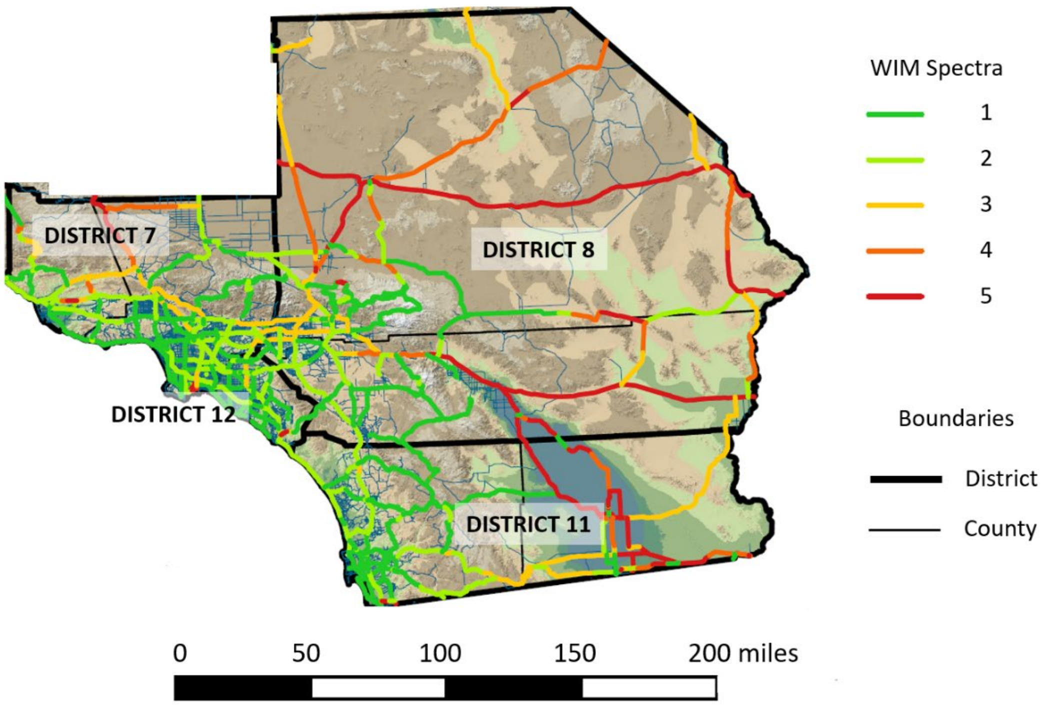


Figure 3.22: Display of WIM spectra on the California highway network: Districts 7, 8, 11, and 12.

4 TRAFFIC CALCULATION TOOL FOR ME PAVEMENT DESIGN

4.1 Scope and Purpose

MEPDG Traffic Input Process (*MEPDG-TIP*) is a software tool developed for Caltrans by the UCPRC.[3] The tool generates a set of traffic-related inputs needed to run *AASHTOWare Pavement* (previously called *MEPDG*), which is used to design pavements following ME methodology. The main traffic input required by the *AASHTOWare Pavement* program is axle load spectra, sorted by WIM group. The 12 years of California highway network WIM data collected, analyzed, and processed—as described earlier—provide this required input. With *MEPDG-TIP,* a user can quickly prepare the necessary traffic input data on project locations in California's network and then run the *AASHTOWare Pavement*.

MEPDG-TIP determines a project site's required WIM spectra based on user inputs, shown in Table 4.1 with the *MEPDG-TIP* outputs. In an "MEPDG Traffic Inputs" window, *MEPDG-TIP* then shows the axle load spectra for each month (January through December) and vehicle class (Class 4 to Class 13), including data on spectra hourly distribution, monthly distribution, vehicle class distribution, axles per truck type (single, tandem, and tridem), and site-specific traffic volume from the Caltrans Traffic Census Program *(1)*. (Note: No quad-axle data have been included in *MEPDG-TIP* because this axle type is not often seen in California.) Figure 4.1 illustrates the process flow of *MEPDG* traffic input generation in *MEPDG-TIP*. After reviewing the output results in the "MEPDG Traffic Inputs" window, the user can export the *MEPDG-TIP* outputs into a selected folder as *AASHTOWare Pavement* input files.

Table 4.1: User Inputs and MEPDG-TIP Outputs

Category	Description
User Inputs	District
	County
	Route
	Direction
	Post Mile
MEPDG-TIP Outputs	WIM Spectra
	Axle Load Spectra for Single Axle
	Axle Load Spectra for Tandem Axle
	Axle Load Spectra for Tridem Axle
	Axle Load Spectra for Quad Axle (will be blank)
	Hourly Distribution
	Monthly Distribution
	Vehicle Class Distribution
	Axle per Trucks
	Traffic Volumes and Other Inputs

[3] *Pavement ME Design Traffic Input Tool*. ucprc.ucdavis.edu/SoftwarePage.aspx.

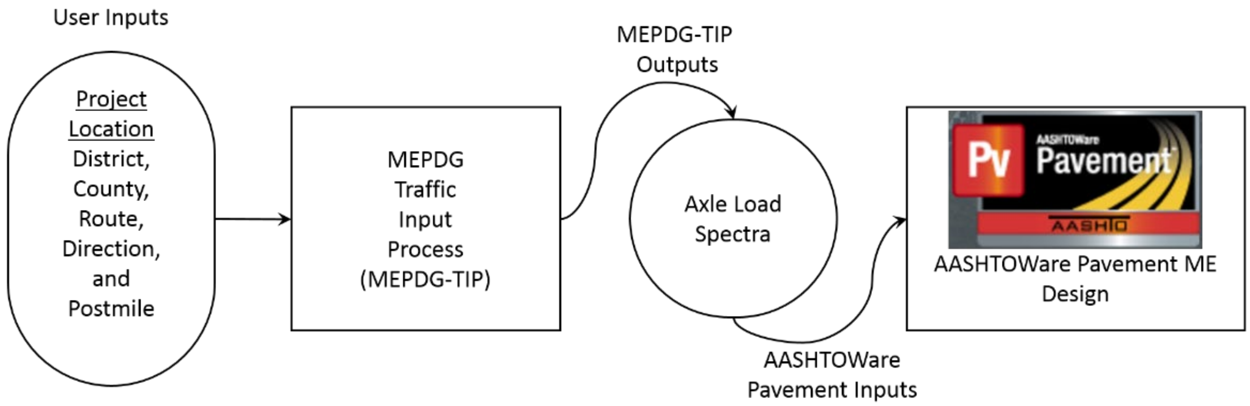


Figure 4.1: Process flow of the traffic calculator tool.

4.2 Installing MEPDG-TIP

Once the *MEPDG-TIP* software is downloaded, it can be installed by double-clicking its setup file to launch an installation wizard that presents a series of instructions.[4] (Note: Installing *MEPDG-TIP* on a Microsoft Windows-based computer requires an administrator account.)

4.3 Using MEPDG-TIP

The main window of *MEPDG-TIP* (version 1.5) will indicate when to open the executable file (*MEPDG-TIP.exe*). After selecting district, county, route, and direction from each dropdown menu and entering the post mile associated with the project in the main window (Figure 4.2), clicking the "View Results" button will reveal the corresponding WIM spectra for the chosen highway location at the bottom of the main window and open the "MEPDG Traffic Inputs" window.

[4] *Pavement ME Design Traffic Input Tool*. ucprc.ucdavis.edu/SoftwarePage.aspx.

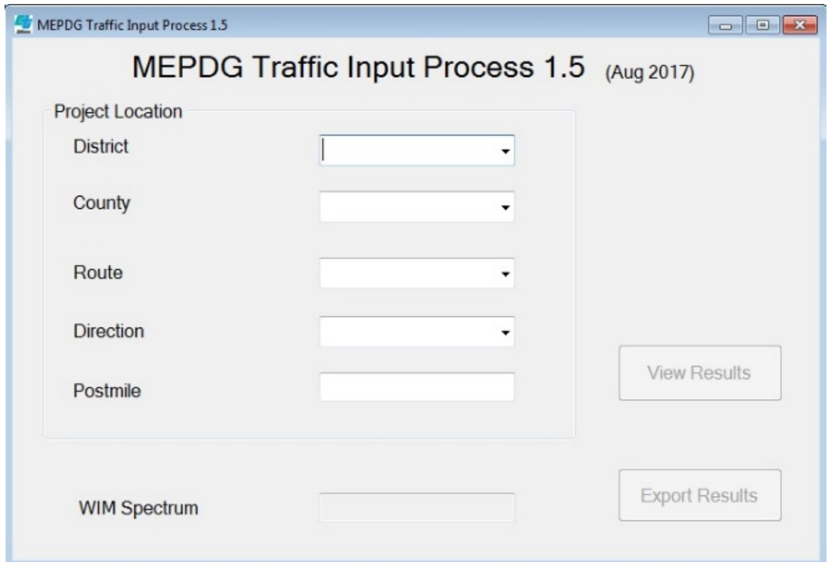


Figure 4.2: Main window of the traffic calculation tool.

4.4 Outputs

Results included in the nine tabs in the MEPDG Traffic Inputs window (Figure 4.3) include the following:

1. Single Axle Spectra: single-axle spectra for truck class for each month.
2. Tandem Axle Spectra: tandem-axle spectra for truck class for each month.
3. Tridem Axle Spectra: tridem-axle spectra for truck class for each month.
4. Quad Axle Spectra: quad-axle spectra for truck class for each month. (This tab is shown as empty because quad axle trucks are rarely operated in California and, therefore, quad-axle spectra information cannot be generated. However, the *AASHTOWare Pavement* software still requires the quad-axle spectra information.)
5. Hourly Distribution: traffic distribution for hours of the day.
6. Monthly Distribution: monthly distribution (January to December).
7. Vehicle Class Distribution: percentage of each vehicle class.
8. Axles per Truck: number of axles per truck class.
9. Traffic Volume and Other Inputs: two-way annual average daily truck traffic (AADTT), number of lanes in design direction, percent of trucks in design direction, and ESALs per 1,000 trucks.

By returning to the main window and clicking the "Export Results" button, the *MEPDG-TIP* traffic outputs from the calculation tool can be exported as *MEPDG* traffic input files readable by *AASHTOWare Pavement*. The six generated files exported into a selected folder can then be imported into *AASHTOWare Pavement*.

MEPDG Traffic Inputs

Single Spectra | Tandem Spectra | Tridem Spectra | Quad Spectra | Hourly Distribution | Monthly Distribution | Vehicle Class Distribution | Axles per Truck | Traffic Volume & Other Inputs

Month	TruckClass	Total	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000	15000	16000	17000	
January	4	100	0.083	0.305	0.505	2.621	6.676	11.055	14.409	15.742	13.777	9.487	5.853	3.680	3.021	2.575	2.946	2
January	5	100	2.451	21.044	15.687	13.456	12.377	9.925	7.218	5.008	3.350	2.282	1.706	1.355	1.141	0.919	0.728	0
January	6	100	0.028	0.710	0.999	1.915	6.267	15.508	21.573	21.323	12.991	6.991	3.878	2.455	1.751	1.320	1.029	0
January	7	100	1.810	1.202	1.136	2.493	2.080	4.435	5.091	8.840	11.861	10.471	5.564	3.741	5.012	6.905	8.795	9
January	8	100	1.602	3.825	4.505	7.627	12.919	18.389	15.159	9.212	6.091	4.565	3.691	3.157	2.619	2.141	1.708	1
January	9	100	0.933	1.609	1.220	0.955	2.994	11.403	21.874	27.892	19.436	6.045	1.218	0.617	0.752	0.951	0.939	0
January	10	100	0.103	0.382	0.377	0.756	3.786	11.898	23.481	30.372	20.133	6.317	1.253	0.401	0.316	0.132	0.125	0
January	11	100	5.541	6.851	6.116	5.643	8.678	11.480	9.158	5.749	3.897	3.640	4.040	4.730	5.743	6.377	5.754	3
January	12	100	3.207	7.124	9.808	9.093	8.594	12.236	12.818	10.942	7.362	4.936	4.168	3.530	2.627	1.757	0.938	0
January	13	100	3.371	4.645	6.773	7.121	8.759	11.364	12.871	10.554	7.925	4.786	3.361	2.200	1.942	1.851	1.936	1
February	4	100	0.045	0.242	0.565	2.544	6.074	10.973	14.339	15.817	14.390	9.921	6.122	3.791	2.598	2.566	2.943	2
February	5	100	2.452	21.225	15.792	13.277	12.166	9.870	7.218	5.077	3.410	2.295	1.692	1.363	1.123	0.927	0.720	0
February	6	100	0.036	0.772	1.080	2.004	6.351	15.301	21.175	21.041	13.419	7.116	4.008	2.367	1.722	1.382	0.994	0
February	7	100	1.852	1.287	1.666	2.447	2.313	4.232	6.286	8.541	11.683	10.509	5.348	4.030	4.475	6.292	8.926	8
February	8	100	1.696	3.975	4.589	7.610	12.649	18.261	15.292	9.250	6.019	4.524	3.682	3.075	2.626	2.165	1.741	1
February	9	100	0.913	1.630	1.282	1.003	2.978	11.183	21.594	27.690	19.767	6.280	1.300	0.627	0.721	0.926	0.930	0
February	10	100	0.148	0.231	0.360	0.659	3.991	12.224	22.434	29.952	20.319	6.302	1.449	0.468	0.249	0.287	0.385	0
February	11	100	5.288	6.636	5.974	5.496	8.357	11.298	9.303	5.727	4.583	3.845	4.153	4.622	5.618	6.424	5.813	3
February	12	100	3.061	6.754	9.061	8.827	8.618	11.734	13.041	11.468	7.610	5.241	4.352	3.454	2.790	1.913	1.136	0
February	13	100	3.219	4.483	5.947	7.138	8.408	11.376	12.240	11.428	6.949	4.455	3.061	2.281	2.164	1.967	2.586	2
March	4	100	0.040	0.163	0.452	2.177	6.426	10.154	14.350	16.123	14.134	10.088	6.352	3.807	2.864	2.771	2.783	2
March	5	100	2.501	21.426	15.758	13.124	12.048	9.749	7.157	5.035	3.399	2.325	1.708	1.392	1.169	0.969	0.751	0
March	6	100	0.036	0.766	1.080	1.853	6.207	15.355	21.133	20.881	13.448	7.244	3.993	2.461	1.745	1.396	1.076	0
March	7	100	1.497	1.384	1.538	2.258	2.441	4.788	6.288	8.882	11.498	9.819	5.104	3.982	4.508	6.866	8.785	9
March	8	100	1.668	4.030	4.554	7.356	12.571	18.079	15.164	9.293	6.089	4.604	3.706	3.118	2.608	2.264	1.782	1
March	9	100	0.853	1.507	1.239	0.984	2.923	10.838	21.051	27.393	20.324	6.890	1.435	0.647	0.721	0.948	0.966	0
March	10	100	0.116	0.354	0.470	0.663	3.331	11.590	23.059	29.445	20.679	7.197	1.269	0.472	0.342	0.268	0.310	0
March	11	100	5.187	6.555	5.982	5.426	8.012	11.392	9.897	6.388	3.936	3.672	3.943	4.534	5.434	6.289	5.894	4
March	12	100	3.372	6.776	8.678	8.291	8.314	11.538	13.046	11.312	7.745	5.303	4.417	3.602	2.875	2.168	1.374	0
March	13	100	2.729	3.945	5.626	6.499	8.402	10.846	12.755	11.233	7.626	4.836	3.317	2.943	2.231	2.315	2.126	2
April	4	100	0.044	0.182	0.435	2.131	5.925	10.476	13.563	15.464	14.538	10.746	6.587	4.041	2.955	2.732	2.650	2
April	5	100	2.526	21.840	15.832	12.896	11.914	9.704	7.149	4.998	3.390	2.312	1.708	1.361	1.153	0.946	0.744	0
April	6	100	0.028	0.831	1.089	1.793	5.738	14.248	21.167	21.439	13.829	7.524	4.068	2.513	1.816	1.386	1.032	0
April	7	100	1.882	1.048	1.927	2.678	2.200	4.472	5.811	7.411	11.415	11.199	5.323	3.075	4.393	6.124	8.158	9
April	8	100	1.729	4.238	4.516	7.204	12.246	17.882	15.477	9.414	6.095	4.568	3.676	3.069	2.583	2.226	1.804	1
April	9	100	0.845	1.518	1.201	0.955	2.599	10.148	20.389	27.025	21.343	7.660	1.609	0.680	0.731	0.922	0.969	0
April	10	100	0.101	0.252	0.414	0.646	3.353	11.273	22.141	29.926	21.309	7.442	1.508	0.632	0.287	0.196	0.218	0
April	11	100	5.423	6.879	6.186	5.374	8.061	11.447	9.251	6.119	3.663	3.513	3.605	4.437	5.500	6.409	6.015	4
April	12	100	3.228	6.966	8.570	7.882	8.376	11.274	12.995	11.628	7.878	5.117	4.239	3.480	3.033	2.423	1.565	0
April	13	100	2.525	4.517	5.768	6.465	8.068	11.292	11.382	12.046	9.021	5.239	3.352	2.520	2.124	1.837	2.078	1
May	4	100	0.042	0.216	0.497	2.064	5.844	9.993	13.448	15.460	14.779	10.826	6.601	4.056	2.772	2.737	2.789	2
May	5	100	2.514	21.519	15.798	12.883	11.867	9.758	7.139	5.021	3.413	2.323	1.735	1.395	1.197	0.992	0.804	0
May	6	100	0.031	0.757	1.091	1.671	5.603	14.417	20.652	21.174	14.221	7.816	4.384	2.563	1.754	1.369	1.016	0

Figure 4.3: The output window of the *MEPDG-TIP* traffic calculation tool.

5 CONCLUSIONS

5.1 WIM Spectra

Using cluster analysis and the decision tree method, the UCPRC developed California's typical axle load spectra from a 12-year set of WIM data (2004 to 2015) collected at 107 WIM sites (53 one-direction and 27 two-direction sites) on the California highway network. The cluster analysis, which was based on varying axle load distributions among the WIM sites, resulted in seven WIM groups. The decision tree method then applied resulted in five WIM spectra, with *truck percent* and the *low-axle/high-axle truck ratio* as the critical explanatory variables determining the WIM spectra. Spectra 1 is the lightest axle load distribution, and it was observed at 16 WIM sites. Spectra 2 is the second lightest axle load distribution, and it was found at 19 WIM sites. Spectra 3 is the medium axle load distribution, and it is the predominant type, appearing at 23 of the 80 California WIM sites. Spectra 4, the second heaviest axle load spectra, was observed at 8 WIM sites, and Spectra 5, the heaviest axle load spectra, was observed at 14 WIM sites. The WIM spectra updated in this study were extrapolated to each highway segment based on their *truck percent* and *low-axle/high-axle truck* ratio.

It is recommended that the WIM data be periodically acquired and processed to compare the new WIM spectra with the previous ones and to identify any significant changes observed at each WIM site over years. WIM analysis every five years would be practical to track axle load spectra trends on the California highway system. Furthermore, a follow-up study is suggested to identify segments that are represented by nearby WIM sites on California highway routes and to develop an algorithm to estimate axle load spectra for those segments.

5.2 Traffic Calculation Tool

In this study, a traffic calculation tool was developed to generate input files for the *AASHTOWare Pavement* software. This tool determines the WIM spectra for a chosen pavement route and post mile and generates the required input files for *AASHTOWare Pavement*. These files can be imported directly into the program, allowing pavement engineers to use them in ME pavement designs.

REFERENCES

1. Lu, Q., Zhang, Y., and Harvey, J. 2009. "Estimation of Truck Traffic Inputs for Mechanistic-Empirical Pavement Design in California." *Transportation Research Record* 2095, no. 1: 62–72.
2. Lu, Q., Harvey, J., Le, T., Lea, J., Quinley, R., Redo, D., and Avis, J. 2002. *Truck Traffic Analysis using Weigh-In-Motion (WIM) Data in California* (Draft) (Research Report: UCPRC-RR-2002-01). Berkeley, CA: University of California, Berkeley, Institute of Transportation Studies, University of California Pavement Research Center.
3. California Department of Transportation. 2018. "Weigh-in-Motion (WIM)." Accessed April 30, 2018. https://dot.ca.gov/programs/traffic-operations/wim.
4. Federal Highway Administration. 2010. *WIM Data Analyst's Manual*. Publication (FHWA-IF-10-018). Washington, DC: Federal Highway Administration. fhwa.dot.gov/pavement/wim/pubs/if10018/if10018.pdf.
5. Transportation Research Board. 2004. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements Structures. Part 2. Design Inputs Chapter 4. Traffic* (NCHRP 1-37A). Washington, DC: Transportation Research Board. onlinepubs.trb.org/onlinepubs/archive/mepdg/part2_chapter4_traffic.pdf.
6. Ishak, S., Shin, H., Sridhar, B.K., and Zhang, Z. 2010. "Characterization and Development of Truck Axle Load Spectra for Implementation of New Pavement Design Practices in Louisiana." *Transportation Research Record* 2153: 121–129.
7. Sayyady, F., Stone, J.R., Taylor, K.L., Jadoun, F.M., and Kim, Y.R. 2010. "Clustering Analysis to Characterize Mechanistic-Empirical Pavement Design Guide Traffic Data in North Carolina." *Transportation Research Record* 2160, no. 1: 118–127.
8. Smith, B.C., and Diefenderfer, B.K. 2010. "Analysis of Virginia-Specific Traffic Data for Use with Mechanistic-Empirical Pavement Design Guide." *Transportation Research Record* 2154, no. 1: 100–107.
9. Swan, D.J., Tardf, R., Hajek, J.J., and Hein, D.K. 2008. "Development of Regional Traffic Data for the Mechanistic-Empirical Pavement Design Guide." *Transportation Research Record* 2049, no. 1: 54–62.
10. Ling, H., and Okada, K. 2007. "An Efficient Earth Mover's Distance Algorithm for Robust Histogram Comparison." *IEEE Transactions on Pattern Analysis and Machine Intelligence* 29, no. 5: 840–853.
11. California Department of Transportation. 2018. "Traffic Census Program." Accessed April 30, 2018. https://dot.ca.gov/programs/traffic-operations/census.

APPENDIX A: WIM SITES

WIM Sites 1 to 37

Sites	Name	District	County	Route	Direction	Post Mile	Number of Lanes	Date Installed
1	LODI	10	SJ	5	—	43.7	2	Pre-2003
2	REDDING	2	SHA	5	—	R24.9	2	Pre-2003
3	ANTELOPE EB	3	SAC	80	E	15	4	Pre-2003
4	ANTELOPE WB	3	SAC	80	W	17.2	4	Pre-2003
5	INDIO	8	RIV	10	—	R59.4	2	Pre-2003
6	PALMDALE	7	LA	14	—	R57.8	2-N, 3-S	No Data
7	SANTA NELLA	10	MER	5	—	20.2	2	Pre-2003
8	CONEJO SB	7	VEN	101	S	12	3	Pre-2003
9	CONEJO NB	7	VEN	101	N	7.7	3	Pre-2003
10	FRESNO	6	FRE	99	—	25	3	Nov-2003
11	SONOMA	4	SON	37	—	2.7	2	No Data
12	VAN NUYS SB	7	LA	405	S	42.9	4	Feb-2003
13	VAN NUYS NB	7	LA	405	N	42.9	4	Feb-2003
14	SAN MARCOS	11	SD	78	—	10.7	3	Pre-2003
15	IRVINE SB	12	ORA	5	S	25.8	5	Pre-2003
16	IRVINE NB	12	ORA	5	N	25.8	5	Pre-2003
17	HAYWARD SB	4	ALA	880	S	14.7	4	Pre-2003
18	HAYWARD NB	4	ALA	880	N	14.7	4	Pre-2003
19	MARTINEZ	4	CC	4	—	R10.7	3	No Data
20	LOLETA	1	HUM	101	—	65.6	2	Pre-2003
22	JEFFREY	11	IMP	8	—	25.8	2	Pre-2003
23	EL CENTRO	11	IMP	8	—	40	2	Pre-2003
24	NAPA	4	NAP	12	—	2.3	2	Pre-2003
25	NEWBERRY	8	SBD	40	—	28.9	2	Pre-2003
26	CAMERON	11	SD	8	—	51.5	2	Pre-2003
27	TRACY	10	SJ	5	—	7.4	2	Feb-2003
28	MACDOEL	2	SIS	97	—	34.5	1	Pre-2003
30	MT. SHASTA	2	SIS	5	—	11.4	2	Jun-2003
31	WOODSIDE SB	4	SM	280	S	R5.6	4	Pre-2003
32	WOODSIDE NB	4	SM	280	N	R5.6	4	Pre-2003
33	BURLINGAME SB	4	SM	101	S	17.5	5	Pre-2003
34	BURLINGAME NB	4	SM	101	N	17.5	5	Pre-2003
35	PACHECO	4	SCL	152	—	R26.9	2	Feb-2003
36	LOS BANOS	10	MER	152	—	23	2	Pre-2003
37	ELSINORE SB	8	RIV	15	S	21.6	3	Pre-2003

WIM Sites 38 to 75

Sites	Name	District	County	Route	Direction	Post Mile	Number of Lanes	Date Installed
38	ELSINORE NB	8	RIV	15	N	21.6	6	Pre-2003
39	REDLANDS	8	SBD	30	E/W	31.7	2/2	Pre-2003
40	COACHELLA	8	RIV	86	N/S	R16.0	2/2	Pre-2003
41	VACAVILLE EB	4	SOL	80	E	30.6	4	Pre-2003
42	VACAVILLE WB	4	SOL	80	W	30.6	4	Pre-2003
43	CHOLAME	5	SLO	46	E/W	44.7	1/1	Pre-2003
44	BANTA	10	SJ	205	W/E	R9.5	2/2	Pre-2003
46	GALT	3	SAC	99	S/N	6.9	2/2	Pre-2003
47	CASTAIC SB	7	LA	5	S	R56.1	6	Mar-2003
48	CASTAIC NB	7	LA	5	N	R56.1	6	Jun-2003
49	AUBURN	3	PLA	49	N/S	9	2/2	Pre-2003
50	ELMIRA	4	SOL	505	N/S	R2.2	2/2	Pre-2003
51	WESTSAC EB	3	YOL	50	E	0.6	4	Pre-2003
52	WESTSAC WB	3	YOL	50	W	0.6	4	Pre-2003
55	DUBLIN SB	4	CC	680	S	R0.1	4	Pre-2003
56	DUBLIN NB	4	CC	680	N	R0.1	4	Pre-2003
57	PINOLE EB	4	CC	80	E	7.5	6	Pre-2003
58	PINOLE WB	4	CC	80	W	7.5	6	Pre-2003
59	LA 710 SB	7	LA	710	S	11.5	4	Pre-2003
60	LA 710 NB	7	LA	710	N	11.5	4	Pre-2003
61	PERALTA EB	12	ORA	91	E	R11.9	4	Pre-2003
62	PERALTA WB	12	ORA	91	W	R11.9	4	Pre-2003
63	MURRIETA	8	RIV	215	N/S	R15.0	2/2	Pre-2003
64	FOSTER CITY	4	SM	92	W/E	R14.1	3/3	Pre-2003
65	PIRU	7	VEN	126	W/E	30.8	2/2	Pre-2003
66	CALICO	8	SBD	15	N/S	R81.4	2/2	Pre-2003
67	DEVORE	8	SBD	215	N/S	14.8	2/2	Pre-2003
68	GILROY	4	SCL	101	S/N	R9.8	3/3	Pre-2003
69	FONTANA SB	8	SBD	15	S	6.1	4	Pre-2003
70	FONTANA NB	8	SBD	15	N	6.1	4	Pre-2003
71	HINKLEY	8	SBD	58	W/E	19.7	2/2	Nov-2003
72	BOWMAN	3	PLA	80	W/E	R23.4	3/3	Pre-2003
73	STOCKDALE	6	KER	5	N/S	48.7	2/2	Pre-2003
74	BAKERSFIELD	6	KER	99	N/S	20.3	3/3	Pre-2003
75	KEYES	10	STA	99	S/N	R8.4	3/3	Pre-2003

WIM Sites 76 to 116

Sites	Name	District	County	Route	Direction	Post Mile	Number of Lanes	Date Installed
76	TEMPLETON	5	SLO	101	S/N	49.5	2/2	Pre-2003
77	COLTON EB	8	SBD	10	E	12.4	4	Pre-2003
78	COLTON WB	8	SBD	10	W	12.4	4	Pre-2003
79	ARTESIA EB	7	LA	91	E	R7.5	5	Pre-2003
80	ARTESIA WB	7	LA	91	W	R7.5	5	Mar-2003
81	POSITAS	5	SB	101	N/S	16.2	3/3	Pre-2003
82	GLENDORA EB	7	LA	210	E	R42.6	5	Pre-2003
83	GLENDORA WB	7	LA	210	W	R42.6	5	Pre-2003
84	LEUCADIA SB	11	SD	5	S	R42.2	4	Pre-2003
85	LEUCADIA NB	11	SD	5	N	R42.2	4	Pre-2003
86	UKIAH	1	MEN	101	S/N	R21.9	2/2	Apr-2003
87	BALBOA SB	11	SD	15	S	R10.9	4	Pre-2003
88	BALBOA NB	11	SD	15	N	R10.9	4	Pre-2003
89	DEKEMA SB	11	SD	805	S	24.5	4	Pre-2003
90	DEKEMA NB	11	SD	805	N	24.5	4	Pre-2003
91	POGGI SB	11	SD	805	S	5.6	4	Pre-2003
92	POGGI NB	11	SD	805	N	5.6	4	Pre-2003
93	LAKEPORT	1	LAK	29	N/S	44.4	2/2	Pre-2003
94	GREENFIELD	5	MON	101	S/N	47.9	2/2	Pre-2003
95	ONTARIO EB	8	SBD	60	E	R7.9	3	Pre-2003
96	ONTARIO WB	8	SBD	60	W	R7.9	3	Pre-2003
97	CHINO	8	SBD	83	N/S	5.7	2/2	Pre-2003
98	PRADO	8	SBD	71	S/N	R5.8	2/2	May-2003
99	TULLOCH	10	TUO	120	E/W	6.4	2/2	Pre-2003
100	MIRAMAR SB	11	SD	163	S	10.4	5	Pre-2003
101	MIRAMAR NB	11	SD	163	N	10.4	4	Pre-2003
103	ORANGE SB	12	ORA	57	S	21	4	Pre-2003
104	ORANGE NB	12	ORA	57	N	21	4	Pre-2003
105	ELKHORN	3	SAC	5	S/N	33.2	S2N2	Feb-2003
106	ELVERTA	3	SAC	99	N/S	34.5	N2S2	Pre-2003
107	CHICO	3	BUT	99	S/N	R34.0	S2N2	Pre-2003
108	WILLOWS	3	GLE	5	N/S	R10.9	N2S2	Pre-2003
109	INYO	9	INY	395	N/S	96.4	N2S2	Pre-2003
110	HONEYLAKE	2	LAS	395	—	83.2	1	Pre-2003
111	SAIGON SB	12	ORA	405	S	18.6	4	Pre-2003
112	SAIGON NB	12	ORA	405	N	18.6	4	Pre-2003
113	CARBONA 2	10	SJ	580	W/E	8.2	W2E2	Feb-2003
114	ARVIN	6	KER	58	E/W	R64.9	E2W2	Aug-2003
115	PORTERVILLE	6	TUL	65	N/S	R23.4	N2S2	Aug-2003
116	LONG BEACH PORT	7	LA	47	—	6.2	3	Mar-2005

APPENDIX B: WIM DATA QUALITY SUMMARY

WIM Sites 1 to 66

Site No.	Site Name	Percent of Good Data per Year												Average
		2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	
1	LODI	40	47	37	86	86	100	81	99	97	89	87	46	75
2	REDDING	35	34	37	30	30	91	67	59	100	100	100	100	65
3	ANTELOPE EB	22	47	42	42	42	91	100	90	81	100	100	100	71
4	ANTELOPE WB	26	40	42	42	42	41	97	77	85	100	100	92	65
5	INDIO	33	41	19	42	42	31	97	83	101	83	89	98	63
7	SANTA NELLA	37	43	37	36	36	55	50	50	86	84	99	99	59
8	CONEJO SB	40	42	42	39	39	93	100	84	85	100	100	100	72
9	CONEJO NB	40	46	43	45	45	56	100	62	89	95	100	100	68
10	FRESNO	40	46	42	45	45	95	93	92	93	53	44	0	57
12	VAN NUYS SB	0	8	0	4	4	80	58	17	88	88	99	96	45
13	VAN NUYS NB	0	19	13	15	15	17	76	5	87	100	99	100	46
14	SAN MARCOS	41	35	8	13	13	38	16	7	90	100	90	100	46
15	IRVINE SB	41	48	28	0	0	94	100	93	97	100	100	100	67
16	IRVINE NB	19	45	14	4	4	97	92	90	98	100	100	100	64
17	HAYWARD SB	21	46	41	42	42	93	100	63	88	89	95	100	68
18	HAYWARD NB	17	46	41	41	41	89	59	49	90	73	93	87	61
20	LOLETA	75	86	47	90	90	100	100	76	81	95	90	98	86
22	JEFFREY	33	42	20	41	41	92	34	67	73	95	95	100	61
23	EL CENTRO	38	46	39	36	36	74	100	97	92	87	92	100	70
24	NAPA	43	42	38	19	19	92	89	79	22	0	45	100	49
25	NEWBERRY	34	38	32	37	37	64	17	67	92	100	86	99	59
26	CAMERON	33	40	20	35	35	82	67	68	83	96	95	97	63
27	TRACY	0	4	14	12	12	76	87	94	94	93	98	82	56
28	MACDOEL	0	19	27	25	25	82	95	63	92	100	100	100	61
30	MT. SHASTA	33	27	30	36	36	69	87	43	85	100	99	100	62
31	WOODSIDE SB	40	46	30	12	12	95	59	75	98	100	100	100	64
32	WOODSIDE NB	40	46	30	25	25	96	59	79	93	92	100	100	65
33	BURLINGAME SB	35	45	27	22	22	0	41	83	83	95	95	100	54
34	BURLINGAME NB	41	18	0	0	0	0	41	93	85	95	96	100	47
35	PACHECO	43	41	35	38	38	75	71	29	98	98	100	100	64
36	LOS BANOS	41	40	42	37	37	9	0	46	84	100	95	100	53
37	ELSINORE SB	21	31	41	41	41	50	0	0	77	100	100	100	50
38	ELSINORE NB	19	31	42	47	47	96	100	16	47	100	100	94	62
39	REDLANDS	42	46	32	42	42	83	87	57	57	100	99	97	65
40	COACHELLA	38	35	12	15	15	58	44	54	76	100	96	97	53
41	VACAVILLE EB	0	18	17	0	0	0	0	0	0	0	30	100	14
42	VACAVILLE WB	0	0	0	0	0	0	0	0	8	0	30	100	12
43	CHOLAME	40	43	41	34	34	84	87	78	98	100	0	8	54
44	BANTA	38	35	18	0	0	8	99	83	94	100	99	94	56
45	CARBONA	0	0	0	0	0	0	0	0	0	0	0	0	0
46	GALT	28	30	24	13	13	77	22	33	92	100	100	100	53
47	CASTAIC SB	17	73	22	61	61	0	0	0	75	100	100	100	51
48	CASTAIC NB	17	79	36	24	24	0	0	0	83	100	100	100	47
49	AUBURN	44	27	25	12	12	79	50	8	86	100	89	96	52
50	ELMIRA	38	23	29	19	19	42	74	73	91	100	97	99	59
51	WESTSAC EB	40	40	38	23	23	57	0	7	24	0	34	8	25
52	WESTSAC WB	8	12	30	31	31	75	39	41	55	88	99	100	51
55	DUBLIN SB	0	0	0	0	0	17	40	8	39	100	100	100	34
56	DUBLIN NB	0	0	0	0	52	0	0	0	41	100	100	100	33
57	PINOLE EB	38	36	8	52	89	100	95	84	88	100	97	100	74
58	PINOLE WB	16	30	32	89	90	100	98	87	78	99	100	100	77
59	LA 710 SB	88	58	65	90	12	0	0	90	61	100	97	100	63
60	LA 710 NB	92	52	6	12	23	0	0	92	76	85	92	99	52
61	PERALTA EB	17	7	8	23	32	0	0	34	0	17	97	100	28
62	PERALTA WB	21	12	12	32	18	92	67	25	0	17	100	100	41
63	MURRIETA	41	41	12	18	25	89	92	33	2	0	0	8	30
64	FOSTER CITY	36	45	57	25	0	89	68	55	79	79	87	100	60
65	PIRU	42	41	2	0	27	33	8	52	87	98	96	100	49
66	CALICO	25	23	16	27	0	10	25	35	89	99	98	99	46

WIM Sites 67 to 872

Site No.	Site Name	Percent of Good Data per Year												Average
		2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	
67	DEVORE	44	23	26	0	31	70	95	20	46	100	100	95	54
68	GILROY	36	35	20	31	47	97	90	93	82	97	93	100	68
69	FONTANA SB	35	38	43	47	39	86	85	70	19	8	100	100	56
70	FONTANA NB	40	41	33	39	42	94	75	50	30	8	100	100	54
71	HINKLEY	33	38	33	42	38	48	86	32	84	100	76	99	59
72	BOWMAN	27	46	34	38	7	89	95	100	101	93	98	100	69
73	STOCKDALE	40	38	18	7	31	19	97	70	77	79	92	100	56
74	BAKERSFIELD	19	31	4	31	38	99	100	100	84	37	50	96	57
75	KEYES	33	38	38	38	35	96	74	90	88	88	85	96	67
76	TEMPLETON	36	44	32	35	42	99	75	67	78	99	100	100	67
77	COLTON EB	39	46	39	42	41	74	50	0	49	91	100	65	53
78	COLTON WB	40	43	38	41	1	100	91	88	38	10	0	0	41
79	ARTESIA EB	4	25	23	1	1	50	17	90	86	100	100	100	50
80	ARTESIA WB	8	18	5	1	40	53	17	39	75	100	100	100	46
81	POSITAS	19	15	26	40	5	76	0	9	92	100	92	100	48
82	GLENDORA EB	38	33	5	5	19	96	100	64	62	100	100	100	60
83	GLENDORA WB	35	35	41	19	81	59	18	35	88	100	54	89	55
84	LEUCADIA SB	95	94	71	81	81	100	99	99	100	99	97	100	93
85	LEUCADIA NB	84	78	68	81	31	100	100	99	85	99	99	100	85
86	UKIAH	41	40	24	31	42	83	78	55	81	100	100	100	65
87	BALBOA SB	28	37	33	42	39	97	83	76	89	94	100	100	68
88	BALBOA NB	38	44	41	39	42	89	96	48	81	100	100	100	68
89	DEKEMA SB	33	42	40	42	35	95	83	96	87	33	0	32	52
90	DEKEMA NB	27	46	33	35	42	91	93	69	98	100	75	0	59
91	POGGI SB	19	35	15	42	42	100	90	100	66	0	0	0	42
92	POGGI NB	25	42	35	42	42	97	100	100	60	0	0	0	45
93	LAKEPORT	40	42	41	42	42	83	83	96	89	100	83	100	70
94	GREENFIELD	40	30	37	42	38	73	91	77	86	99	97	100	68
95	ONTARIO EB	4	15	38	38	38	97	50	98	74	100	84	100	61
96	ONTARIO WB	34	22	24	38	42	72	76	60	73	100	91	100	61
97	CHINO	9	0	16	42	36	98	100	90	83	100	100	98	64
98	PRADO	38	46	28	36	88	97	100	91	86	100	85	42	70
99	TULLOCH	94	85	61	88	41	100	100	92	78	100	71	100	84
100	MIRAMAR SB	43	47	24	41	24	99	0	0	70	99	100	100	54
101	MIRAMAR NB	28	51	36	24	0	62	100	86	85	100	100	100	64
103	ORANGE SB	19	19	7	0	29	58	0	64	41	100	100	100	45
104	ORANGE NB	19	27	35	29	15	83	0	8	90	100	100	100	51
105	ELKHORN	22	24	38	15	35	64	0	0	4	0	0	0	17
106	ELVERTA	41	31	37	35	42	90	53	83	59	33	53	93	54
107	CHICO	19	46	41	42	42	92	100	91	77	100	97	100	71
108	WILLOWS	31	46	38	42	73	91	96	93	79	94	82	94	72
109	INYO	88	55	58	73	36	92	92	50	61	96	97	100	75
110	HONEYLAKE	40	47	37	36	38	63	100	64	90	100	100	100	68
111	SAIGON SB	36	33	27	38	42	97	76	66	98	100	100	100	68
112	SAIGON NB	36	48	41	42	42	91	75	81	99	100	98	100	71
113	CARBONA 2	34	47	41	42	15	97	98	81	90	94	100	93	69
114	ARVIN	19	35	37	15	42	82	97	0	59	100	100	100	57
115	PORTERVILLE	40	46	42	42	83	97	98	92	76	100	100	95	76
116	LONG BEACH PORT	0	0	69	83	25	100	33	34	16	0	0	0	30
804	SANTA NELLA SB	36	35	0	25	27	72	50	62	95	21	25	8	38
812	COTTONWOOD NB	25	51	33	27	44	99	50	34	56	84	99	93	58
814	SANTA NELLA NB	30	29	16	44	42	99	57	71	72	59	85	99	59
828	BLACKROCK WB	40	53	39	42	4	58	59	91	92	96	79	0	54
834	DONNER PASS WB	15	49	7	4	0	93	62	74	87	99	73	58	52
844	CALEXICO NB	0	0	0	0	38	0	90	73	53	77	81	86	42
846	COTTONWOOD SB	21	53	41	38	42	80	92	73	41	82	100	100	64
848	OTAY MESA WB	0	23	41	42	42	99	71	92	100	100	100	98	67
854	RAINBOW SB	40	51	43	42	12	100	96	82	99	97	98	100	72
856	MISSION GRADE NB	19	19	30	12	0	75	0	10	78	59	99	99	42
870	CARSON NB	0	0	0	0	0	0	0	0	0	0	0	0	0
872	CARSON SB	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX C: VEHICLE CLASS AVERAGE SPEED AT EACH WIM SITE (2015)

Average Speed (mph) by Vehicle Class on WIM Sites 1 to 50

WIM Site	Average Speed (mph) for Vehicle Class											
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 14	Class 15	Class 4 through 15
1	66	66	60	58	59	59	58	59	59	57	58	57	60
2	64	64	59	58	59	58	58	58	58	57	58	58	59
3	61	62	58	56	58	57	56	59	59	54	56	57	58
4	62	61	56	60	56	56	56	57	57	58	55	55	57
5	66	68	61	53	59	58	58	60	59	55	58	59	59
7	68	71	62	59	61	60	60	61	61	59	59	61	62
8	64	64	59	57	57	58	59	58	59	56	56	58	59
9	63	63	58	58	57	57	57	58	58	61	55	59	59
12	52	49	46	46	46	48	46	46	47	43	47	49	47
13	53	52	52	53	50	53	56	56	57	52	53	53	53
14	56	55	53	53	52	53	50	55	53	48	53	52	53
15	58	58	55	51	55	56	54	57	58	54	55	55	56
16	57	55	51	50	52	54	51	56	58	51	54	50	53
17	53	52	49	50	49	49	47	50	54	47	50	46	50
18	51	48	49	49	49	49	52	54	56	52	51	51	51
20	63	64	59	56	58	58	56	58	58	52	57	46	57
22	67	68	60	57	59	59	59	60	59	58	58	61	60
23	65	67	59	57	59	59	59	59	58	57	58	61	60
24	59	62	57	56	57	56	56	58	57	53	58	57	57
25	68	66	62	60	61	60	61	61	61	61	62	61	62
26	65	68	60	55	58	58	57	58	57	51	56	59	58
27	67	69	60	57	60	59	60	59	60	60	58	57	60
28	63	62	59	59	59	59	58	60	59	58	59	59	59
30	65	67	60	59	59	58	58	59	58	56	58	59	60
31	64	64	59	54	58	58	57	59	58	54	58	55	58
32	63	63	59	53	56	57	54	56	56	48	56	56	56
33	56	55	53	50	52	54	51	55	56	51	54	53	53
34	61	58	58	54	56	56	55	57	57	55	56	56	56
35	66	64	61	58	59	59	59	59	59	58	59	59	60
36	61	62	56	54	56	56	56	56	56	55	56	56	57
37	69	67	62	59	60	60	61	61	60	60	60	62	62
38	69	69	60	61	59	59	60	60	60	59	59	62	61
39	60	59	56	54	55	57	56	57	57	55	57	54	56
40	62	65	60	57	60	60	60	61	60	58	59	68	61
41	66	65	60	61	58	59	59	60	60	58	58	59	60
42	67	66	61	59	59	59	60	60	60	58	59	60	61
43	64	65	57	56	59	59	59	59	59	59	57	58	59
44	64	65	60	59	60	60	59	61	60	59	60	61	61
46	65	64	60	58	59	59	59	60	60	58	59	48	59
47	64	63	58	53	57	57	57	58	57	54	56	59	58
48	65	67	60	55	60	59	60	60	60	58	58	59	60
49	57	62	57	51	56	55	54	55	54	49	55	64	56
50	69	70	62	59	60	60	60	61	59	59	60	61	62

Average Speed (mph) by Vehicle Class on WIM Sites 51 to 100

WIM Site	Average Speed (mph) for Vehicle Class											
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 14	Class 15	Class 4 through 15
51	64	64	59	59	57	58	57	59	58	60	57	49	58
52	64	65	59	57	58	59	59	60	60	59	58	57	60
55	66	66	60	58	59	59	58	60	60	56	59	59	60
56	63	62	57	53	57	57	55	58	58	53	56	55	57
57	59	56	55	58	54	54	55	57	58	55	55	52	56
58	59	56	52	46	51	51	49	49	52	44	49	49	50
59	55	57	54	52	53	53	53	54	53	55	54	48	53
60	63	62	58	57	57	57	56	58	58	54	57	64	58
61	67	65	58	57	57	57	57	58	60	56	57	59	59
62	65	65	59	56	58	58	58	58	60	56	57	60	59
63	64	62	58	55	58	59	58	60	60	58	58	63	59
64	54	57	53	54	51	54	49	55	54	52	54	51	53
65	61	63	57	54	57	57	57	57	57	54	58	58	58
66	68	69	62	60	60	60	60	61	61	57	59	60	61
67	63	68	60	53	60	59	58	60	60	55	58	61	60
68	66	64	58	56	57	57	56	57	57	55	56	59	58
69	66	66	59	55	58	58	59	59	60	56	58	59	59
70	66	62	58	62	57	57	61	59	59	70	57	70	62
71	68	68	61	57	61	60	61	61	61	58	61	60	61
72	66	68	63	62	61	61	61	61	60	62	59	66	62
73	69	70	62	57	61	60	60	61	61	59	60	62	62
74	61	57	54	51	53	53	54	54	54	52	52	54	54
75	64	63	59	56	58	58	58	59	59	57	57	58	59
76	65	65	58	56	59	59	59	59	60	58	58	59	60
77	58	57	54	52	52	54	53	57	57	53	54	61	55
79	55	55	51	52	51	51	50	54	53	50	52	52	52
80	56	56	53	52	52	53	53	55	56	52	53	52	54
81	57	56	54	52	55	56	56	57	57	53	55	52	55
82	61	59	56	56	54	54	54	57	55	48	54	61	56
83	57	56	54	51	54	56	55	56	58	52	53	52	55
84	57	53	52	47	52	52	47	52	55	50	50	50	51
85	62	59	57	54	56	57	56	58	60	52	55	55	57
86	64	66	57	58	59	58	57	58	59	55	58	57	59
87	58	64	56	55	55	55	53	58	58	56	55	53	56
88	62	63	58	56	58	58	58	59	59	52	56	57	58
89	54	56	53	51	52	53	52	55	55	43	53	48	52
93	62	63	57	57	57	57	56	58	58	55	57	59	58
94	67	66	59	57	58	59	59	59	59	59	57	59	60
95	63	58	56	53	55	56	57	58	59	54	56	56	57
96	60	59	55	52	53	55	54	56	57	52	53	52	55
97	43	46	43	40	41	40	39	40	42	35	41	40	41
98	62	66	57	55	57	57	57	58	58	56	58	58	58
99	64	60	59	57	58	58	58	59	57	59	58	55	58
100	63	64	59	57	59	59	58	59	60	57	57	55	59

Average Speed (mph) by Vehicle Class on WIM Sites 101 to 116 and Average Speed on All WIM Sites

WIM Site	Average Speed (mph) for Vehicle Class											
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13	Class 14	Class 15	Class 4 through 15
101	63	65	59	56	59	58	58	58	58	59	57	59	59
103	61	65	54	52	54	55	55	55	58	61	53	65	57
104	50	51	49	49	47	48	46	51	52	40	48	41	48
106	69	69	62	61	61	61	61	62	61	60	61	65	63
107	59	60	57	54	56	57	54	58	58	55	57	53	56
108	66	68	61	58	60	59	59	59	59	58	60	60	61
109	67	68	60	58	60	60	60	61	60	58	60	63	61
110	59	61	56	49	56	56	54	55	52	54	53	56	55
111	58	58	53	51	53	54	53	55	54	52	53	53	54
112	59	60	57	58	57	57	57	57	58	54	55	38	56
113	66	68	60	55	58	58	58	58	59	57	58	54	59
114	65	66	57	55	59	58	59	59	59	55	57	58	59
115	61	63	57	55	56	57	56	57	57	56	57	56	57
116	57	49	48	47	47	47	47	51	—	39	43	50	47
All WIM sites	62	62	57	55	56	57	56	57	58	55	56	56	57