Final Research Report

IMPROVING TRAFFIC CHARACTERIZATION TO ENHANCE PAVEMENT DESIGN AND PERFORMANCE: LOAD SPECTRA DEVELOPMENT

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16. ABSTRACT

This research addresses the understanding of, and need for, load spectra in future pavement design procedures and as a stepping stone toward more complete pavement design.

The primary objective of this project was to develop truck axle load spectra for Washington State. To do this, axle load data collected at WIM stations throughout Washington State were used. The developed load spectra encompass the principal truck axles on the roadway network: single, tandem, and tridem. Achieving this objective allows the Washington State Department of transportation, or any state highway agency with analogous traffic patterns, to accommodate the requirements of the *2002 Design Guide*, developed through NCHRP Project 1-37A.

A secondary objective of this project was to determine whether ESALs obtained from the developed load spectra are significantly different from historical values. Because the developed load spectra are transformable to ESALs, state highway agencies that decide not to use the new guide can still choose to employ the ESALs produced with the load spectra.

The project concluded that the developed load spectra are reasonable. For single axles they are comparable to the *2002 Design Guide* and MnROAD defaults. For tandem and tridem axles they are slightly more conservative than defaults of the *2002 Design Guide* and MnROAD, but they are still within reason. In addition, the ESALs per vehicle class associated with the developed load spectra are comparable to Washington State historical ESALS for vehicle classes 9, 10, and 13. The use of the newly developed ESALs per vehicle will generally increase design ESALs, but that increase will be due to inclusion of the less predominant vehicle classes (4, 6, 7, 8, and 11).

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DISCLAIMER

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CHAPTER 1: INTRODUCTION

PROBLEM STATEMENT

Pavements are complex systems, involving the interaction of numerous variables. Their performance is influenced by material properties, traffic, the environment, and construction practices. Numerous researchers have worked to improve materials specifications and prediction of the behavior of various mix designs. Efforts to improve traffic data collection, ongoing for the past fifty years, have resulted in a more representative depiction of the roadways, and the higher quality of collected traffic and environmental data has resulted in more accurate historical data for future pavement design and rehabilitation. In addition, state highway agencies (SHAs) are becoming more insistent that construction companies execute consistent construction practices. In all these ways, the understanding and quality of pavement systems are being advanced. This research focused on the development of truck axle load spectra for improved pavement design.

To provide more representative estimates of loading conditions, SHAs normally collect several types of traffic data. Static weight stations, automatic vehicle classifiers (AVC), automatic traffic recorders (ATR), and, more recently, weigh-in-motion (WIM) sensors are the most typical traffic data collection devices. A common practice of SHAs is to use the information provided by these devices to convert mixed traffic data streams into equivalent single axle loads (ESALs) by using equivalency factors.

ESALs are a traffic estimate that is required by most pavement design procedures, including the American Association of State Highway and Transportation Officials

(AASHTO) 1993 Pavement Design Guide. However, ESALs are influenced by pavement type (flexible or rigid), surface thickness, and type of distress or failure. Consequently, even roadways with fairly constant loads and traffic volumes may produce significantly varying ESALs along their lengths, depending on the interaction of these factors. Hence, some researchers have concluded that the use of ESALs with mechanistic-based performance models produces less than desirable predictions and have recommended the use of axle load and vehicle classification data instead (Hajeck, 1995; Rauhut, et al., 1984).

Another problem facing pavement design and analysis professionals is that the majority of currently accepted design procedures depends on empirical relationships based on field assessments made 40 years ago. Most significantly, AASHTO pavement design guides are based on relationships developed at the American Association of State Highway Officials (AASHO) Road Test in the late 1950s and early 1960s. Although the relationships between traffic data and pavement performance obtained from the AASHO Road Test are most applicable to the conditions under which they were developed, the AASHO relationships have been extrapolated to conditions not included in the original test. Furthermore, pavement damage caused by new vehicle characteristics and configurations may differ from damage experienced at the AASHO Road Test. Therefore, properly extrapolating such relationships to current conditions is problematic.

One of the latest efforts aimed at improving pavement design and analysis procedures is the National Cooperative Highway Research Program (NCHRP) Project 1-37A (Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures). A significant aspect of this new guide is the use of truck axle load spectra rather than ESALs. (Although the team responsible for NCHRP Project 1-39–Traffic Data for Mechanistic Pavement Design, a complementary project to NCHRP 1-37A, was also interested in determining whether collecting more accurate tire pressure distributions would be helpful for the *2002 Design Guide*, the NCHRP 1-37A team decided to defer the application of tire pressure distributions to simplify the complex design process.)

PROJECT OBJECTIVES

The primary objective of this project was to develop truck axle load spectra for Washington State. To do this, axle load data collected at WIM stations throughout Washington State would be used. The developed load spectra would encompass the principal truck axles on the roadway network: single, tandem, and tridem. Achieving this objective would allow the Washington State Department of Transportation (WSDOT), or any SHA with analogous traffic patterns, to accommodate the requirements of the *2002 Design Guide*.

Because the developed load spectra would be transformable to ESALs, SHAs that decided not to use the new guide could still choose to employ the ESALS produced with the load spectra. Therefore, a secondary objective of this project was to determine whether ESALs obtained from the developed load spectra would be significantly different from historical values. If the new ESALS were significantly different, SHAs would need to reevaluate their historical ESAL data in light of the new load spectra-induced ESALs.

This research was intended to aid the understanding of, and address the need for, load spectra in future pavement design procedures and as a stepping stone in the quest for more complete pavement design.

REPORT ORGANIZATION

This report is organized as follows:

Chapter 2 presents a literature review. The first part of the chapter includes a brief description of NCHRP projects 1-37A and 1-39, emphasizing the aspects most relevant to this research. The second part of the chapter briefly describes traffic data classification and weigh-in-motion (WIM) technology.

Chapter 3 describes Washington State's experience with traffic data collection and classifications for the past 15 years, along with an evaluation of axle weights from 1960 through 1983.

Chapter 4 outlines the report's methodology.

Chapter 5 discusses sensitivity analyses of the *2002 Design Guide*, ESALs, and statistical testing utilized before development of the load spectra.

Chapter 6 outlines the criteria for developing the load spectra. Additionally, the ESALs associated with the developed load spectra are compared with historical ESALs calculated for Washington State.

Chapter 7 summarizes the conclusions of the report along with recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

PAVEMENT DESIGN GUIDE DEVELOPMENT

For the past four decades, pavement designers have faced the challenge of adequately applying well-recognized design procedures—such as the AASHTO guidelines in 1959 (Guideline), 1962 (Interim Guide), 1972 (Revision of Guide), 1981 (Chapter III Revisions), the all new guide in 1986, and 1993 guide (Overlay Design and minor revisions)—to the conditions of their roadway networks. Because most pavement design procedures depend on empirical relationships based on field tests, the adequacy of the design procedures depend on compatibility between the roadway and field test with respect to [1] environmental conditions, [2] mixed truck traffic, [3] axle loads, and [4] pavement structure.

AASHTO Pavement Design Guide

Currently, pavement design guides provided by AASHTO are based on AASHO Road Test results from the late 1950s and early 1960s that have been theoretically extended to include conditions not incorporated into these tests. The portions of the experiment pertaining to flexible pavements in the Road Test involved 288 100-ft. flexible pavement test sections (332 counting replications) separated by transition pavement sections of at least 15 ft. The experiment was designed as a full factorial, with asphalt concrete (AC) thickness, base, and subgrade thickness as the design factors (see Table 2-1). Although the AASHO Road Test produced good correlations between pavement structures and traffic data elements, its experimental nature created the following limitations (Highway Research Board, 1962):

1. The experiments tested specific pavement materials and roadbed soils that were not inclusive of all materials used in practice.
2. The test site experienced particular environmental conditions not representative of conditions in all regions.
3. An accelerated two-year test period was extrapolated to longer design periods (15-30 years).
4. Vehicles with similar axle loads and configurations were employed, as opposed to mixed traffic.

Table 2-1. AASHO Road Test flexible pavement layer thicknesses (from Highway Research Board, 1962)

Loop No.	AC Thickness (in.)	Base Thickness (in.)	Subgrade Thickness (in.)
1	1.0 3.0 5.0	0.0 6.0	0.0 8.0 16.0
2	1.0 2.0 3.0	0.0 3.0 6.0	0.0 4.0
3	2.0 3.0 4.0	0.0 3.0 6.0	0.0 4.0 8.0
4	3.0 4.0 5.0	0.0 3.0 6.0	4.0 8.0 12.0
5	3.0 4.0 5.0	0.0 3.0 6.0	4.0 8.0 12.0
6	4.0 5.0 6.0	0.0 3.0 6.0	8.0 12.0 16.0

An added limitation, pertinent to flexible pavements, was that only one loop of the test course, Loop 4, experienced loads equivalent to then legal limits. Loops 1 through 3, which coincided with thinner AC layers, experienced significantly lighter loads, while loops 5 and 6 experienced significantly heavier loads (see figures 2-1 and 2-2 and Table 2-1). Furthermore, because all of the pavement sections included thin AC layers, the single greatest weakness for the AASHO Road Test was that all flexible section failures occurred in the spring thaw period (March).

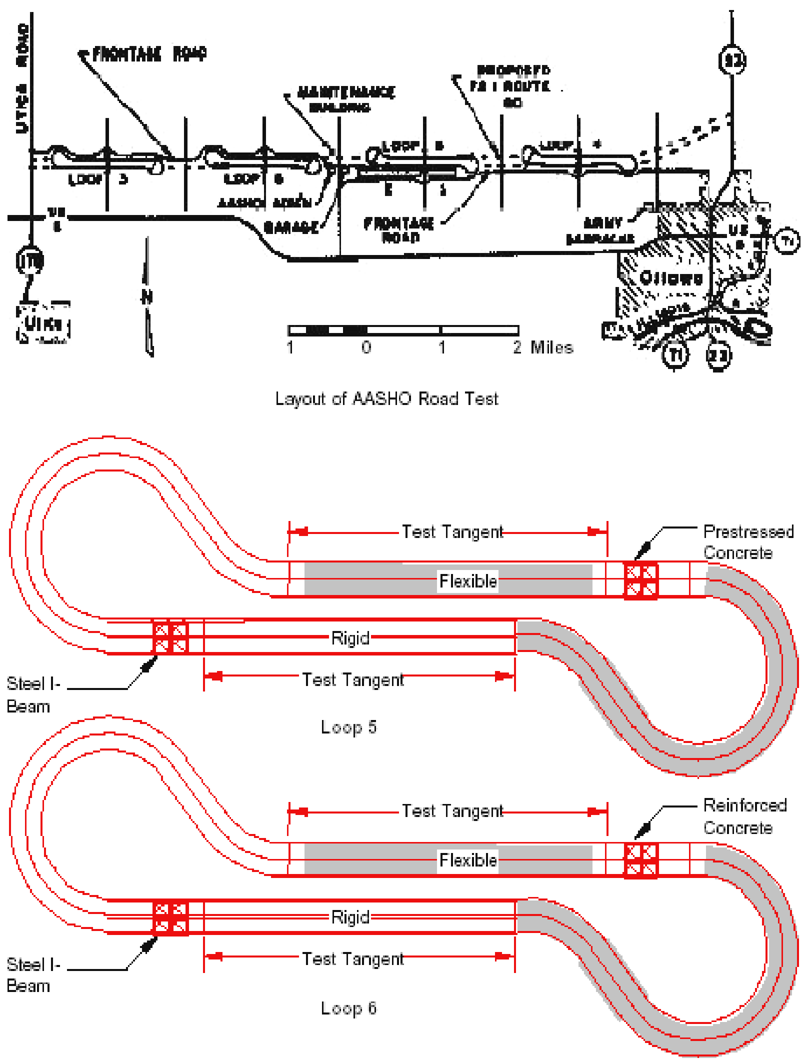


Figure 2-1. Layout and location of the AASHO Road Test and test loops examples (loops 5 and 6) (from Highway Research Board, 1962)

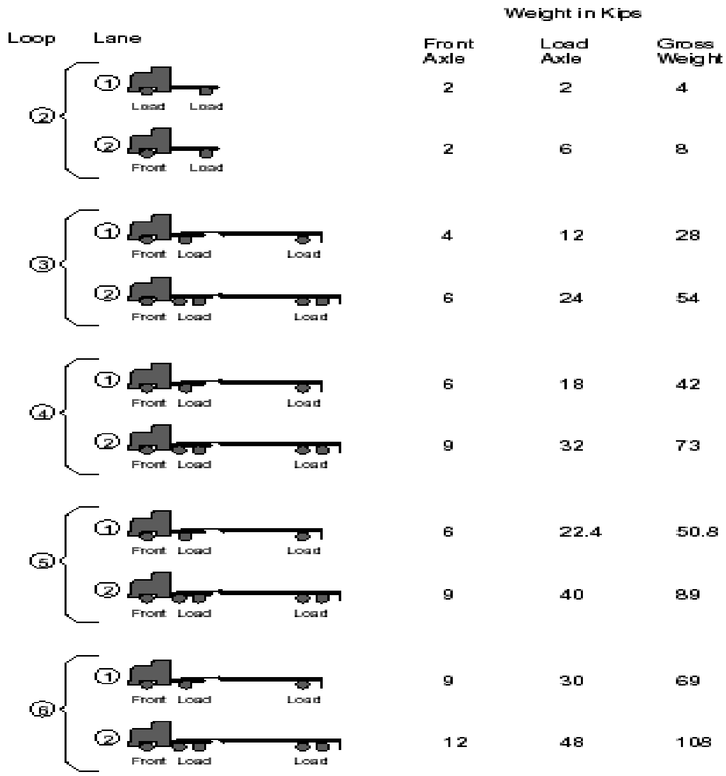


Figure 2-2. Truck types and axle loads at the AASHO Road Test (from Highway Research Board, 1962)

Although the AASHTO design guides extrapolated the results of the AASHO Road Test to numerous flexible pavement sections with varying environmental conditions and layer characteristics, realistically they are most applicable to the conditions under which they were developed.

NCHRP Project 1-37A

The National Cooperative Highway Research Program (NCHRP) was established in 1962 to provide a continuing program of highway research. The research is mainly focused on problem areas that affect highway planning, design, construction, operation, and maintenance nationwide. The NCHRP is administered by the Transportation Research Board (TRB) and sponsored by the state departments of transportation that are members of AASHTO in cooperation with the Federal Highway Administration (FHWA). Each research project in the program is customarily assigned to a panel of professionals knowledgeable in that particular problem area, which analyzes the problem, outlines the project objectives, solicits proposals from qualified research agencies, recommends contract awards, and finally reviews the report of accomplished contracts (NCHRP, 1988).

NCHRP 1-37A produced the latest national pavement design guide, which was scheduled for release in 2002. However, its complexity has repeatedly delayed its projected release date. The *2002 Design Guide's* uniqueness is partly attributable to its inclusion of automatic vehicle classifier (AVC) and weigh-in-motion (WIM) data in its traffic data calculations. Accurate traffic data are necessary to determine the number of applied axles required to estimate each pavement distress mode (e.g., fatigue cracking, rutting). Combining the procedures of the *2002 Design Guide* with more accurate traffic loading data should result in a more realistic design process and more cost-effective pavement structures. However, increasing the levels of accuracy of the input data to obtain excessively precise designs may make implementing the *2002 Design Guide* difficult.

Comprehensive axle load spectra are needed for calculations described in the *2002 Design Guide*; however, some SHAs and/or small municipalities may not possess the resources necessary to collect such data. To facilitate the utilization of the guide, the guide authors devised a hierarchical approach that divides data requirements into four levels (ERES Consultants Inc., 2000):

- Level 1 Inputs: Site-Specific Vehicle Classification and Axle Weight Data

  This level is considered the most accurate because it employs actual axle weights and vehicle classification spectra measured over or near the project site. The process includes counting and classifying the number of vehicles traveling over the roadway by lane and direction, and measuring the axle loads for each vehicle class over a sufficient period to truly determine the design traffic.

- Level 2 Inputs: Site-Specific Vehicle Classification Data and Regional Axle Weight Data

  Level 2 is identical to Level 1 with the exception that it does not need site-specific axle weight data. Levels 1 and 2 are most suited for the design of new roadways.

- Level 3 Inputs: Regional Vehicle Classification and Axle Weight Data

  Only site-specific average annual daily truck traffic (AADTT) and percentage of trucks data are needed for this level. Regional or state vehicle classification and axle weight data for similar highways are used to develop the axle load spectra for each vehicle class. Level 3 is most suited for designing rehabilitation strategies where AVC and WIM are unavailable for a specific roadway. ERES Consultants Inc. anticipates that levels 2 and 3 will be those most commonly used for both new pavement designs and rehabilitation designs.

- Level 4 Inputs: Site-Specific Vehicle Count Data

  For this level, only average annual daily traffic (AADT) and the percentage of trucks are required. The *2002 Design Guide* default axle load spectra and vehicle classification distributions are used with AADT and the percentage of trucks to estimate the *2002 Design Guide's* required traffic data.

All of these levels produce equivalent types of information; however, they vary in terms of input. The four levels produce average daily axle load distributions, by axle type, in each month throughout the design period. The inputs for each of the levels are discussed below (ERES Consultants Inc., 2000).

Level 1

- General inputs
    - Opening year: The year that the pavement is expected to open to traffic.
    - Design period: The time period for forecasted traffic. The default period is 30 years.
    - Directional distribution factor (DDF): The proportion of AADT in each direction. For Level 1, the default factor is set to 0.55 (it is assumed that truck traffic is measured in both directions).
    - Lane distribution factor (LDF): The proportion of directional AADT and AADTT in the design lane. The following are recommended values when no other data exist:
        - Lane specific traffic data: LDF = 1.0
        - 4-lane roadway: LDF = 0.90
        - 6-lane roadway: LDF = 0.60
        - 8-lane roadway: LDF = 0.40
        - 8+ lane roadway: LDF = 0.40
- Truck and axle/tire configuration
    - Tire pressure: The hot or operational inflation pressure of the individual tires for single and dual tires. The hot inflation pressure may be obtained by increasing the cold inflation pressure by 10 to 15 percent. The default operational values are 120 psi for single and dual tires.

- Dual tire spacing: The center-to-center distance between dual tires. The default value is 11.3 in.
- Tandem axle spacing: The median distance between tandem axles. The default value is 51.6 in.
- Tridem axle spacing: The median distance between tridem axles. The default value is 51.6 in. between each of the three axles.
- Quad axle spacing: The median distance between quad axles. Presently there is no default value for this type of axle.

- Average number of axles per truck: Figure 2-3 includes the default values. The FHWA classes are explained more fully below.

Number Axles/Truck | Axle Configuration | Wheelbase

	Single	Tandem	Tridem	Quad
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

Figure 2-3. *2002 Design Guide* default number of axles per truck

- Truck hourly distribution factors: The percentages of daily trucks in each hour of the day. Figure 2-4 shows the default values.
- Seasonal/monthly truck traffic adjustment factors: The user inputs the monthly adjustment factors for each combination of truck class and month for the base year.

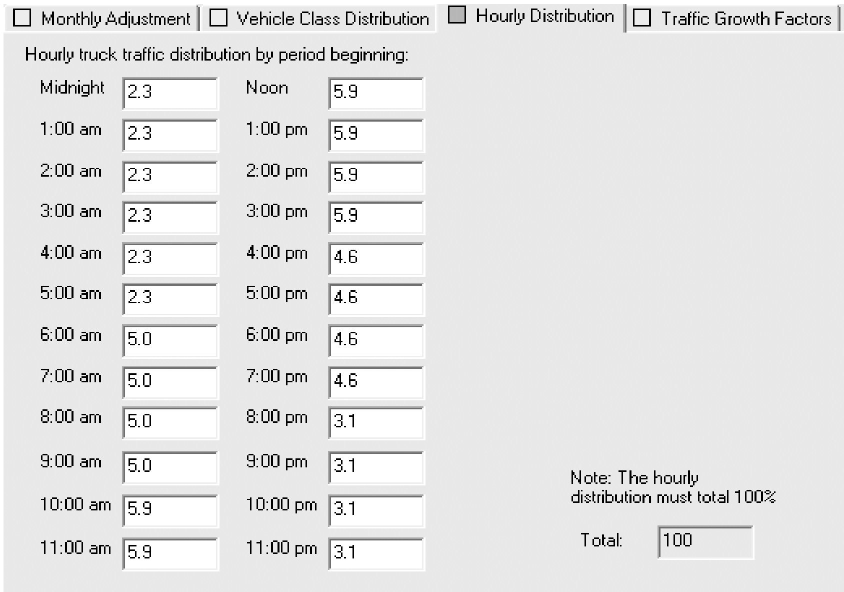


Figure 2-4. *2002 Design Guide* default truck hourly distributions

- AADTT and normalized truck traffic distribution factors.
- Truck traffic forecasting inputs: The user can select a compound, linear, or no growth functions to forecast traffic throughout the design life.
- Normalized axle load distribution: Obtained by analyzing the WIM data and determining the percentage within each load group of the total number of individual axle types (i.e., single, tandem, tridem, and quad) for each truck class.

<u>Level 2</u>

This level is identical to Level 1 in terms of input and computation procedures; however, the normalized axle load distribution factors for each truck class are based on regional data for similar roadways.

<u>Level 3</u>

This level is identical to levels 1 and 2 in terms of input and computation procedures; however, both normalized axle load distribution and vehicle class distribution factors are based on regional data for similar roadways.

Level 4

This level is used when both vehicle class distribution and axle load distribution factors are unattainable; nevertheless, the user is required to enter an AADT value and percentage of total trucks. Default truck and axle load distribution factors are provided for various roadway structural classification groups. The user must also select one of 17 truck traffic classifications (TTC) defined for pavement structural design purposes (see Table 2-2). The classifications were founded on commonly encountered vehicle distribution spectra and primarily include vehicle classes 5, 9, and 13. Table 2-3 tabulates the types and percentages of vehicles included in each truck classification group. The TTC groups represent distributions observed in the Long-Term Pavement Performance (LTPP) program database.

Table 2-2. ***2002 Design Guide*** **truck traffic classification (from ERES Consultants Inc., 2001)**

TTC	Description
1	Major single-trailer truck route (type I)
2	Major single-trailer truck route (type II)
3	Major single- and multi- trailer truck route (type I)
4	Major single-trailer truck route (type III)
5	Major single- and multi- trailer truck route (type II)
6	Intermediate light and single-trailer truck route (I)
7	Major mixed truck route (type I)
8	Major multi-trailer truck route (type I)
9	Intermediate light and single-trailer truck route (II)
10	Major mixed truck route (type II)
11	Major multi-trailer truck route (type II)
12	Intermediate light and single-trailer truck route (III)
13	Major mixed truck route (type III)
14	Major light truck route (type I)
15	Major light truck route (type II)
16	Major light and multi-trailer truck route
17	Major bus route

Table 2-3. Classifications based on commonly encountered vehicle distribution spectra (from ERES Consultants Inc., 2001)

Buses in Traffic Stream	Multi-Trailer	Type of Truck: Single-Trailers & Single-Units	TTC Group No.
Low to None (<2%)	Relatively High Amount of Multi-Trailer Trucks (>10%)	Predominantly single-trailer trucks	5
		High percentage of single-trailer trucks, but some single-unit trucks	8
		Mixed truck traffic with a higher percentage of single-trailer trucks	11
		Mixed truck traffic with about equal percentages of single-unit and single-trailer trucks	13
		Predominantly single-unit trucks	16
	Moderate Amount of Multi-Trailer Trucks (2-10%)	Predominantly single-trailer trucks	3
		Mixed truck traffic with a higher percentage of single-trailer trucks	7
		Mixed truck traffic with about equal percentages of single-unit and single-trailer trucks	10
		Predominantly single-unit trucks	15
Low to Moderate (>2%)	Low to None (<2%)	Predominantly single-trailer trucks	1
		Predominantly single-trailer trucks, but with a low percentage of single-unit trucks	2
		Predominantly single-trailer trucks with a low to moderate amount of single-unit trucks	4
		Mixed truck traffic with a higher percentage of single-trailer trucks	6
		Mixed truck traffic with about equal percentages of single-unit and single-trailer trucks	9
		Mixed truck traffic with a higher percentage of single-unit trucks	12
		Predominantly single-unit trucks	14
Major Bus Route (>25%)	Low to None (<2%)	Mixed truck traffic with about equal single-unit and single-trailer trucks	17

The *2002 Design Guide* also makes three major assumptions about truck and axle load distributions and vehicle class distributions, although legislative or economic changes may occasionally invalidate any of them (ERES Consultants Inc., 2001):

- Truck and axle load distributions remain constant, whereas vehicle class distributions can change from year to year.
- Truck and axle load distributions do not change throughout the day or over the week (weekday versus weekend and night versus day), whereas vehicle class distributions can change over the aforementioned times.
- Neither distributions changes from site to site within a specific region.

NCHRP Project 1-39

The objective of the NCHRP Project 1-39 study was to find a workable compromise between the need for scientifically proven accuracy of the developed loading estimates and the realities of state highway agencies' data collection capabilities and practices. Consequently, SHAs have been provided with guidelines and software that reduce the effort needed to convert their data into the format required by the *2002 Design Guide*. Following these guidelines should significantly improve states' traffic loading estimates (Cambridge Systematics Inc., 2000).

The following issues were addressed in the course of Project 1-39 (Cambridge Systematics Inc., 2000):

- axle load distribution
- site characteristic and input levels
- traffic data collection equipment
- vehicle classification and WIM equipment
- tire pressure and tire configuration monitoring
- software.

Phase 1 of Project 1-39 included the following tasks:

- Task 1. Traffic data elements: The objective was to identify the traffic data elements needed for each of the four levels of input data (1 through 4).

- Task 2. Plans were developed to collect the data needed to obtain reliable estimates of the traffic elements identified in Task 1, which included the following:

    - AADTT, AADTT monthly factors, truck traffic distribution factors (TTDF), and AADT vehicle classification (AADTVC)
    - Axle load distribution factors (ALDF): For sites corresponding to Input Level 1, ALDFs were developed for each vehicle class and axle-group size using WIM data collected at the site. For sites corresponding to Input levels 2 through 4, Project 1-39's team recommended that each state develop a separate set of ALDFs for several sites (develop typical load spectra).
    - AADT, percentage of trucks, and TTCs
    - Directional distribution factors (DDF) and lane distributional factors (LDF).
- Task 3. Equipment specifications and data handling. This task was divided into two parts:
    - A. Development of a plan for load spectra forecasting
    - B. Interim report.

Phase 2 of Project 1-39 included the following tasks:

- Task 1. Revise the guidelines and draft the forecasting guide.
- Task 2. Develop software.

TRAFFIC DATA TAXONOMY

For the past 50 years, traffic data in most of the U.S. state highway agencies (SHAs) have been available in the FHWA W-Table format. Trucks have customarily been weighed at weigh stations to ensure their compliance with gross vehicle weight regulations (GVW) as well as axle load limits imposed by the SHAs. Such limits are primarily based on a bridge formula originally adopted in 1944 to ensure that trucks with various truck axle configurations and GVWs do not overstress bridges (Federal Highway Administration, 1984).

SHAs have traditionally installed and implemented limited data collection stations to measure vehicles and axle loads on their roadway networks. Data collection efforts employing the FHWA W-Tables format were primarily prompted by FHWA weight studies in conjunction with truck weight enforcement practices. However, during the past two decades, weight studies have placed more emphasis on the use of vehicle classification and axle load data. Major initiatives such as the Long-Term Pavement Performance (LTTP) program have attempted to improve the quality of collected traffic data in conjunction with performing a series of prolonged field experiments to determine the causes of highway pavement deterioration.

As part of the LTPP studies, the FHWA and SHAs collected data from nearly 2,300 pavement test sections throughout the U.S. The LTPP database includes information on the environment, traffic, inventory, monitoring, maintenance, materials, and rehabilitation of each test section. The bulk of traffic data in the LTPP database has been collected with AVC and WIM installations. Technological advancement in the fields of data collection and processing are expected to facilitate the design of more practical pavement structures (Senn, et al., 1997; ERES Consultants Inc., 2000).

FHWA W-Tables

From the 1950s to the 1980s, SHAs primarily gathered traffic and weight data from weigh stations located throughout the U.S. The weigh stations were used for weight limitation law enforcement purposes, along with providing traffic data for FHWA truck weight studies. Various sorts of information were gathered at the weigh stations and categorized as FHWA tables 1 through 8 (Annual Truck Weight Study, 1962):

- W-1: Describes each station, location, day and date weighed, and compares the number of cars counted, and the number of trucks and truck combinations counted and weighed at each station.
- W-2: Shows the number and percentages of vehicles for each type counted by highway category.
- W-3: Shows the number of trucks by type counted and weighed, by highway category, and the average weight for each type empty and loaded.
- W-4: Shows the number of axles weighed, by weight group, from under 3,000 lbs. to 54,999 lbs. by truck type and highway category.
- W-5: Shows the number of gross weight loads by weight groups from under 4,000 lbs. to 129,999 lbs. by truck type and highway category.
- W-6: Lists the characteristics of trucks that exceed total weight, axle load and axle spacing laws for trucks and truck combinations.
- W-7: Compares the number and cumulative percentages in percentage groups of the number of the trucks, by axle type, within or exceeding the State of Washington legal limits.
- W-8: Shows the class of operation for each vehicle type weighed by highway system.

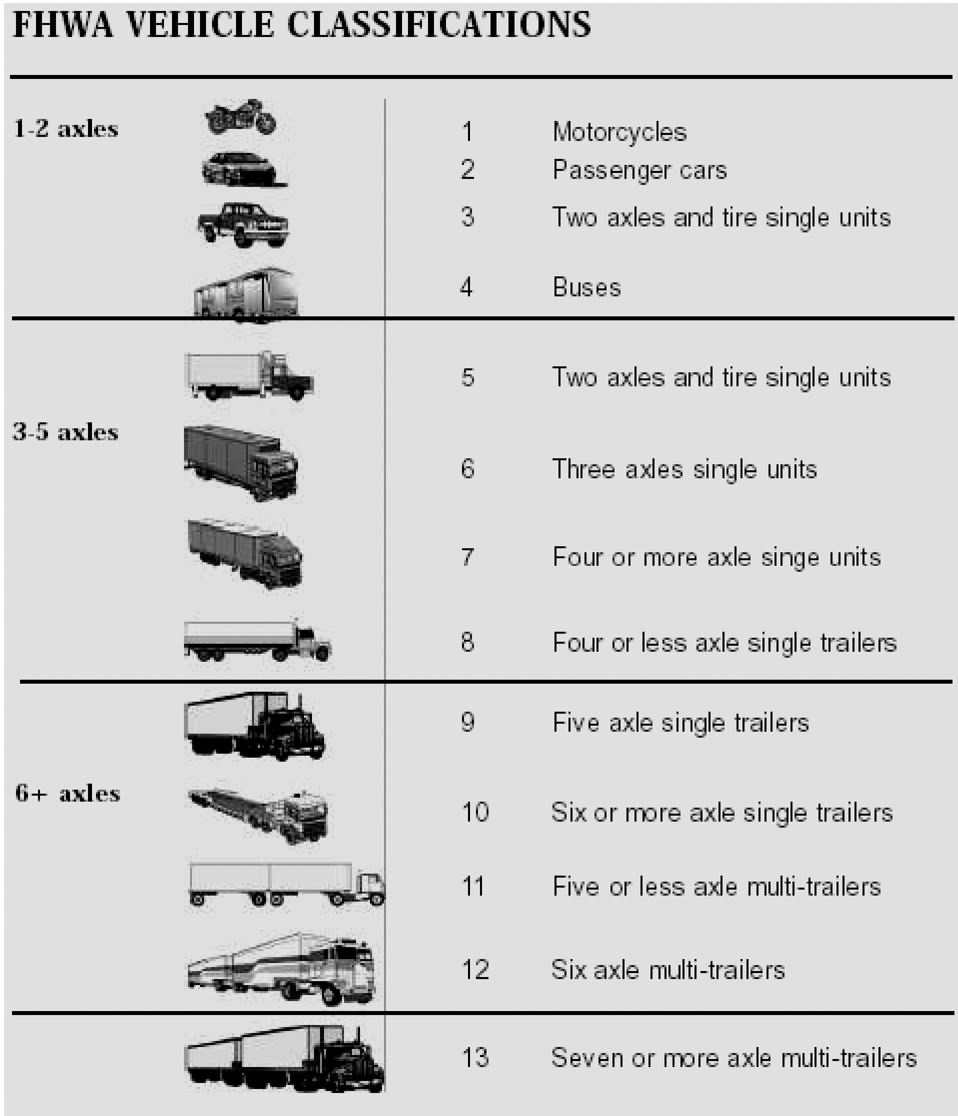
FHWA Vehicle Classification

The traffic data collection process requires categorizing vehicles into specified subsets. The FHWA developed 13 vehicle class categories that encompass all vehicles, with classes 4 through 13 incorporating truck traffic (see Figure 2-5). The following is a brief description of the FHWA vehicle classification (Hallenbeck, 1991):

- Class 1: [Motorcycles] (Optional). All two- or three-wheeled motorized vehicles. Typical vehicles in this category have saddle-type seats and are steered by handle bars rather than wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles. (This vehicle type may be reported at the option of the state).

- Class 2: [Passenger Cars]. All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.

- Class 3: [Other Two-Axle, Four-Tire, Single-Unit Vehicles]. All two-axle, four-tire vehicles other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, and carryalls. Other two-axle, four-tire, single-unit vehicles pulling recreational or other light trailers are included in this classification.



FHWA VEHICLE CLASSIFICATIONS

1-2 axles	1	Motorcycles
	2	Passenger cars
	3	Two axles and tire single units
	4	Buses
3-5 axles	5	Two axles and tire single units
	6	Three axles single units
	7	Four or more axle singe units
	8	Four or less axle single trailers
6+ axles	9	Five axle single trailers
	10	Six or more axle single trailers
	11	Five or less axle multi-trailers
	12	Six axle multi-trailers
	13	Seven or more axle multi-trailers

Figure 2-5. FHWA 13-vehicle classification (from ERES Consultants Inc., 2001)

- Class 4: [Buses]. All two-axle, four-tire, single-unit vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered trucks and classified appropriately.

- Class 5: [Two-Axle, Six-Tire, Single-Unit Trucks]. All vehicles on a single frame, including trucks, camping and recreational vehicles, and motor homes, that have two axles and dual rear wheels.

- Class 6: [Three-Axle Single-Unit Trucks]. All vehicles on a single frame, including trucks, camping and recreational vehicles, and motor homes, that have three axles.

- Class 7: [Four-or-More-Axle Single-Unit Trucks]. All trucks on a single frame with four or more axles.

- Class 8: [Four-or-Fewer-Axle Single-Trailer Trucks]. All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.

- Class 9: [Five-Axle Single-Trailer Trucks]. All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.

- Class 10: [Six-or-More-Axle Single-Trailer Trucks]. All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.

- Class 11: [Five-or-Fewer-Axle Multi-Trailer Trucks]. All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.

- Class 12: [Six-Axle Multi-Trailer Trucks]. All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.

- Class 13: [Seven-or-More-Axle Multi-Trailer Trucks]. All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.

Additionally, the following criteria should be employed to the classifications:

- Truck tractor units traveling without a trailer are considered single unit trucks.
- A truck tractor unit pulling other such units in a "saddle mount" configuration is considered one single-unit truck and is defined only by the axles on the pulling unit.
- Vehicles are defined by the number of axles in contact with the roadway. Therefore, "floating" axles are counted only when in the down position.
- The term "trailer" includes both semi- and full trailers.

SHAs may opt for the FHWA vehicle classification or choose to develop a vehicle classification more suited to their needs. For instance, the WSDOT Pavement Management System (PMS) accesses the Transportation Information and Planning Support (TRIPS) traffic data computer system for three basic truck designations (FHWA classes 1, 2, 3 are designated as vehicles):

1. single units, which include FHWA vehicle classes 4 through 7
2. single trailers (double units), which include FHWA vehicle classes 8 through 10
3. multi-trailers (multiple units or trains), which include FHWA vehicle classes 11 through 13.

This classification scheme has performed satisfactorily for WSDOT, particularly in regions with low traffic volumes.

WEIGH-IN-MOTION

Increasing emphasis on the trustworthiness of collected traffic data has prompted increased utilization of both vehicle classification and axle load data. The bulk of WIM sensors are capable of providing both types of data. The following sections present brief descriptions of WIM technology to allay some of the doubts concerning their performance (Cunagin, et al., 1986).

WIM History

One of the first attempts to develop a WIM device was reported by Normann and Hopkins (1952) of the U.S. Bureau of Public Roads (BPR), presently the FHWA. The device included the construction of a reinforced concrete platform on the surface of the pavement, which measured 12 ft wide by 3 ft long by 1 ft deep. Additionally, strain gage load cells that translated tire loads into electrical potential difference were installed on the plate's corners.

In 1957, the United Kingdom Transport and Road Research Laboratory (TRRL) developed a similar system that was less massive. It consisted of three aluminum plates mounted across one of the wheel paths of incoming trucks (Trott, et al., 1959; 1965; 1968; Currer and O'Conner, 1979). Other researchers attempted to enhance such devices; however, by the early 1960s, most of the effort to use massive BPR-type WIM devices had been abandoned (Lee, 1974). The abandonment was attributable to the devices' great mass and stiffness compared with the forces they were supposed to measure. The platform did not respond to rapid changes, nor did it return to its static condition before subsequent axles passed over it.

Hutchinson and Fitzgerald (1952) attempted develop more portable WIM devices. They wanted to produce a lightweight weighing platform that rested on strain gages. The Radian Corporation WIM device, developed at the University of Texas and sponsored by the Texas Highway Department, was one of these devices. The device's weighing area was 4 ft, 6 in. wide and 1 ft, 8 in. long in each wheel path. The weight-bearing surface utilized six triangular steel plates that rested on eight load cells.

Development continued by the German Bundesanstalt fur Strassenwessen (BAST), and the device was utilized extensively throughout Germany. It employed strain gages bonded to the bottom of a steel plate, resulting in proportional strains to applied loads. The Prozess-Automatisierungstechnik (PAT) WIM device, currently manufactured in the U.S., is illustrative of this device (De Cate and Hendriks, 1976). More development led to another device that utilized hydraulic displacement by filling the cavity formed between two welded steel plates with a fluid and monitoring the loads forcing the fluids out (Keller, 1972).

In 1967, the French government, through Laboratories Central des Ponts et Chausses (LCPC), developed a WIM device that utilized three piezoelectric quartz crystals to support a weighing platform. Tire loads caused the crystals to deform, producing an electrical signal that was subsequently interpreted as weight (Siffert, 1972). The LCPC group also adopted a unique approach in designing portable WIM devices that employed a coaxial cable filled with pressure-sensitive powdered piezoelectric ceramic material. The cable deformed under tire loads and produced an electric signal, which was interpreted as weight. The cable was placed in a groove cut in the travel lane and covered with a sealant (Sodern, not dated).

In 1967, South Africa's National Institute for Road Research initiated an effort to produce a truly portable WIM device. The research resulted in a weighing mat that consisted of layers of rubber and steel designed to convert loads into a change in capacitance. A version of the device is currently offered by Golden River Traffic (Bassoon, 1981).

By the early 1970s, WIM research was aimed at incorporating strain gage load cells underneath highway bridges, such as the load cell developed at Case Western Reserve University. The device utilized strain-gage load cells clamped to the support beams on the underside of a highway bridge (Fothergill, et al., 1983). In 1972, the University of Saskatchewan in Canada produced a device that used a single oil-filled piston to which load was mechanically transmitted (Bergan and Dyck, 1976).

WIM Necessity

The need for effective monitoring of gross vehicle and axle weights has been demonstrated in numerous studies. One of the earliest studies was conducted by the FHWA between 1969 and 1979. The study revealed that, in that ten-year period, truck volumes on rural Interstate highways increased by 25 percent, while ESALs increased by 150 percent. Analogous results were also found in Washington, Oregon, and Montana. The increase in ESALs was primarily attributed to a shift in truck population to heavier and larger types—the result of economic factors and federal legislative changes in 1974 and 1978 (Kent, 1981). The need for better weight monitoring equipment was also necessitated by increases in legal weight limits and their associated damaging effects on the roadway system.

Before the mid 1980s, the collection of truck weight data by SHAs was generally dependent on their participation in the FHWA Truck Weight Studies (TWS). The limited availability of reasonably priced microprocessors and the cost and time for collecting ample truck weight data were beyond the budgets of most SHAs. However, participation in the TWS guaranteed the availability of reasonable estimates of truck weight characteristics for the design of projects funded with federal dollars. Thus, static weight stations were principally utilized for weight data collection and law enforcement.

In 1985, the FHWA Traffic Monitoring Guide (TMG) recommended that a minimum of 90 truck-weighing sessions be performed by each state over a period of three years. Thirty of the sessions were assigned to Interstate locations, while the remaining sessions were conducted on non-Interstate roadways. The FHWA intended to provide a statistically representative measure of vehicle weights within 10 percent of actual vehicle weights for 95 percent of measured trucks. This vehicle-weight database enabled the FHWA 1986 and 1993 pavement design guides to incorporate more reliable vehicle classifications, traffic volumes, annual truck growth rates, average axle and gross vehicle loads, and their associated ESALs into the design process. The improvement of WIM technology along with the development of superior microprocessors resulted in a more representative and easily accessible vehicle-weight database.

The availability of reliable traffic data will notably increase the effectiveness of pavement management practices, consequently providing SHAs with better insight into the relationship between the pavement’s condition and the factors that most influence it (i.e., load magnitude and distribution, and environmental conditions).

WIM Strengths

The following are the advantages that SHAs gain by monitoring their roadway networks with WIM technology (Cunagin, et al., 1986):

1. Processing rate: Trucks can be weighed as they as they travel at highway speeds, resulting in a significantly greater number of counted vehicles in a shorter period of time that when static weigh stations are used.
2. Safety: Minimizing static weighing significantly decreases vehicle queues in highway lanes leading to weigh stations.
3. Continuous data processing: WIM weighing operation is continuous as opposed to static weighing, which incorporates traffic stream samples. Thus, the inherent data bias in static weighing may be eliminated.
4. Management: Several states have reported field crew reductions of as much as 75 percent by converting to WIM technologies.
5. Increased coverage: More sites may be covered with WIM devices, at the same cost, than with portable static scales.
6. Minimized scale avoidance: With some WIM devices it is possible to monitor truck traffic without the truck drivers being aware of it. It has been shown that as many as 30 percent of trucks are overweight when the traffic stream is covertly weighed, whereas only 1 percent of weighed trucks are overweight when drivers know that weighing operations are under way (Cunagin, et al., 1986).
7. Reduced cost: The cost per truck weighed with WIM devices is generally much less than with static weighing.

8. Dynamic loading data: WIM provides some information on the dynamic axle loads to which the roadways are subjected, whereas static weight loads can be, in some instances, significantly smaller.

WIM Shortcomings

The following shortcomings are inherent with WIM technology (Cunagin, et al., 1986):

- Accuracy in measuring static weights: A major disadvantage of WIM systems is their relative inaccuracies in comparison with static scales. According to the National Bureau of Standards, wheel load weighers are required to have an accuracy of ±1 percent when tested for certification and must be maintained thereafter at ±2 percent. The nature of dynamic weighing implies that such a standard is difficult to achieve. The best accuracy obtained with the most expensive, commonly used WIM device (single load cell device) is 6 percent of actual vehicle weights for 95 percent of measured trucks.
- Reduced information: Information that is readily obtained at weigh stations and needed for the FHWA TWS, such as fuel type, state of registry, year model, loaded or unloaded status, origin, and destination cannot be obtained with typical WIM systems.
- Installation: The complexity and safety hazards associated with installing, activating, or deactivating a WIM site are disadvantages.
- High initial cost: Although many states have found WIM to be cost effective, the initial capital cost can be quite high.

- Increased staff technical requirements: WIM systems require a more technically qualified operating crew for repair and maintenance of the system.

- Susceptibility to damage from electromagnetic transients: Similar to all equipment that use sensitive electronic devices, WIM systems are sensitive to electromagnetic disturbances caused mostly by lightning strikes near the equipment. The equipment can be protected by increasing its tolerance for reasonable levels of electromagnetic disturbance and installing adequate grounding and shields.

- Susceptibility to weather elements: Some WIM systems are sensitive to rapid temperature changes in the surrounding pavement.

Factors That Influence WIM

WIM sensors measure the effective/dynamic weight of axles in actual driving conditions. As a result, factors that may vary such weights, in comparison to static weights, are shown in Table 2-4 (Lee, 1988).

Table 2-4. Factors that may influence WIM (from Lee, 1988)

Vehicle Factors	Gross Vehicle Weight (GVW) Distribution of weight Vehicle suspension Tire type Aerodynamic characteristics
Roadway Factors	Horizontal and vertical alignment Road surface condition
Environmental Factors	Wind Ice
WIM System Factors	Bump or depression Stiff sensor Sensor oscillation of damping

The WIM site is important for an accurate sensor reading. International Road Dynamics (IRD), which supplies WSDOT with its WIM sensors, recommends the following road characteristics for correct measurement of truck weights:

- The roadway alignment should be straight for 300 feet both before and after the sensor.
- The roadway's cross slope should be less than 2.
- The vertical alignment should not exceed 2 percent.
- The sensor should be located at a site of minimal lane and speed changes.
- Sensors should be located a minimum distance of 0.6 miles from ramp entrances and exits.
- The sensors should not be installed in rutted or rough roadways that cause increased dynamic motion during vehicle passes.

These recommendations are in accordance with ASTM Designation E 1318: Highway Weigh-In-Motion Systems with User Requirements and Test Methods.

Contemporary WIM Technology

Bushman and Pratt (1998) affirmed that the most current and widely utilized WIM devices in North America today are [1] the piezoelectric sensor (figures 2-6 through 2-8), [2] bending plate scale (figures 2-9 through 2-11), and [3] single load cell scale (figures 2-12 to 2-13). The piezoelectric sensor is the most widely used. Its popularity can be attributed to its relatively low installation cost, low maintenance costs, and simplified installation procedures.

Piezoelectric Sensor

Description: The basic construction of the typical piezoelectric sensor consists of a copper strand surrounded by a piezoelectric material that is covered by a copper sheath. The sensor is embedded in the pavement and produces a charge that is equivalent to the deformation induced by the tire loads on the pavement's surface. It is common to install two inductive loops and two piezoelectric sensors in each monitored lane.

Installation: The piezoelectric sensor is installed by making a relatively small cut on the surface of the monitored lane. The size of the cut varies depending on the sensor being installed but is generally 1 to 2 in. deep and 1 to 2 in. wide. The sensor is then placed and covered with a non-toxic resin. A complete lane installation can be accomplished in less than a full day, including resin curing time. The installed cables typically used are not portable, but the low cost of the device allows SHAs to install the system in several locations and move the electronics from site to site. Once installed, the device is usually left unattended (Hallenbeck, 1989).

Reliability and cost: A properly installed and calibrated piezoelectric WIM system is expected to provide gross vehicle weights that are within 15 percent of the actual vehicle weight for 95 percent of the measured trucks. However, the popularity of WIM has caused SHAs to install some devices in less than favorable conditions (e.g., rough pavements), which reduces the device's expected precision and results in greater data variation. The approximate cost to supply and install one lane of a piezoelectric system is $9,000. The system is expected to have a 4-year life with an annual net present value (NPV) of $4,750 per lane.

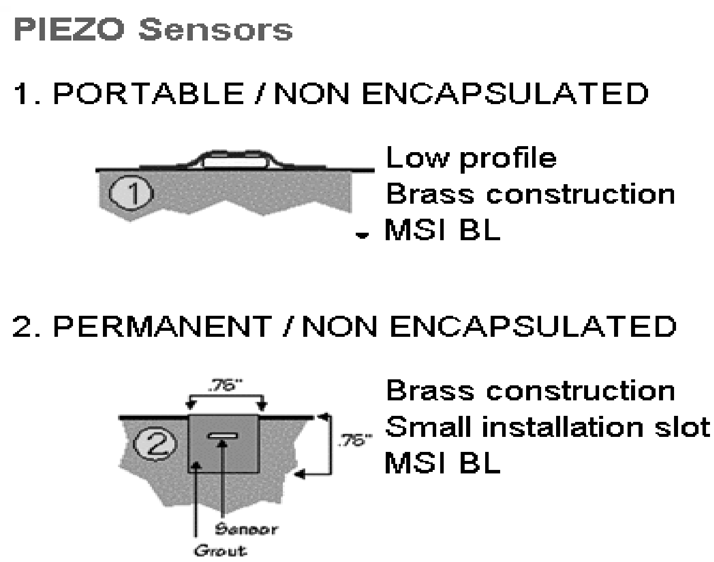


Figure 2-6. Piezoelectric scale layout (from Pat America, www.patamerica.com)

Figure 2-7. Piezoelectric scale layout (from International Road Dynamics Inc., www.irdinc.com)

Figure 2-8. Piezoelectric scale layout (from the University of Hawaii, www.eng.hawaii.edu)

Bending Plate

Description: The bending scale consists of two steel platforms that are generally 2 ft by 6 ft, adjacently placed to cover a 12-ft lane. The plates are instrumented with strain gages that measure tire load-induced plate strains. The measured strains are then analyzed to determine the tire load.

Installation: The installation of the bending plates differs depending on pavement type. Installation in thick concrete roadways is achieved by excavating a sufficient depth (typically 5 in.) on the surface of the pavement and placing and anchoring the device's frame with anchoring bars and epoxy. In asphalt or thin concrete roadways, the installation is generally accomplished by building a concrete vault that encompasses the device. A cut is made and excavated to form a pit 2 ft, 6 in. deep by 4 ft,10 in. wide and 13 ft, 10 in. long. The frame is then placed and cast into the concrete to form a secure and durable foundation for the device. Installing a complete lane of scales, loops, and axle sensor can be accomplished in one day for thick concrete roadways and in three days for asphalt or thin concrete roadways. The system is considered a permanent scale, although the plates may be moved to different locations, provided that frames are present in all locations.

Reliability and cost: The installation and yearly maintenance costs are significantly greater than that of piezoelectric sensors. The approximate cost for a fully installed lane is $21,500, in conjunction with an annual NPV of $6,400 per lane. However, the system is expected to last for six years and is also expected to provide gross vehicle weights that are within 10 percent of actual vehicle weight for 95 percent of the trucks measured. The system has a reputation for good performance, although its reputation may be partially attributable to the fact that it is usually installed in concrete pavements in excellent condition (Hallenbeck, 1989).

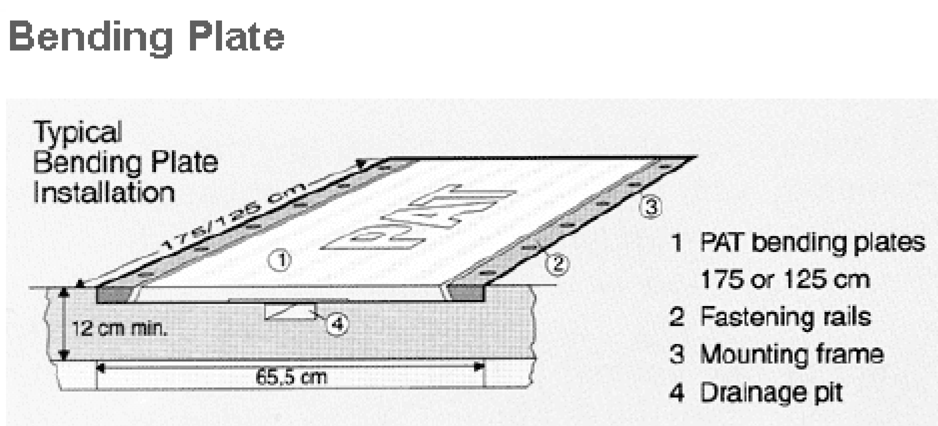


Figure 2-9. Bending plate layout (from PAT America, www.patamerica.com)

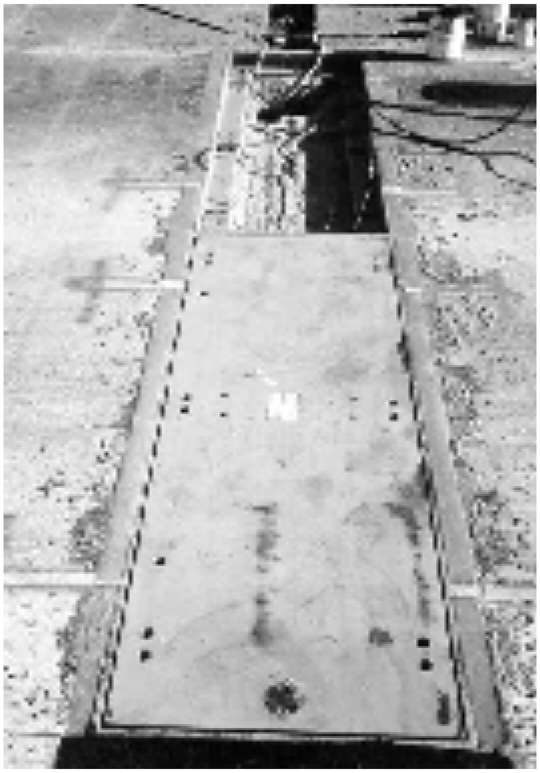


Figure 2-10. Bending plate installation (from Oakridge National Laboratory www.ornl.gov)

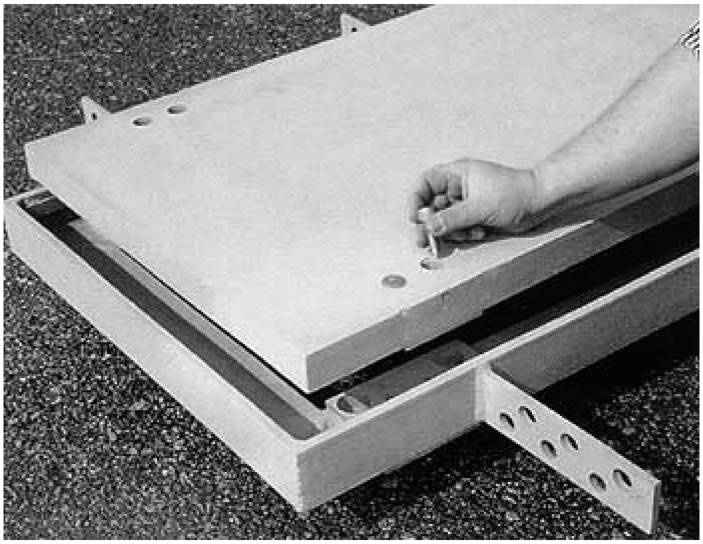


Figure 2-11. Bending plate (from International Road Dynamics Inc., www.irdinc.com)

Single Load Cell

Description: This device consists of two 6-ft x 3-ft, 2-in. platforms placed adjacently to cover the 12-ft monitored lane. A single hydraulic load cell is installed at the center of each platform to measure the tire load-induced forces that are then transformed into tire loads.

Installation: The installation of this device requires the use of a concrete vault similar to the one used for the bending plate sensor. However, the size of the vault is slightly larger, measuring 3 ft deep by 13 ft, 9 in. long and 4 ft, 10 in. wide. The device is commonly installed in a lane with two inductive loops and an axle sensor, and installation can be completed in three days. This system is designed only as a permanent station because of the platform's 2,000-lbs. weight. Moving the sensor to different locations is not practical.

Reliability and cost: This system is the most expensive of all three commonly used WIM devices. The approximate cost for a fully installed lane is $48,700, including a mandatory overhaul after six years. Its expected life is 12 years. The NPV annual maintenance cost per lane is $8,300. This significantly higher cost is offset by the device's reliability—it is expected to provide gross vehicle weights that are within 6 percent of actual vehicle weights for 95 percent of measured trucks.

Figure 2-12. Single load cell installation (from International Road Dynamics Inc., www.irdinc.com)

Figure 2-13. Single load cell (from International Road Dynamics Inc., www.irdinc.com)

CHAPTER 3: HISTORICAL TRAFFIC DATA

EXAMINING WASHINGTON STATE'S HISTORICAL ESALS

To better understand existing traffic conditions in Washington State, a survey of historical traffic data is important. In Washington State, traffic data in the form of FHWA W-1 through W-8 tables have been collected since 1960 (see Section 2.2.1). In 1983, the University of Washington performed a truck weight trend study that encompassed 25 years of WSDOT data. FHWA truck weight tables (W-4) were utilized to calculate ESALs per axle per truck. Single-unit, tractor-trailer, and multi-unit trucks (trains) with varying axle configurations were included in the study. However, for some of the years studied, data were not available; furthermore, data were collected from a limited (five to fifteen) number of weigh stations that operated for no more than 24 hours during a period of no longer than five days each year.

Axle loads associated with truck types and axle configurations, shown in the first and second columns of Table 3-1, were used for ESAL calculations. Several roadway classifications were employed in the study and designated as follows:

- Interstate rural
- Other rural
- All rural
- All urban
- All classes.

Historical ESALs were not available in the FHWA vehicle classification format (i.e., vehicle classes 4 though 13). Therefore, vehicle classification was restructured to approximate vehicle classes (see Table 3-1).

Table 3-1. Vehicle classification and axle configuration (from Mahoney and Field, 1984)

Truck Type	Axle Configuration	Approximate FHWA Vehicle Classification
Single unit	2 axles with 6 tires	Class 5
	3 axles or greater	Class 6 & 7
Double unit (tractor semi-trailer)	3 axles	Class 8
	4 axles	
	5 axles or greater	Class 9 & 10
Multi-trailer (train)	5 axles or greater	Class 11, 12 & 13

Truck Volume Analysis

Before the historical ESALs were analyzed, the volumes per vehicle class were examined to determine whether sufficient data existed for each year. A 100-vehicle requirement was arbitrarily set to alleviate inconsistencies that would be incurred by including years without sufficient volumes.

Figure 3-1 shows the yearly volumes per vehicle class for urban and rural Interstate roadways. After 1970, volumes of vehicle classes 9 and 10, at rural sites, were substantially higher than the volumes of other vehicle classes. Urban site data did not exhibit similar volumes, except in 1983. There was a significant difference between the volumes of vehicle classes 9 and 10 and those of all other vehicle classes (see Figure 3-1). To clarify the trends associated with the volumes of the remaining vehicle classes, data from vehicle classes 9 and 10 were excluded from Figure 3-2. Figure 3-2 shows that the truck volumes at rural sites increased substantially after 1970, especially Class 5 vehicles and multi-trailers. Urban sites did not exhibit such trends (with the exception of 1983) for any classes except Class 5, which experienced volume increases throughout the 1970s and 1980, and greatly increased in 1983.

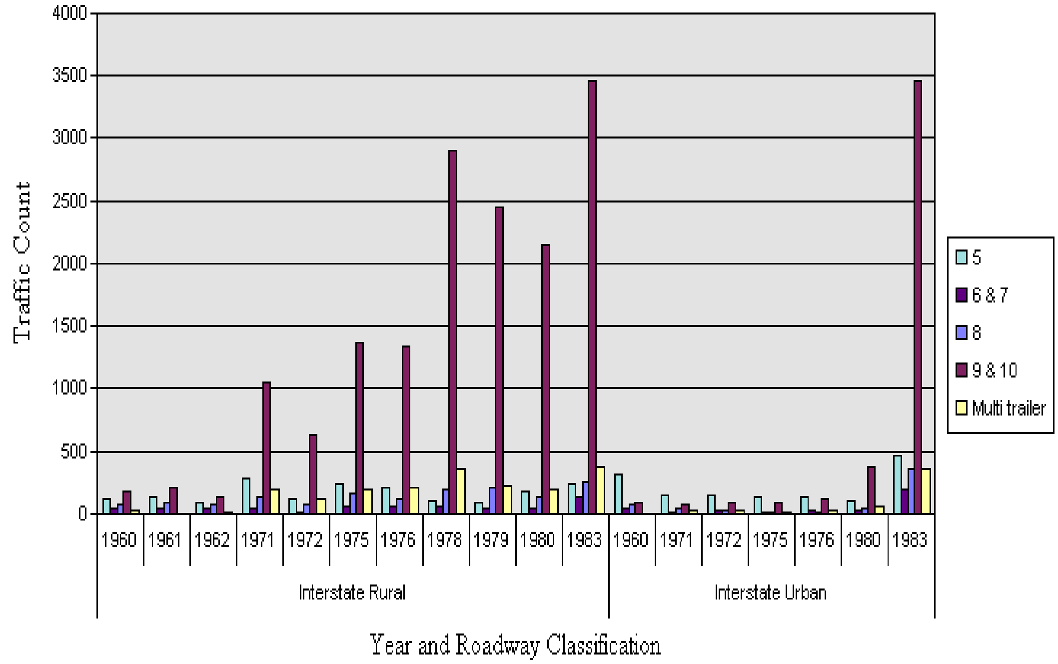


Figure 3-1. Traffic count for all vehicle classes from 1960 through 1983 (from Mahoney and Field, 1984)

Vehicle classes 5, 9 and 10, and multi-trailers typically made up 80 to 85 percent of all truck traffic (*2002 Design Guide* default). Figure 3-1 shows that these defaults are applicable to rural Interstates from 1971 through 1983.

Inferences from small samples are prone to errors. The following may be concluded about the data validity associated with each vehicle class (not all of which contained at least 100 trucks):

- Traffic volumes for vehicle classes 5, 9, and 10 throughout the years were sufficient for proper data inference.
- Traffic volumes for multi-trailers in rural sites after 1970 were sufficient for proper data inference.
- Traffic volumes for multi-trailers in urban sites, except for 1983, were very low and could inhibit proper data inference.

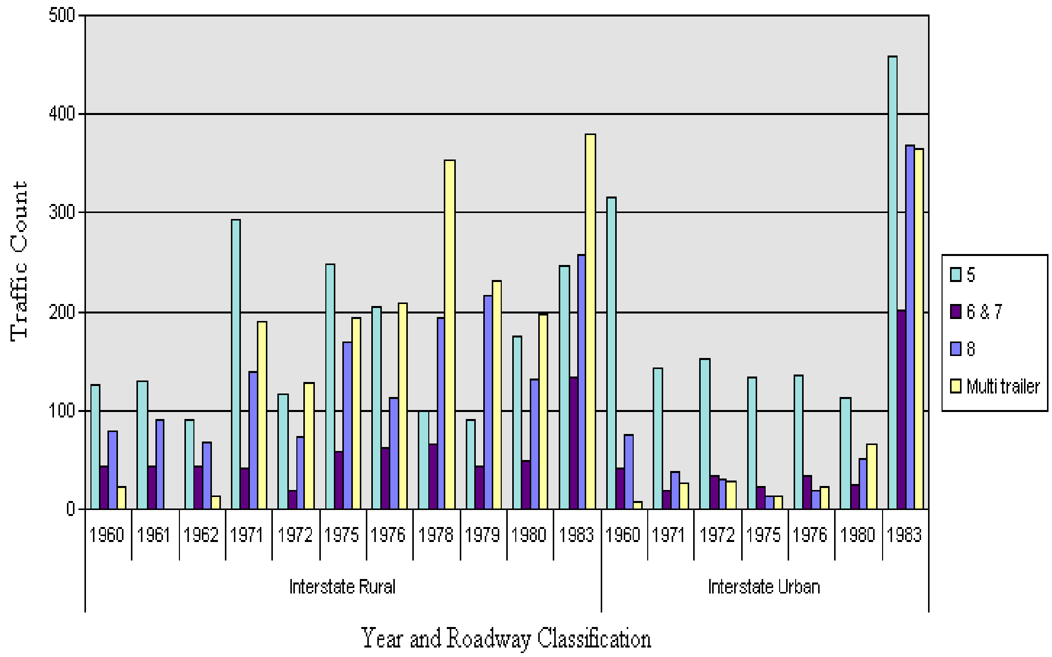


Figure 3-2. Traffic count for all vehicle classes except vehicle classes 9 and 10 from 1960 through 1983 (from Mahoney and Field, 1984)

<u>ESAL Analysis</u>

Figures 3-3 and 3-4 show the ESALs per axle per vehicle class on rural and urban Interstate roadways from 1960 through 1983, respectively. The regression lines for the primary vehicle classes (i.e., 5, 9, 10, and multi-trailers) show that the ESALs slightly increased throughout the years. Furthermore, the ESAL increase rate, associated with each vehicle class, varied slightly. The ESAL increase rates for the primary vehicle classes on rural Interstate roadways were similar, whereas the ESAL increase rates on urban Interstate roadways were variable.

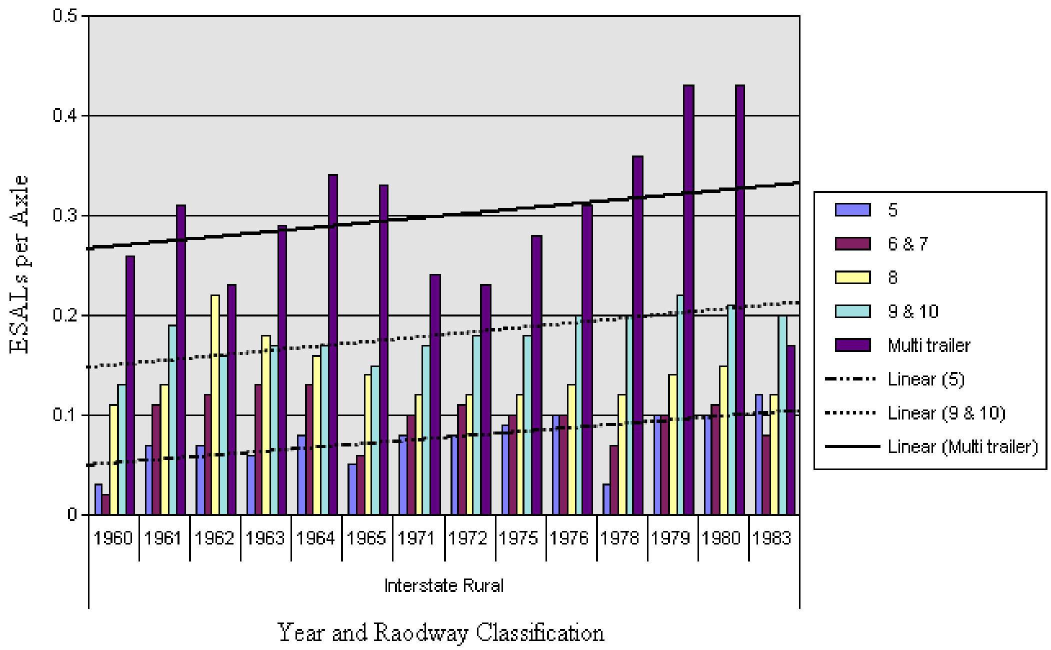


Figure 3-3. ESAL Trend from 1960 through 1983 for dominant vehicle classes on rural Interstates (from Mahoney and Field, 1984)

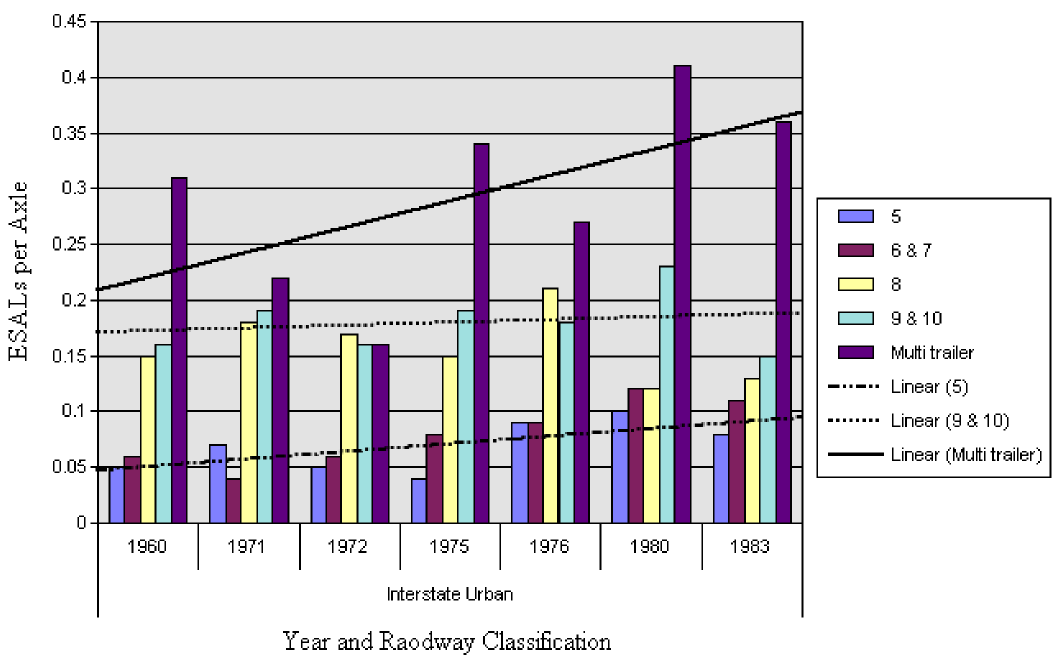


Figure 3-4. ESAL trend from 1960 through 1983 for dominant vehicle classes on urban Interstates (from Mahoney and Field, 1984)

WASHINGTON STATE'S WIM

The spread of WIM technology throughout the U.S. in the mid-1980s has influenced many SHAs to utilize WIM for data collection purposes. Several factors contributed to WSDOT's conversion from weigh stations to WIM stations. (Note that truck weight enforcement is still pursued with static weigh stations.) In the late 1980s, WSDOT participated in four programs and/or studies that increased its use of WIM for data collection (Hallenbeck, 1989):

- the Heavy Vehicle Electronic License Plate project (HELP)
- the Strategic Highway Research Program (SHRP)
- the Traffic Monitoring Guide (TMG)
- the Data Rationalization Study.

The HELP project was developed to allow properly documented trucks of legal limits to bypass weighing stations without stopping. Facilitation of this goal necessitated the installation of WIM sensors along the roadways to automatically identify the trucks, calculate gross and axle weights, and send the information to a computer system. The system would then employ the bridge formula; verify the operating, safety, and other credentials required by SHAs; and send a message to the driver to either bypass or enter the weighing station.

The SHRP program concentrated on six crucial areas for pavements and bridges: [1] asphalt, [2] long-term pavement performance, [3] maintenance effectiveness, [4] protection of bridge components, [5] cement and concrete, and [6] snow and ice control. To address these areas, SHRP's Long-Term Pavement Performance (LTPP) program required the following data collection:

- vehicle classification data for a minimum of one year at each of the 23 SHRP/LTPP sites in Washington
- data collected for two consecutive days during both weekends and weekdays for each truck season, at each site
- data for seasonal, daily, and hourly fluctuations in truck traffic at SHRP/LTPP-selected “master” or “regional” locations.

As previously described, the Traffic Monitoring Guide (TMG) required 90 measurements during three years for each SHA in an effort to provide a statistically representative measure of vehicle weights within 10 percent of actual vehicle weights for 95 percent of the measured trucks.

The Data Rationalization Study (Ritchie and Hallenbeck, 1986) involved an extensive review of WSDOT’s traffic data needs and resulted in the development of statistically based procedures to meet those needs. The study involved collecting data from 15 sites per year, which provided sufficient geographical spread for the state’s highway system.

TRUCK LOADING PATTERNS

Hallenbeck and Kim (1993) analyzed truck loading patterns observed at ten WIM sites to verify the soundness of the standard ESAL estimates (ESALs per vehicle and per axle). The ten sites were geographically dispersed throughout the state and incorporated various functional classes (i.e., urban, suburban, and rural) and traffic volumes. The sites are described in Table 3-2.

Table 3-2. WIM site descriptions (from Hallenbeck and Kim, 1993)

Site Name	Station / Remark	Location	State Route	Geographic Location
B01	P8	Kelso	I-5	Southwest
B02	B02	Brady	SR-12	West (Rural)
B03	B03	Pasco	SR-395	South-central
B04	B04 (no longer a WIM site)	Cle Elum	I-90	Central
P04	P04	Ferndale	I-5	West (Canadian Border-Rural)
P05	P05 (low traffic volume →exclude from future analysis)	Dayton	SR-12	Southeast
P06	P06	Camas	SR-14	West (Suburban)
P15	P15	Spokane	SR-195	East
P19	P19	Woodinville	SR-522	West (Suburban)
P3	P3	Seattle	I-5	West (Urban)

Three measurements were recorded at the WIM sites: [1] ESAL per vehicle for specific vehicle classes, [2] total volume, and [3] total ESALs per day. All estimates were monthly averages computed from the seven average days of the week. Average days of the week were calculated for each month (e.g., average Monday, Tuesday), and then the average day of the month was the simple average of the calculated average days. This practice is consistent with AASHTO Guidelines for Traffic Monitoring and accounts for the uneven distributions of the number of weekdays and weekends in each month. The following subsections provide a brief description of the report's findings.

WIM Calibration and Data Reliability

The project team conducted limited WIM calibration by using the estimated weight of the steering axles of Class 9 vehicles (tractor semi-trailer), which range between 8,500 and 12,000 pounds. However, in several instances, the steering axle weights were measured and calibrated accurately while the weights of the other axles appeared invalid. Furthermore, equipment failures encountered by the project team limited vehicle volumes and ESAL estimates. As a result, the project team stated that their results may have underestimated ESALs and should therefore be treated as preliminary.

Seasonal Patterns

Interestingly, the ten WIM sites produced distinct seasonal patterns. As a general rule, ESALs per single truck remained stable during the year, whereas the value for double- and multi-units changed substantially during the year. Other findings with respect to ESALs per vehicle and volume trends at each site are summarized in tables 3-3 and 3-4.

Table 3-3. Vehicle volume seasonal patterns (from Hallenbeck and Kim, 1993)

Site Name	Location	State Route	Seasonal Patterns
B01	Kelso	I-5	Volume increase in the summer months for both single and double unit vehicles but not for multi-unit vehicles.
B02	Brady	SR-12	Volume increase in the fall and winter seasons for both single and double units but not for multi-unit vehicles.
B03	Pasco	SR-395	Slight increase in October and November.
B04	Cle Elum	I-90	Minor rise in volume in September and October.
P04	Ferndale	I-5	High degree of volume fluctuation. The site exhibited increasing volume of single and double-unit trucks during the summer months associated with decreasing volume for double-unit trucks, and vice versa during February and October.
P05	Dayton	SR-12	Volume decreased in the summer months.
P06	Camas	SR-14	Fairly flat pattern with slight volume increase in double-units volume in the summer.
P15, P19, and P3	Spokane Woodinville Seattle	SR-195 SR-522 I-5	Fairly flat pattern with minor variation.

Table 3-4. ESALs per vehicle seasonal patterns (from Hallenbeck and Kim, 1993)

Site Name	Seasonal Patterns
B01	ESALs per vehicle in double and multi-units rose from May to August.
B02	ESALs per vehicle for multi-units significantly increased during the winter months, whereas the double units' value decreased during October and November.
B03	ESALs per vehicle for double and multi units increased from October to December.
B04	Pattern similar to site B01 with the exception of more severe winter lows. The two sites (B01 and B04) were the only ones that showed such similarity, which may be attributed to their locations on Interstates subjected to relatively stable traffic loadings.
P04	Much more peaked ESALs per vehicle patterns from May through August for all truck types. Note that this site is an Interstate location that is located near the Canadian borders and may not be subject to the same traffic patterns as other Interstate sites.
P05	Unusual twin peaked pattern during November and February, which is opposite to site P04. The pattern in this site is disregarded due its low traffic volume.
P06	Showed a pattern similar to sites B01 and B04, except for having a shorter peak (May to July) and fluctuating values in the peak months, as opposed to stable values, for the aforementioned sites.
P15	Showed a relatively flat pattern with a minor drop in November. The drop in multi-units was more significant than the other vehicle classes.
P19	Had no fluctuation throughout the year for all vehicle classes.
P3	Showed a reasonably flat pattern throughout the year with the exception of decreased values during November to February, for multi units, and increased values for double units during March and April.

Day of the Week

Because of the project's limited scope, the day of the week analysis included only seven sites associated with Class 9 vehicles. The analysis showed that weekend vehicle loads often differed from weekday loads; however, consistent patterns were not evident. In most sites, total vehicle loadings on Sundays were lower than on the weekdays. The project team concluded that weighing trucks solely on weekdays may yield biased average loads per vehicle.

Summary of ESALs

Table 3-5 presents the average ESAL per vehicle and per axle for trucks traveling Washington State roadways in conjunction with their associated standard of deviation and coefficient of variation values.

Table 3-5. ESALs per vehicle class (from Hallenbeck and Kim, 1993)

Vehicle Class	4	5	6&7	8	9	10	11	12	13
Mean ESAL per Vehicle	0.569	0.265	0.417	0.304	1.200	0.932	0.816	1.061	1.390
Standard Deviation	0.150	0.092	0.086	0.119	0.314	0.321	0.395	0.398	0.433
Number of Axles	2.5	2	3	4	5	6	5	6	7
Mean ESAL per Axle	0.228	0.133	0.139	0.076	0.240	0.155	0.163	0.177	0.199
Standard Deviation	0.060	0.046	0.029	0.030	0.063	0.054	0.079	0.066	0.062
Coefficient of Variation	26%	35%	21%	39%	26%	34%	48%	38%	31%

TRUCK LOADS AND FLOW

Hallenbeck (1993; 1994) analyzed truck volume data from 1988 through 1993. The majority of data from 23 AVC and three WIM sites were sorted according to WSDOT's four vehicle classifications. Nineteen WIM sites were not in place for a full calendar year, so they were not included in the study. However, data collected at those 19 WIM sites were utilized to examine weekday/weekend patterns and axle correction factors.

The study's two primary objectives were to

- investigate truck volume patterns at various locations
- determine the feasibility of developing seasonal factors associated with short-duration truck volumes to estimate AADTT.

For the first objective, the following data were collected at each site:

- functional classification

- geographic location
- urban/rural designation
- proximity to urban areas
- whether a class was subject to recreational travel patterns.

The study revealed that the four vehicle classes had distinct seasonal patterns, regardless of volume, roadway functional classification, or geographic location. Typically, large truck categories (i.e., double and multi-units) showed less seasonal variation than short trucks (i.e., single units) and automobiles. Additionally, traffic volumes for single units (i.e., mostly large single-unit trucks and RVs) varied the most. The variance was attributed mainly to recreational vehicles.

The functional classification and geographic location of the roadways significantly influenced their traffic patterns. Generally, the higher the functional road classification, the higher the traffic volumes in all vehicle classes, and vice versa for lower classified roadways. As for stability over time, the higher the traffic volumes, the more stable the traffic volumes from month to month and from year to year, and vice versa for low traffic volumes. Moreover, studying the stability of factors over distances on a roadway showed that each observed roadway, for all four vehicle classes, experienced similar traffic patterns along its length. Unfortunately, the findings were inherently biased by the geographic and functional distribution of the sites included in the analysis.

The investigation of weekday versus weekend traffic patterns showed that, in most cases, Saturday and Sunday traffic volumes differed significantly from weekday volumes. Weekday traffic volumes were significantly higher, especially for large truck classes. However, weekend traffic volumes for recreational vehicles were consistently higher volumes than on weekdays. The project team decided to use Tuesday though Thursday data to represent weekday traffic because of frequent occurrences of statistically different traffic data on Mondays and Fridays.

For the study's second objective—to determine the feasibility of developing seasonal factors associated with short-duration truck volumes to estimate AADTT—the following techniques were used to compute the composite factor groups:

- Visual analysis: A subjective and pictorial approach that included graphing the daily and average monthly traffic volumes and visually matching volume patterns from different sites.
- Modified cluster analysis: A combination of objective (i.e., functional roadway class and traffic volume) and subjective (i.e., whether the road was subjected to recreational travel or agricultural harvest movements) criteria to classify roadways from each count location into factor groups.
- Regression technique: The principals of multiple linear regressions along with the inputs for the modified cluster analysis were employed in computing different seasonal factors for each site.

Unfortunately, none of the techniques worked adequately. The high variability associated with truck volumes limited the use of these techniques. Consequently, other methods for estimating annual traffic estimates based on short-duration counts were explored.

The most basic method was counting vehicles at multiple times during the year at the same location and averaging the counts. The initial test included collecting weeklong data every three months. The collected data were significantly better than all of the factoring techniques. Moreover, this method provided estimates of annual traffic, for each of the four vehicle classes, within 10 percent almost 90 percent of the time. However, it did have three major drawbacks:

- Obtaining staff resources for collecting seven consecutive days of traffic data four times per year per roadway section was difficult.
- The propensity for portable sensors, used by the classifiers, to come loose before the end of the scheduled count increased dramatically with the duration of the count.
- Obtaining such a high number of counts was costly.

The project team utilized alternative counting approaches to overcome the drawbacks: [1] count duration reduction, [2] number of counts per year reduction, and [3] a combination of these. Under the "best case scenario," the alternatives provided comparable results to the more costly and resource exhaustive approach of collecting weeklong traffic data four times per year. However, accuracy depended greatly on traffic volume variation at each site. The accuracy of the count reduction alternatives was inversely proportional to the degree of variation at each site.

TRUCK FLOWS AND LOADS FOR PAVEMENT MANAGEMENT

Hallenbeck and O'Brien (1994) suggested ways for SHAs to design cost-effective programs to meet their pavement-oriented traffic data needs. The procedures were based on a series of analyses performed with WIM data from Florida, Washington, and other published WIM data. The analyses showed that different states could have different truck travel patterns. Such states or regions may experience varying truck volumes throughout the year, while others may experience fairly consistent truck volumes with little seasonal variation. To determine and/or improve the accuracy of pavement loading estimates, SHAs must initially determine their truck data variability.

Truck data variation can be accounted for by [1] time of day, [2] day of week, [3] season of the year, and [4] geographic location. Time of day variation may be accounted for by collecting data for a 24-hour period.

Collecting WIM data for all roadways is not feasible. Therefore, the report recommended that SHAs collect site-specific data whenever possible and supplement those data with vehicle classification and volume data. Continuously operating sites at a limited number of locations is a typical way to accomplish that. Unfortunately, no simple formula for determining the optimum number and distribution of long- and short-term data collection sites exists. Each SHA must determine these numbers by balancing its informational needs with its resource limitations.

The design of short- and long-term data collection systems is dependent on a combination of both statistics and professional judgment. Therefore, Hallenbeck and O'Brien encouraged SHAs to employ the following steps to begin their data collection site allocation:

One: Create a group of roadways. This may be accomplished by dividing the state into basic groups of roadways that contain reasonably homogeneous truck populations and patterns. The more alike the roadways are in the group, the fewer are the data collection points needed to accurately estimate the mean population statistics, and vice versa.

Two: Determine the homogeneity of groups. SHAs must determine whether the roadways in each group possess similar patterns. This may be accomplished by plotting the daily mean ESAL for the most dominant trucks (e.g., Class 9 vehicles) over time, and by comparing the plots from different sites within each group. Differences between weekdays and weekends, along with variations throughout the year, must also be evaluated.

Three: Determine the number of required sites. The following general statistical equation may be utilized to determine the number of required sites:

$$n = [t * COV / d]^2$$

where

n = the number of required sites

t = the Student's t-statistic for n-1 degrees of freedom

COV = the coefficient of variation for the mean ESAL per truck within the sample, and

d = the desired precision or allowable error expressed as a fraction of the mean ESAL per truck

Note that the use of the equation requires the following assumptions:

- The mean ESALs per truck within each roadway group are normally distributed around the mean value.
- The limited sites available for calculating the mean ESALs per truck are randomly selected and representative of the roadways incorporated in the group. Fulfilling the randomness condition may not be feasible; therefore, some bias is inherent in the majority of truck data collection practices.

- The mean ESALs per truck used in the calculations are the “true” mean values for each site (i.e., WIM devices are assumed to have operated correctly throughout the year).
- The precision being measured is actually the error associated with calculating the mean for the roadway group. Note that a much larger error associated with geographic variability exists.

CHAPTER 4: RESEARCH METHODOLOGY

For WSDOT to use the *2002 Design Guide* effectively, the percentage of axles within each load group (normalized axle load distributions) for each month and single, tandem, tridem, and quad axles must be computed externally. These distributions may be obtained by analyzing the WIM data at different stations throughout Washington State.

Piezoelectric cables are the WIM sensors primarily used throughout Washington State. These sensors are known to be sensitive to environmental effects (mainly freezing conditions) as well as heavy loading, especially in thin pavements. This issue, along with the fact that Washington State historically reported the heaviest loads of all surrounding states, caused FHWA to question data collected in Washington State before 2000. In response, WSDOT recalibrated its sensors. Today, the WSDOT Traffic Data Office (TDO) has confidence in the dataset collected from the year 2000 onward. Additionally, 23 SHRP/LTPP and 29 WSDOT stations and numerous permanent and non-permanent vehicle classifiers and traffic recorders are now located throughout Washington State (see figures 4-1 and 4-2). Moreover, 600 72-hour non-permanent count projects are performed yearly. The result is up-to-date traffic data at 1,800 sites every three years.

Figure 4-1 shows the site locations.

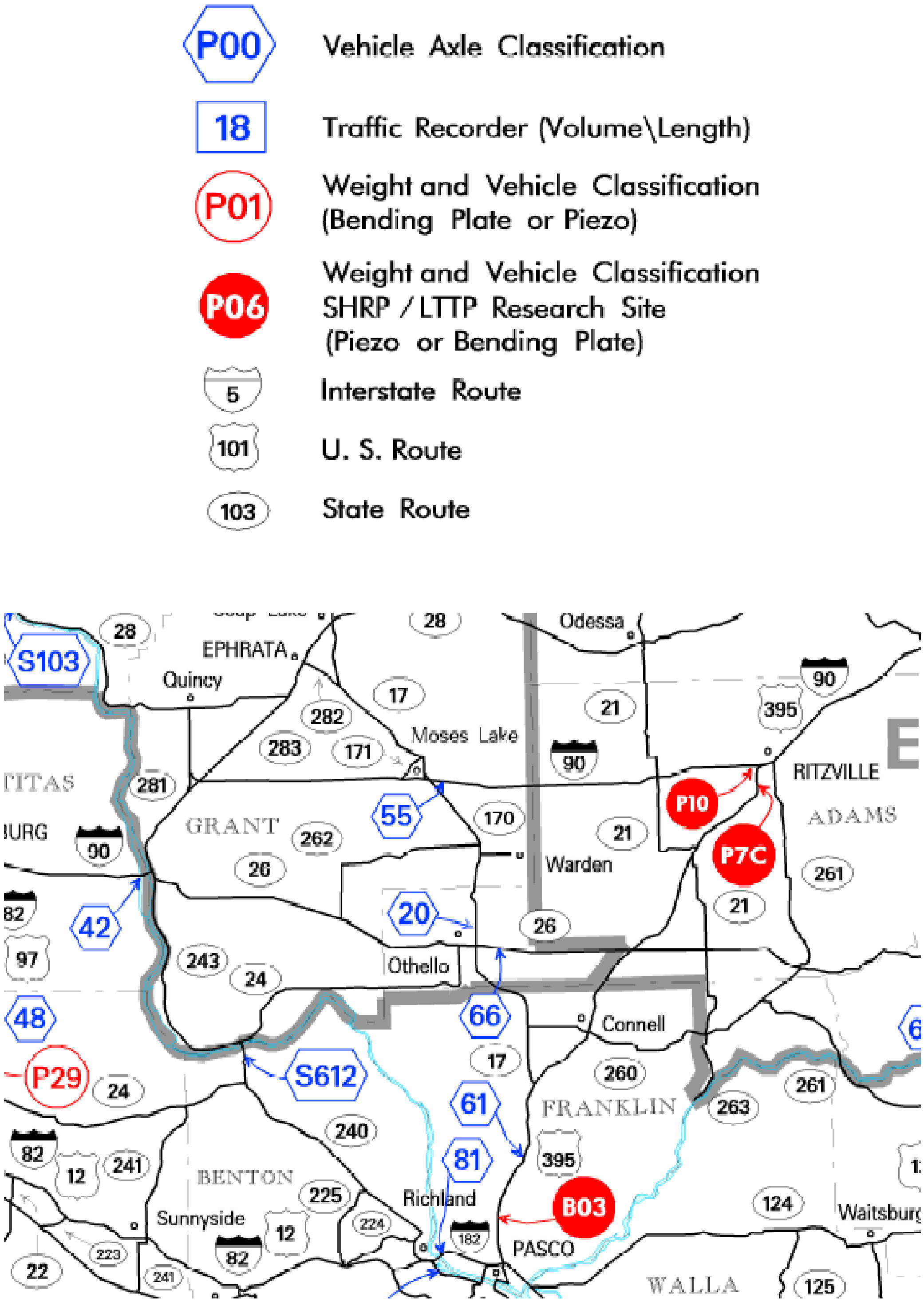


Figure 4-1. Some automated data collection sites in Eastern Washington.

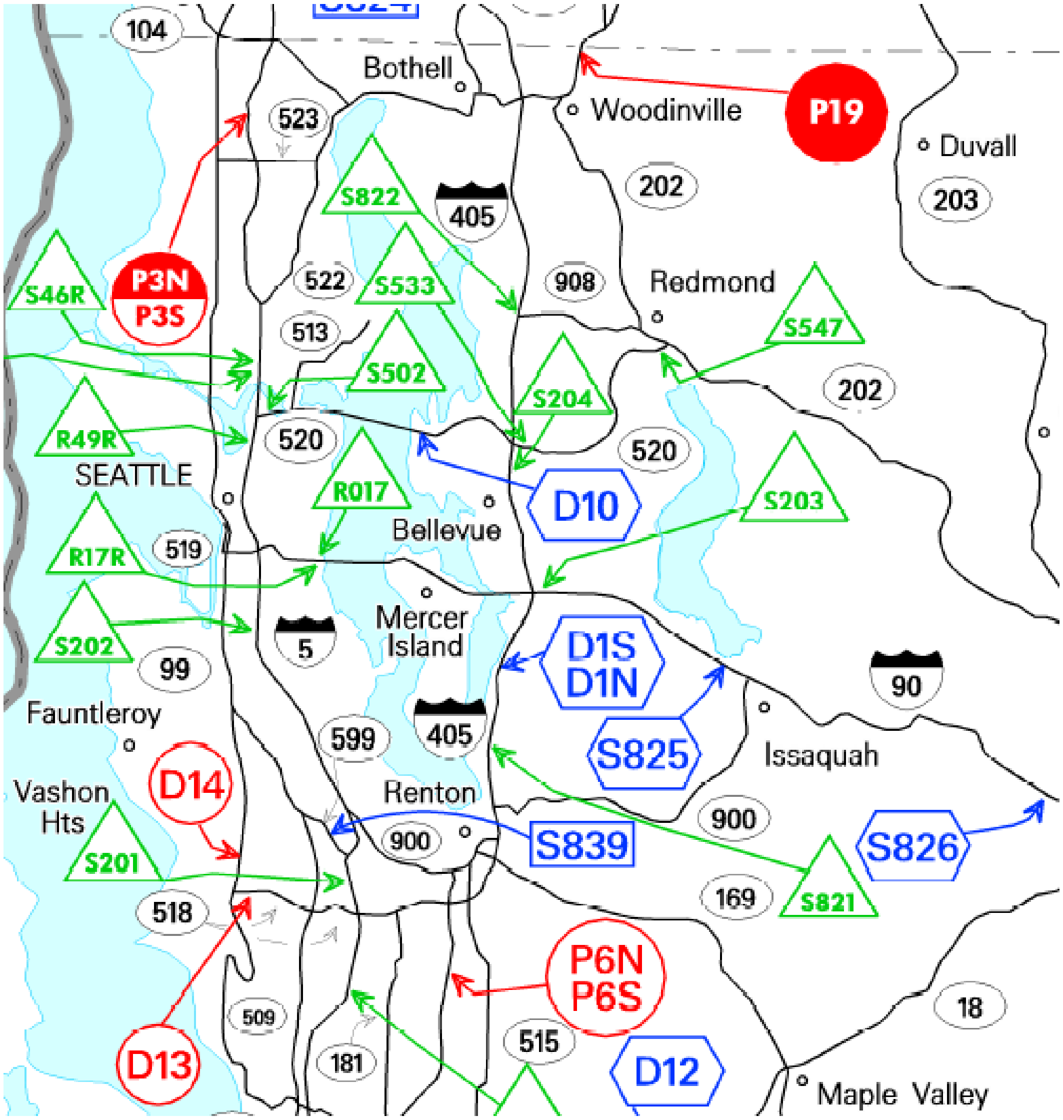


Figure 4-2. Some automated data collection sites in King County

The following eight-step process is proposed to calculate axle load spectra for Washington State:

Step 1

Obtain traffic data from the WSDOT Traffic Data Office (TDO). For this study, data were obtained for January 2000 through April 2003.

Step 2

Note stations that have unusable data (to be defined later), in part from reports prepared by WSDOT for the FHWA.

Step 3

Evaluate the traffic data from each station to determine accuracy. To determine data accuracy, the following analysis, based on information from the FHWA *Traffic Monitoring Guide* (2001), the California Department of Transportation (Caltran) (Lu et al, 2002), and Mark Hallenbeck of the Washington State Transportation Center (TRAC), was used:

Plot Class 9 vehicles' gross vehicle weight (GVW) versus frequency and/or number of trucks to produce the following scenarios:

1) An ideal plot:

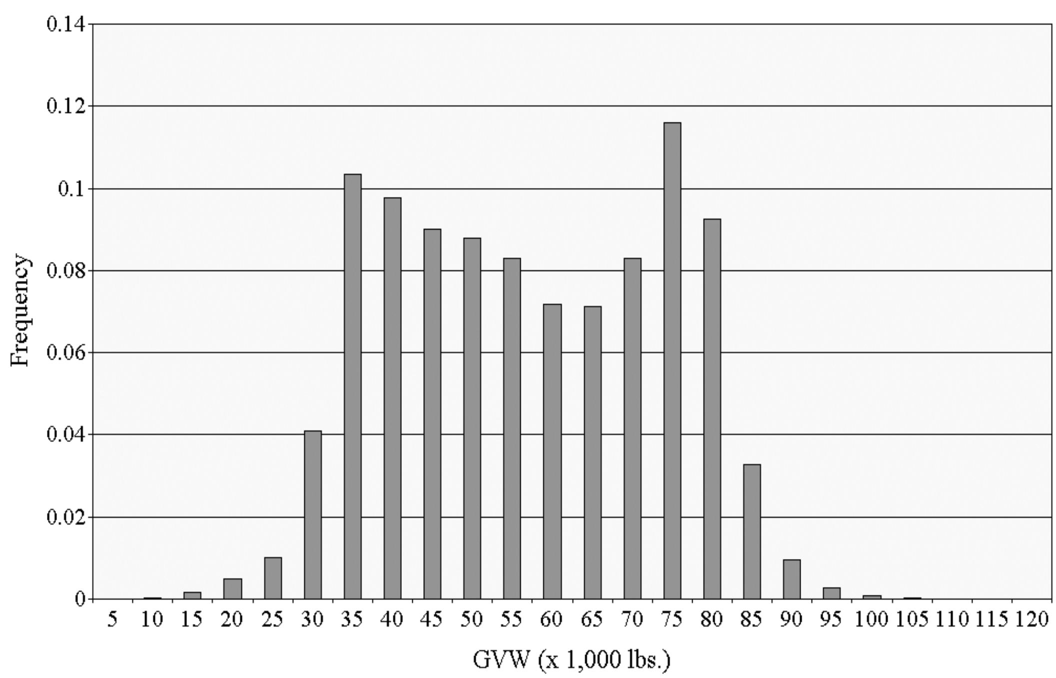
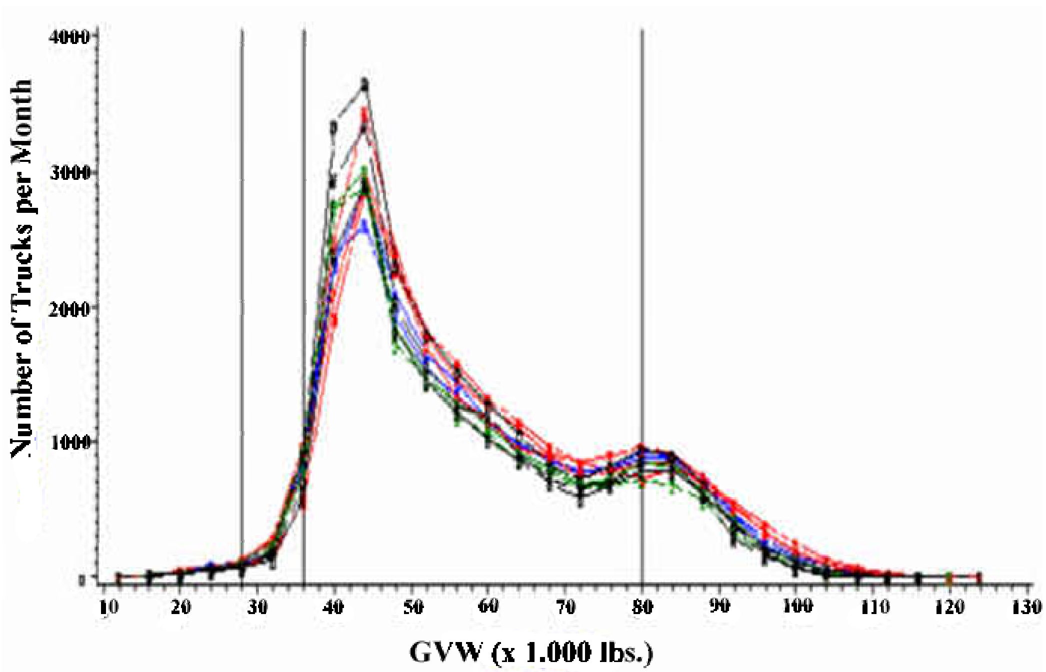


Figure 4-3. GVW (Class 9 vehicle) versus frequency for Station P04 (2000)

The plot in Figure 4-3 exhibits two peaks at 30 to 35 and 75 to 80 kips. The federal weight limit for Class 9 vehicles is 80 kips. Empty Class 9 vehicles typically weigh 28 to 35 kips. The majority of trucks is expected to be either fully loaded up to the federal limit or empty after delivering their shipments. Consequently, the peaks in the ideal plot coincide with the weights of empty and fully loaded Class 9 vehicles.

2) An acceptable but not ideal plot:

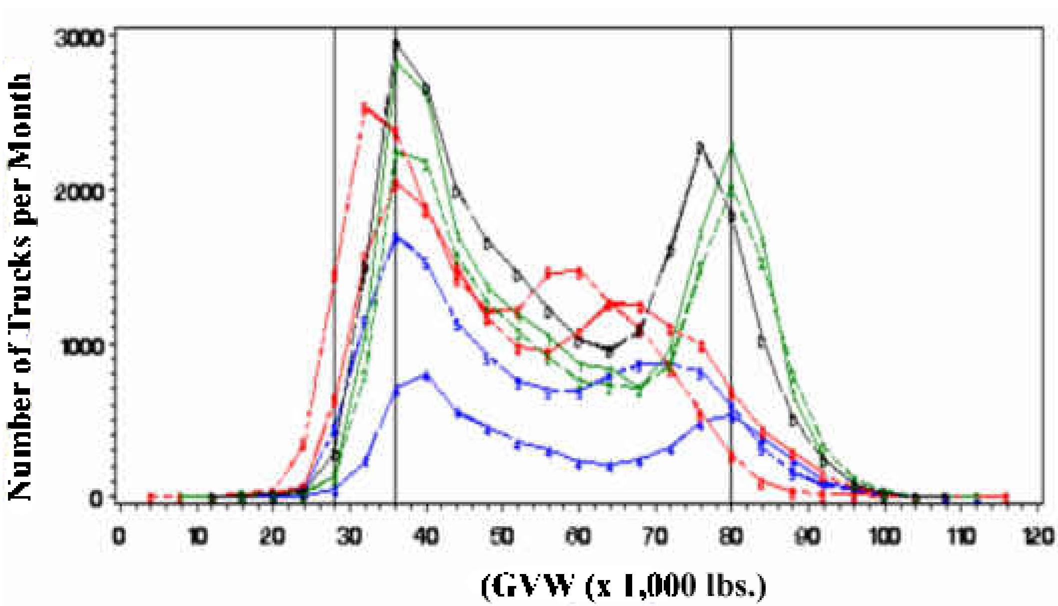


LEGEND: January-March April-June July-September October-December

Figure 4-4. GVW (Class 9 vehicle) versus number of trucks per month for Station P6 (SB) (2001)

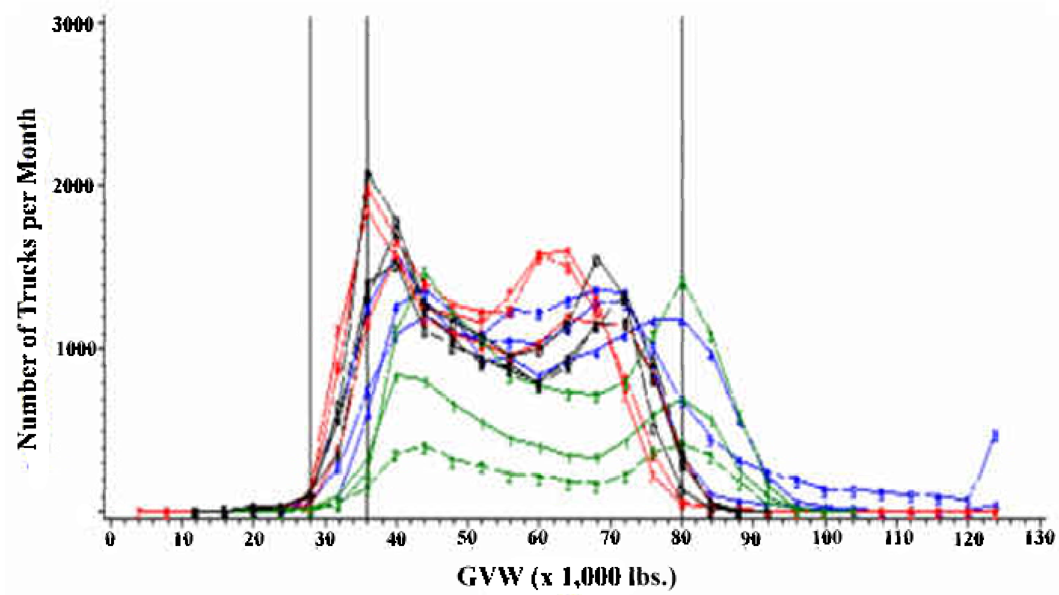
The plot in Figure 4-4 shows consistent traffic (similar peaks for different time spans) and sufficient traffic (rule-of-thumb: the sum of trucks is greater than 5,000 per month) throughout the year with an overestimated empty truck peak. Because heavy truck axles are significantly more damaging to pavement structures than light axles, attaining accurate data for the heavier axles is of great importance, whereas the inclusion of less accurate data for light axles is less important. Furthermore, piezoelectric sensors are often nonlinear; thus, overestimation of light axles is often encountered when heavy axles are correctly reported. Consequently, the data from WIM sites that produce GVW versus frequency plots similar to that in Figure 4-4 are acceptable.

3) A plot that leads to partial use of the WIM data: The plots in figures 4-5 and 4-6 exhibit peaks at the full and empty truck values for only some months, along with sufficient traffic. Only the months that exhibit fully loaded truck peaks equal to 75 to 80 kips should be included. (Figure 4-5 includes data for January-March, and October-December. Figure 4-6 includes data for January-March and April.)



LEGEND: January-March April-June July-September October-December

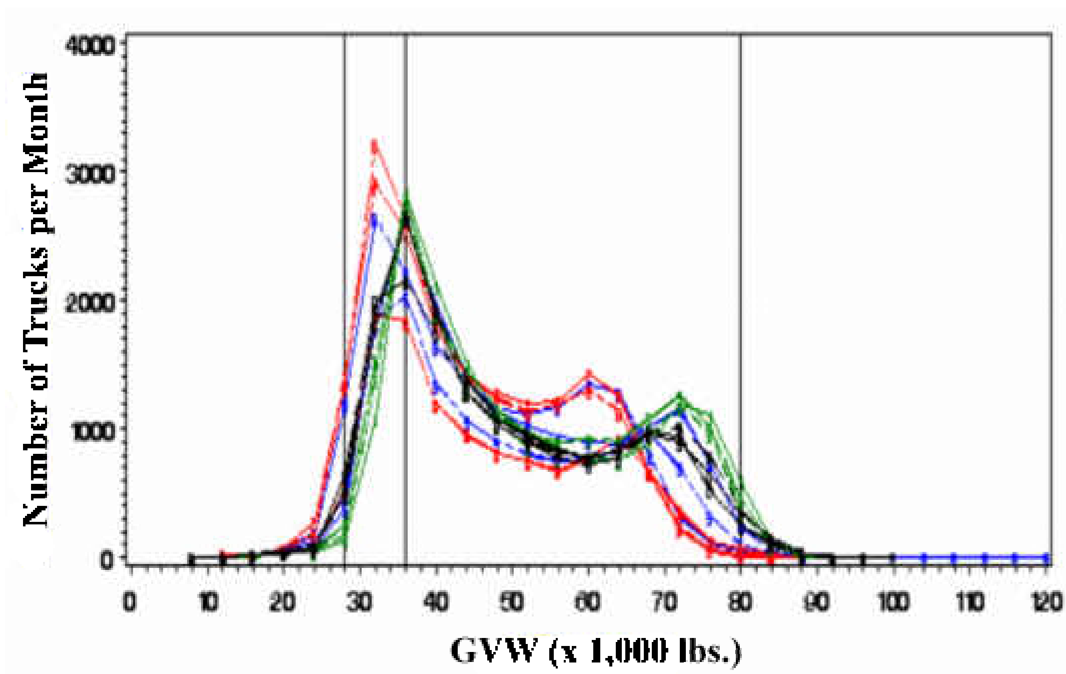
Figure 4-5. GVW (Class 9 vehicle) versus number of trucks per month for Station P3 (SB) (2002)



LEGEND: January-March April-June July-September October-December

Figure 4-6. GVW (Class 9 vehicle) versus number of trucks per month for Station P04 (NB) (2001)

4) A plot that leads to elimination of a WIM station—Trend 1:

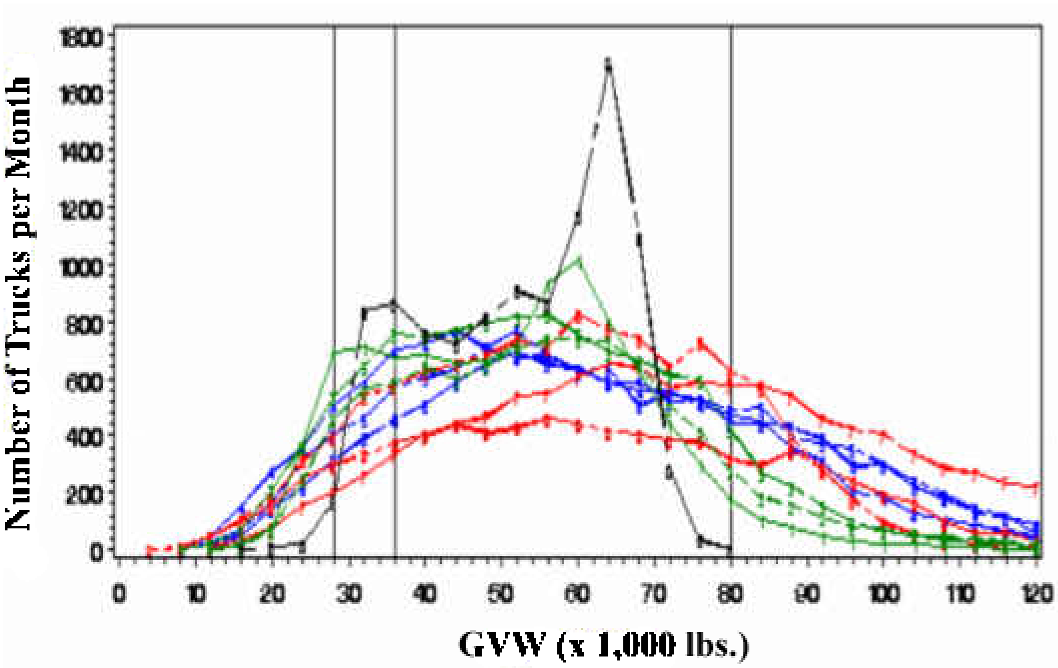


LEGEND: January-March April-June July-September October-December

Figure 4-7. GVW (Class 9 vehicle) versus number of trucks per month for Station P3 (NB) (2002)

The plot in Figure 4-7 shows consistent and sufficient data throughout the year with a shifted, fully loaded truck peak. Such a plot may result from WIM sensor undercalibration for heavy axle weights. Therefore, the data from this station should be discarded.

5) A plot that leads to elimination of a WIM station—Trend 2: The plot in Figure 4-8 does not exhibit the customary weight peaks shown in Figure 4-3. Therefore, the data from this WIM station should be discarded.



LEGEND: January-March April-June July-September October-December

Figure 4-8. GVW (Class 9 vehicle) versus number of trucks per month for Station P7C (NB) (2002)

Step 4

Plot the weight of the steering axle for Class 9 vehicles versus frequency or average steering axle weight throughout the year (see figures 4-9 and 4-10, respectively). The steering axle for Class 9 vehicles has a consistent weight ranging from 8,500 to 12,000 lbs. This test will result in one of three outcomes:

1) All months of the year exhibit plots similar to those in figures 4-9 and/or 4-10. In this case all the months should be included.

2) Some months exhibit plots similar to those in figures 4-9 and 4-10; only these months should be included.

3) None of the months reflect the dominance of the weight range shown in figures 4-9 and/or 4-10; therefore, the data from the station should be discarded.

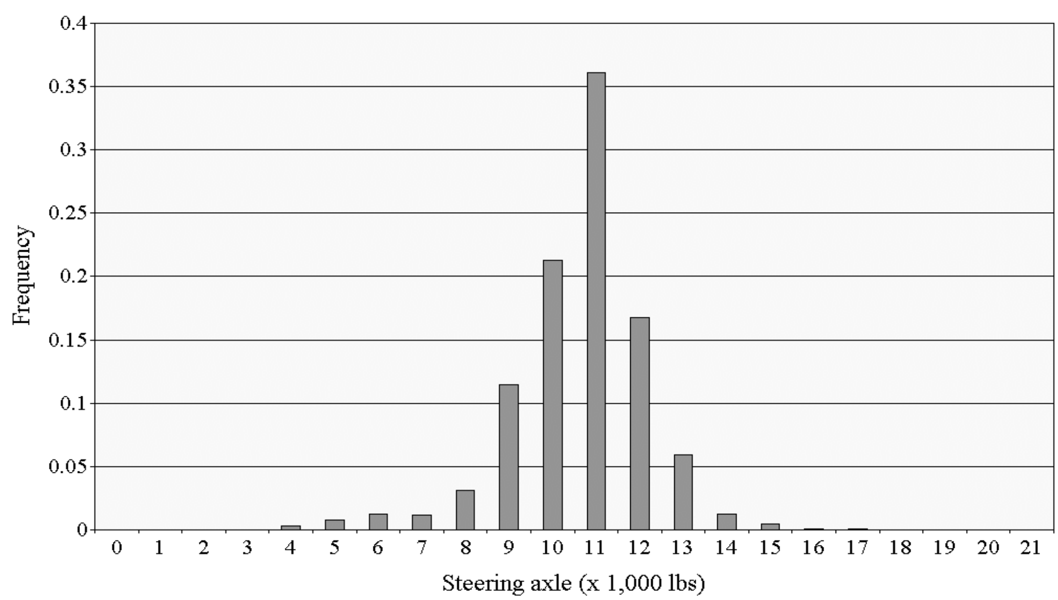
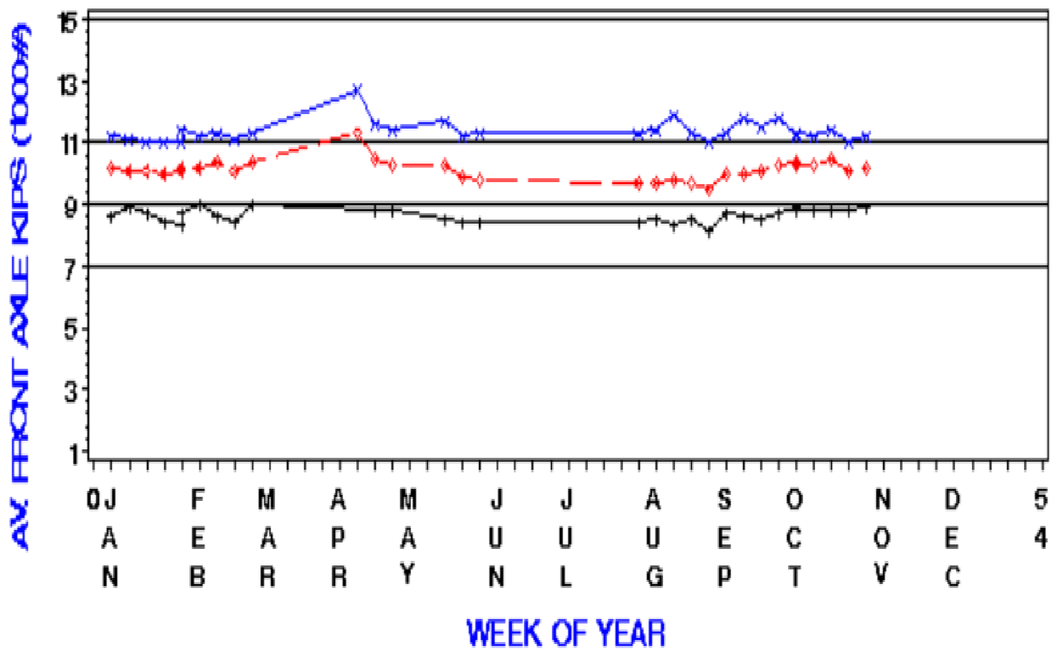


Figure 4-9. Steering axle weight (Class 9 vehicle) versus frequency for Station P04 (2000), which shows an acceptable steering axle trend.



LEGEND: GVW< 30 kips GVW (30-70) kips GVW >70 kips

Figure 4-10. Average steering axle weight throughout 2002 for Station P3 (SB)

Step 5

Raw truck weight data are typically collected and reported as shown in Table 4-1. The next step is to import the raw data into database software (e.g., Microsoft Access) and evaluate them. Table 4-2 is a sample dataset, imported into Access, for Class 11 vehicles at station P07 for January 2000.

Table 4-1. Example of weight data table (from FHWA.dot.gov)

OLD	FILE		NEW	FILE	
Column	Width	Comment	Column	Width	Default
1	1	Record Type	1	1	W
2-3	2	State FIPS Code	2-3	2	
6-8	3	Station ID	4-9	6	
9	1	Direction of Travel	10	1	
35	1	Lane of Travel	11	1	
10-11	2	Year of Data	12-13	2	
12-13	2	Month of Year	14-15	2	
14-15	2	Day of Month	16-17	2	
16-17	2	Hour of Day	18-19	2	
18-23	6	Vehicle Class	20-21	2	
None		Vehicle Length (optional)	22-24	3	
42-45	4	Total Weight of Vehicle	25-28	4	
None		Number of Axles	29-30	2	Calculate
46-48	3	A-Axle Weight	31-33	3	
61-63	3	A-B Axle Spacing	34-36	3	
49-51	3	B-Axle Weight	37-39	3	
64-66	3	B-C Axle Spacing	40-42	3	
52-54	3	C-Axle Weight	43-45	3	
67-69	3	C-D Axle Spacing	46-48	3	
55-57	3	D-Axle Weight	49-51	3	
70-72	3	D-E Axle Spacing	52-54	3	
58-60	3	E-Axle Weight	55-57	3	
53-55*	3	E-F Axle Spacing	58-60	3	
29-31*	3	F-Axle Weight	61-63	3	
56-58*	3	F-G Axle Spacing	64-66	3	
32-34*	3	G-Axle Weight	67-69	3	

Table 4-2. Axle weight data transformed with Microsoft Access for Class 11 vehicles at Station P07 (January 2000)

W	W	W	W	W	W	W	W	W	W	W
State	53	53	53	53	53	53	53	53	53	53
Site	P07	P07	P07	P07	P07	P07	P07	P07	P07	P07
DIR	7	3	7	7	3	7	7	3	7	3
Lane	1	1	1	1	1	1	1	1	1	1
Year	0	0	0	0	0	0	0	0	0	0
Month	1	1	1	1	1	1	1	1	1	1
Day	2	3	4	6	7	7	10	11	11	11
Hour	5	13	13	17	5	7	8	9	9	10
Vehicle Class	11	11	11	11	11	11	11	11	11	11
GVW (x 100 kg)	254	314	224	105	73	89	283	75	279	221
No. of Axles	5	5	5	5	5	5	5	5	5	5
W1 (x 100 kg)	43	43	45	23	17	18	55	22	53	46
S1 (x 100 mm)	38	39	40	38	33	33	41	40	38	37
W2 (x 100 kg)	68	68	51	31	24	26	36	24	36	46
S2 (x 100 mm)	63	66	66	63	72	72	16	92	19	63
W3 (x 100 kg)	60	71	42	16	10	14	66	7	59	47
S3 (x 100 mm)	29	35	35	8	9	9	14	9	13	28
W4 (x 100 kg)	42	63	44	18	11	14	64	9	60	42
S4 (x 100 mm)	67	68	68	8	9	9	93	9	88	66
W5 (x 100 kg)	41	69	41	18	11	17	61	13	70	40

*W1 through W5 represent Axle weight 1 through 5 and S1 through S4 represent the spacing between the axles.
**Axle weights are to nearest tenth of a metric ton (100 kilograms) without a decimal point.
***Axle spacings are to the nearest tenth of a meter (100 millimeters) without a decimal point.
**** 100 kilograms = 220.5 lbs., 100 mm = 3.9 in.

Evaluation of the data from WIM sites throughout Washington State (a total of 52 were considered for this research) reveals that only 11 sites pass the GVW and steering axle weight tests described in Step 4 (see Table 4-3).

Table 4-3. Locations of WIM sites that pass the tests in Step 4.

Site Name	Location	State Route	Roadway Classification	Geographic Location
B03	Pasco	SR-395	Rural	East
B04	Cle Elum	I-90	Rural	East
P1N	Seattle	I-5	Urban	West
P1S	Seattle	I-5	Urban	West
P3N	Seattle	I-5	Urban	West
P3S	Seattle	I-5	Urban	West
P4N	Olympia	I-5	Urban	West
P6N	Seattle	I-5	Urban	West
P6S	Seattle	I-5	Urban	West
P04	Ferndale	I-5	Rural	West
P18	Hoodsport	SR-101	Rural	Olympic Peninsula

Step 6

The selected stations are evaluated to determine whether the traffic trends of vehicle classes 4 through 13 are similar and whether the stations have the following loading patterns:

- seasonal loading pattern (i.e., average ESALs per axle for single, tandem and tridem axles)
- typical axle load spectra for single, tandem, and tridem axles.

Step 7

Develop seasonal and typical ESALs per axle for each vehicle class.

Step 8

Develop typical load spectra that satisfy the requirements of the *2002 Design Guide*.

CHAPTER 5: SENSITIVITY AND STATISTICAL TESTING

When applied to the currently available data, the methodology proposed in Chapter 4 limited the number of months and stations included in this report. To ensure that the excluded months and/or stations were significantly different from the ones included in this report, sensitivity analyses that would determine significance of the various load spectra for pavement design, as well as statistical testing, were conducted.

SENSITIVITY ANALYSIS

To examine the significance, from the perspective of pavement design, of excluding certain load spectra, this study evaluated the resulting ESALs as well as the sensitivity of the *2002 Design Guide*. The following steps were followed.

Step 1: Select WIM Stations with Distinct GVW Distributions

On the basis of the criteria in Chapter 4, the following WIM stations were selected and designated as over-calibrated, undercalibrated, slightly undercalibrated, and ideal:

- Station P1N had significantly high GVWs, which appeared to be caused by sensor overcalibration (see Figure 5-1).
- Station P18 had significantly low GVWs, which appeared to be caused by sensor undercalibration (see Figure 5-2).
- Station P4N had an ideal GVW distribution (see Figure 5-3).
- Stations P6 (NB and SB) ere slightly under-calibrated (see figures 5-4 and 5-5). The two directions were not significantly different; however, the NB

direction had a fully loaded truck peak at 65 kips, whereas the SB direction had a fairly constant fully loaded truck peak between 60 and 70 kips followed by a slight increase at 75 kips.

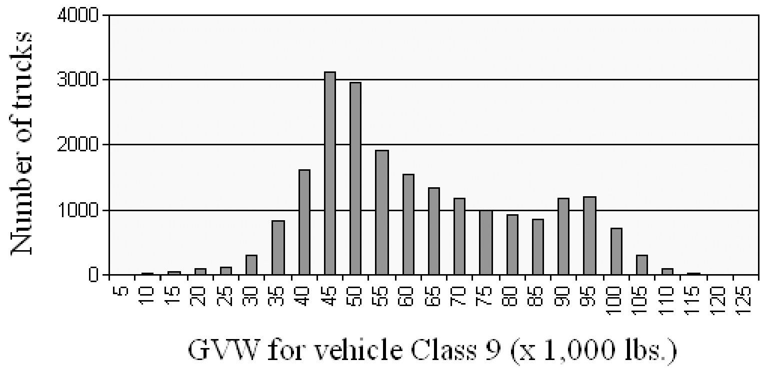


Figure 5-1. GVW distributions for station P1N (2000) (overestimated GVW)

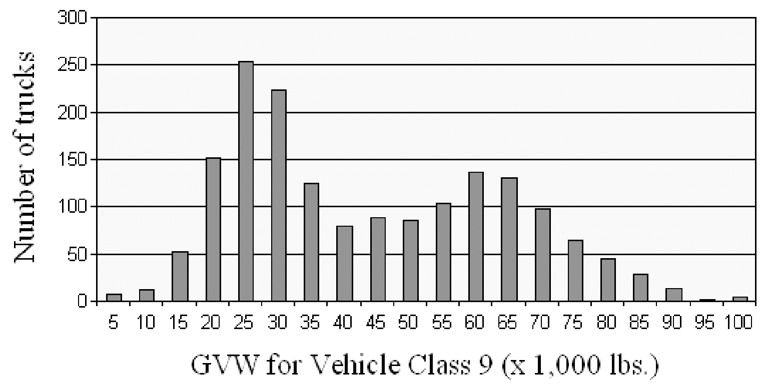


Figure 5-2. GVW distributions for station P18 (2001) (underestimated GVW)

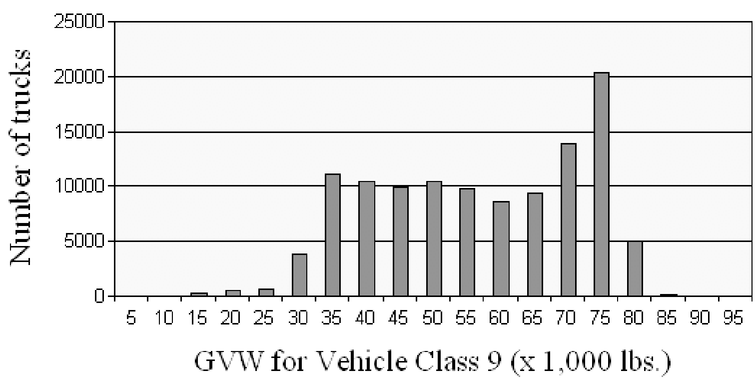


Figure 5-3. GVW distributions for station P4N (2000) (ideal GVW)

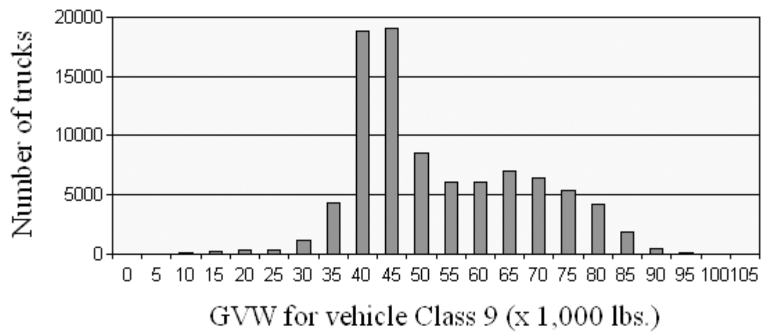


Figure 5-4. GVW distributions for station P6N (NB) (2001) (slightly underestimated)

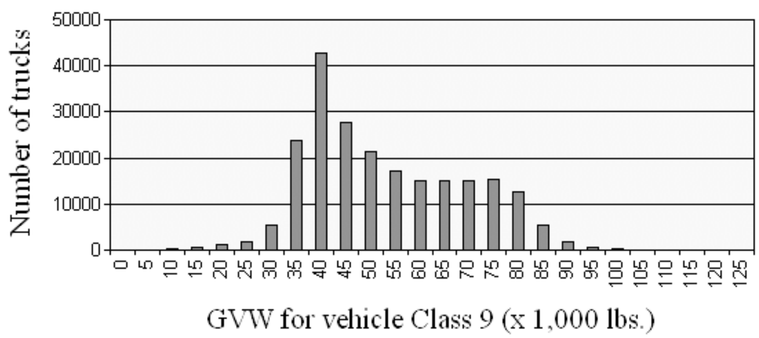


Figure 5-5. GVW distributions for station P6N (SB) (2001) (slightly underestimated)

Step 2: Determine Single and Tandem Axles from the Database

This was done by designating the axles as the following:

- single axle if their spacing was greater than 8 ft.
- tandem axle if their spacing was less than 8 ft. and the spacings before and after are greater than 8 ft.
- tridem axle if the spacing between the outer tires was less than 12 ft. and the spacings before and after were greater than 8 ft.

Step 3: Plot Single and Tandem Axles versus Frequency

A tandem axle load equal to 33.25 kips was used with the generalized fourth power law for ESAL estimation. This value is associated with a flexible pavement with structural number (SN) = 5 and terminal serviceability index (p_t) =2.5.

Step 4: Multiply the ESALs

The ESALS were multiplied by their associated frequencies for single and tandem axles and summed to get the average ESAL per axle.

Step 5: Multiply These Values

These values were multiplied by the equivalent number of axles associated with an arbitrary value (e.g., one million Class 9 trucks, with one steering axle and two tandem axles) (see Table 5-1).

The total ESALs associated with the evaluated stations were within an order of two compared with Station P4N (see Table 5-1). Doubling the ESALs typically resulted in increased pavement thickness equal to 1 inch or less. Thus, the difference had a relatively low impact on pavement design.

The single and tandem axle load spectra for the selected stations are shown in figures 5-6 through 5-15. These figures show that the single axle load spectra for all stations were fairly similar, but the tandem axle load spectra were directly proportional to the GVW distributions.

Table 5-1. ESALs associated with varying load spectra

Station	Station P18	Station P6	Station P6	Station P4N	Station P1N
Direction	NB	NB	SB	NB	NB
Lane	2	3	1	2	2
Duration	3 months	1 year	1 year	3 months	1 month
Period	Sept, Oct, Dec (2001)	2001	2001	Jan-Mar (2000)	Feb (2000)
Description	Under-estimated	Slightly Under-estimated	Slightly Under-estimated	Ideal	Over-estimated
Average single axle ESAL	0.07	0.17	0.17	0.11	0.22
Average tandem axle ESAL	0.29	0.29	0.33	0.41	0.74
Single axle ESALs*	69,507	172,499	167,943	114,633	215,031
Tandem axle ESALs*	579,062	584,560	660,966	831,224	1,470,751
Total ESALs*	648,569	757,059	828,909	945,857	1,685,782

* The ESALs are for 1 million Class 9 vehicles

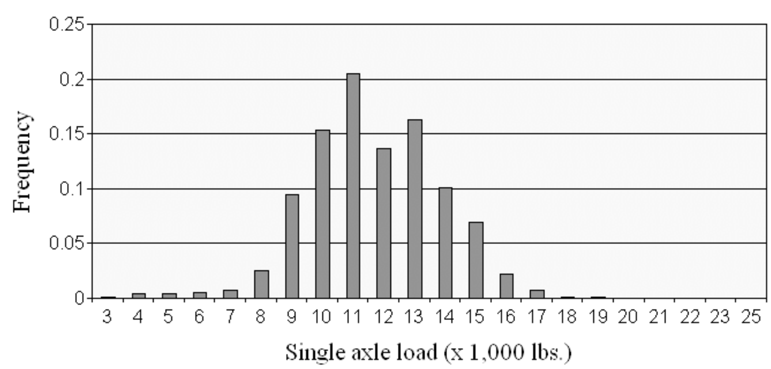


Figure 5-6. Single axle load spectrum for station P1N (2000)

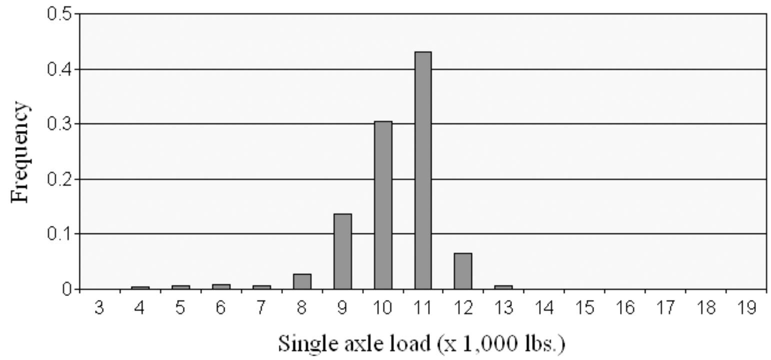


Figure 5-7. Single axle load spectrum for station P4N (2000)

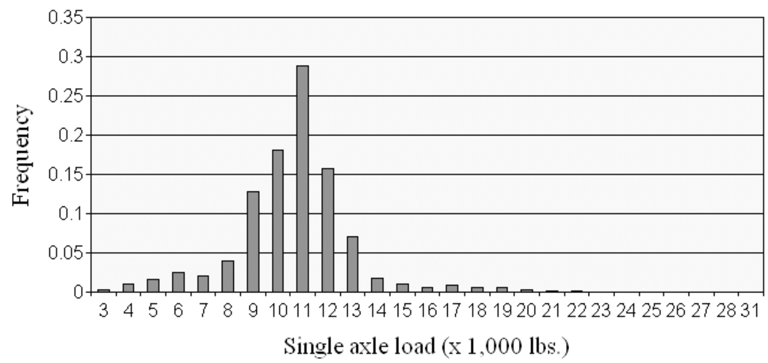


Figure 5-8. Single axle load spectrum for Station P6N (SB)

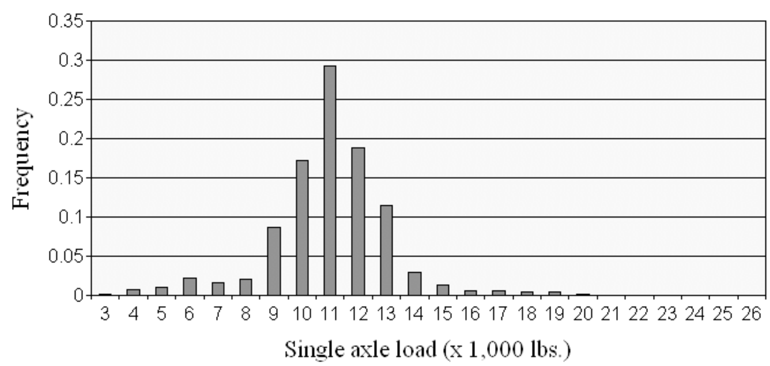


Figure 5-9. Single axle load spectrum for Station P6N (NB)

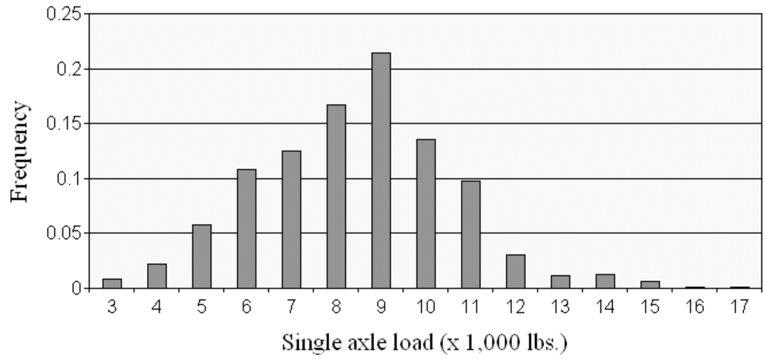


Figure 5-10. Single axle load spectrum for station P18 (2001)

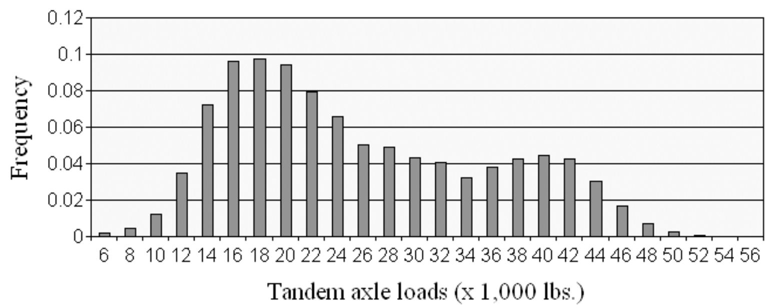


Figure 5-11. Tandem axle load spectrum for station P1N (2000)

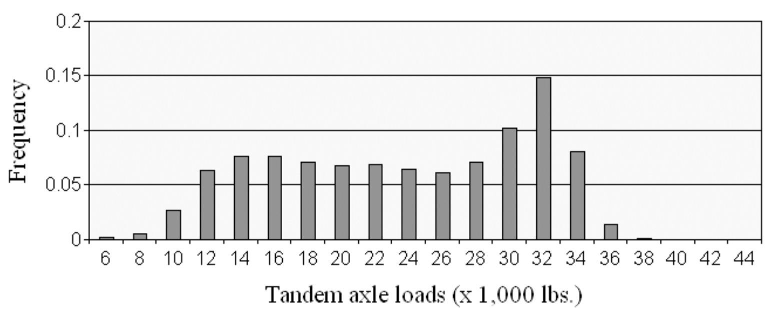


Figure 5-12. Tandem axle load spectrum for station P4N (2000)

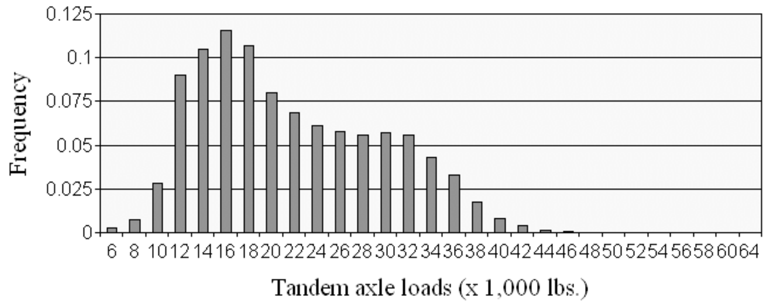


Figure 5-13. Tandem axle load spectrum for Station P6N (SB)

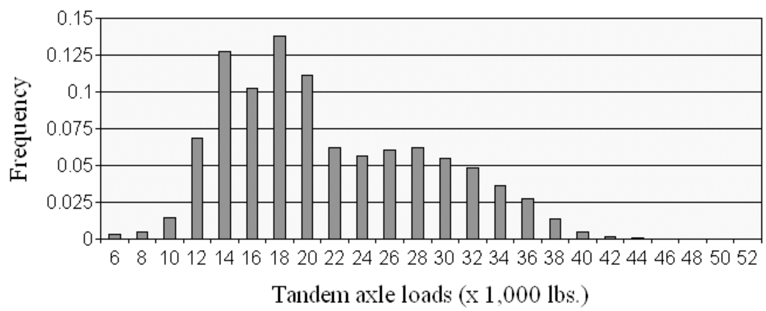


Figure 5-14. Tandem axle load spectrum for Station P6N (NB)

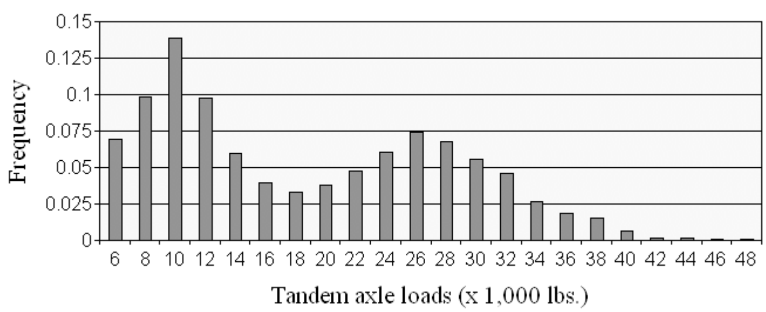


Figure 5-15. Tandem axle load spectrum for station P18 (2001)

Step 6: Perform a Sensitivity Analysis

A sensitivity analysis of the *2002 Design Guide* was conducted by including the load spectra associated with the stations in Table 5-1, along with a pavement structure typical of Washington Interstates (e.g., 8-in. AC [PG 64-23], 12-in. granular base (40-ksi) on top of subgrade [14 ksi]). Daily traffic of 10,000 Class 9 vehicles, without annual growth, were used in the analysis. This traffic was equivalent to 3.5 million yearly

ESALs, given that the average ESAL per Class 9 vehicle, for the ideal load spectrum, is 0.93 (see P4N, Table 5-1). Such ESALs are found in heavily traveled sections of I-5 near Seattle and Tacoma. The input summary for these analyses is in Appendix G.

The pavement damage criteria—rutting, bottom-up (fatigue) cracking, and International Roughness Index (IRI)—incurred with the employed load spectra are shown in figures 5-16 through 5-18. Figure 5-18 shows that the *2002 Design Guide* was relatively insensitive to changes in IRI associated with any of the employed load spectra. Therefore, the primary factors used to evaluate the sensitivity of the *2002 Design Guide* were rutting and fatigue cracking.

As previously noted, the load spectra used were associated with [1] Station P1N, which had significantly overestimated GVWs, [2] Station P4N, which had an ideal GVW distribution, [3] Station P6 (NB), [4] Station P6 (SB), which had slightly underestimated GVWs, and [5] Station P18, which had significantly underestimated GVWs.

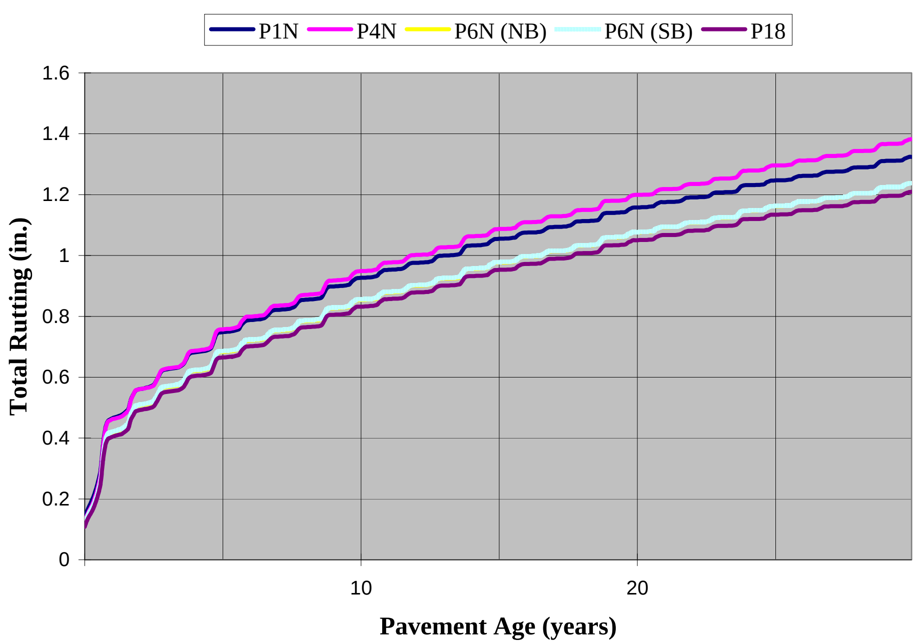


Figure 5-16. Total rutting associated with the various load spectra (typical HMA)

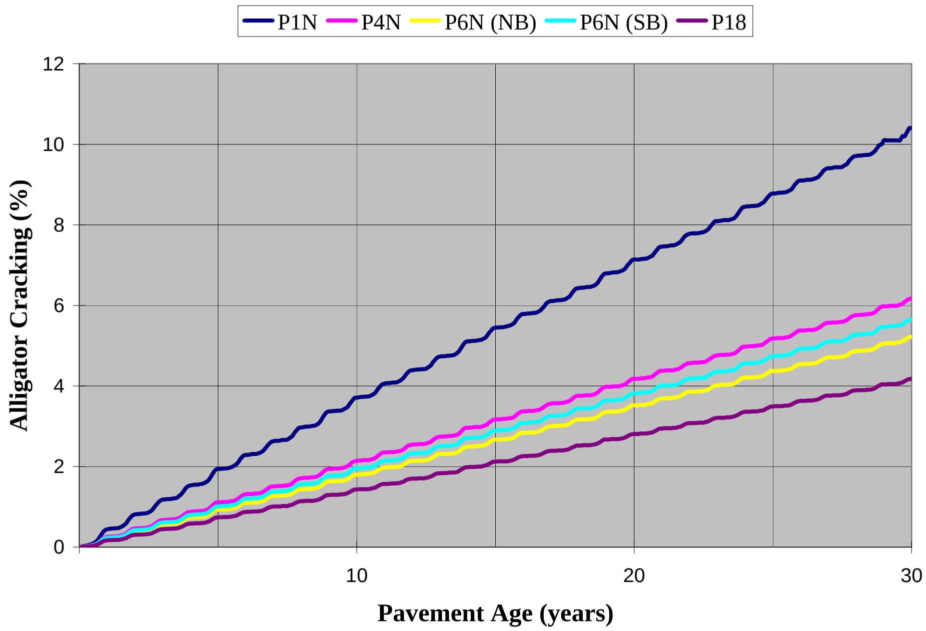


Figure 5-17. Bottom up fatigue cracking associated with the various load spectra (typical HMA)

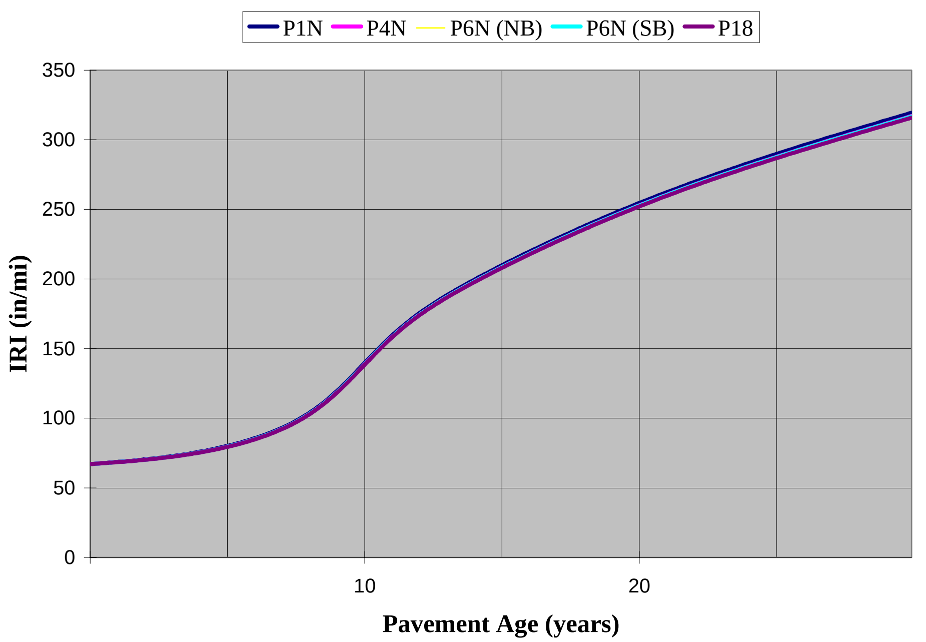


Figure 5-18. IRI (in/mi) associated with the various load spectra (typical HMA)

WSDOT's experience is that the mean age for resurfacing flexible pavements is 13 years (see Figure 5-19). Maintenance trigger points are typically 10 percent cracking in the wheel path area or 0.5-in. rutting. However, cracking rather than rutting is what typically triggers resurfacing in Washington State. Therefore, the cracking damage associated with Station P4N is expected to be 10 percent at 13 years, while the rutting is expected to reach 0.5 inch in about 20 years. It is apparent from figures 5-16 and 5-17 that both criteria need to be calibrated to fit the prevailing conditions in Washington State.

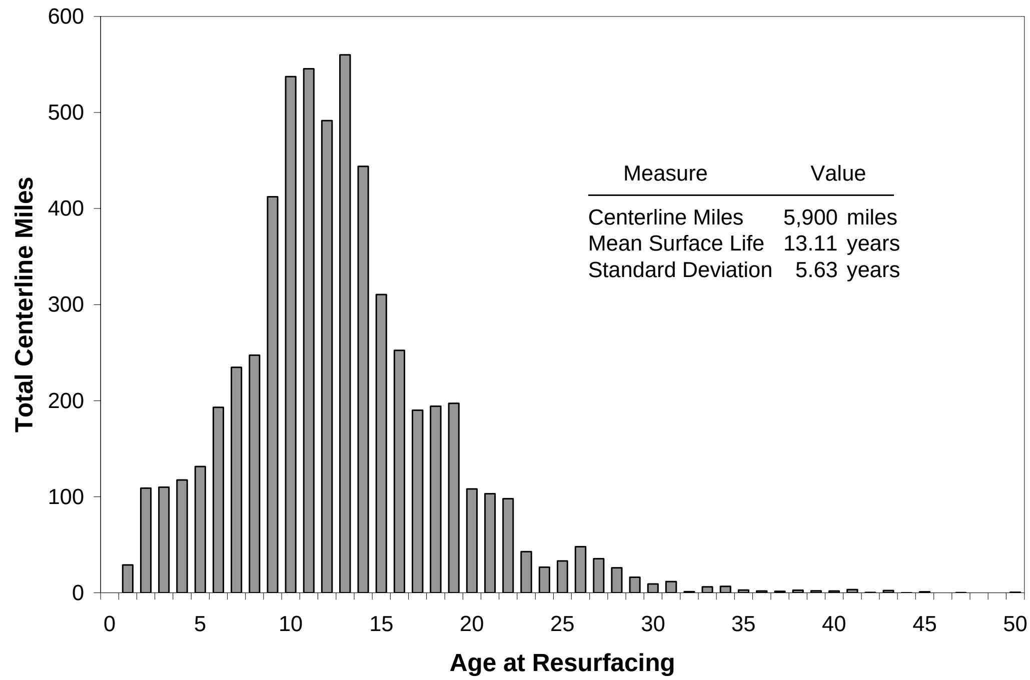
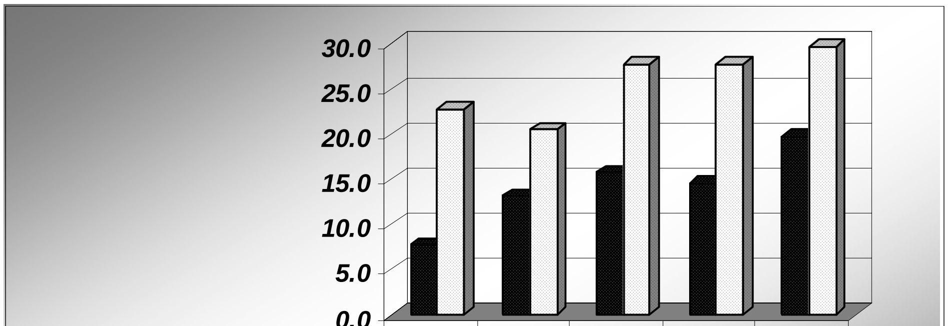


Figure 5-19. Age at resurfacing for flexible pavement sections in Washington State (from Muench, 2003)

To account for the necessary calibration, arbitrary rutting and cracking trigger points that corresponded to prevailing conditions in Washington State were chosen. WSDOT's cracking and rutting trigger points are 10 percent and 0.5 inch, respectively. Because the cracking model is linear, and the rutting model is linear after the initial densification, these approximations were used as substitutes for the model calibration. Thus, the chosen cracking damage percentage associated with Station P4N, at approximately 13 years, was 2.75 percent (see Figure 5-17). The rutting failure corresponding to 20 years was equal to 1.2 inches (see Figure 5-16).

The standard deviation associated with the mean age for resurfacing flexible pavements in Washington State is about 5.6 years (see Figure 5-19). This standard of deviation is due to errors associated with the quality of traffic data, construction practices, and varying environmental conditions. Therefore, it would be wise to employ load spectra with minimal variance. (A two-year standard deviation is proposed.)

On the basis of these arbitrary rehabilitation trigger points (i.e., 2.75 percent and 1.2 in.) and the proposed two-year standard deviation, Figure 5-20 shows that the *2002 Design Guide* is particularly sensitive to significantly overestimated and underestimated load spectra (e.g., the rehabilitation trigger points for stations P1N and P18 differed from Station P4N by about 7 years) and is moderately sensitive to slightly underestimated load spectra (e.g., the rehabilitation trigger points for stations P6 (NB and SB) differed from Station P4N by 2.5 to 4 years).



	P1N	P4N	P6N (NB)	P6N (SB)	P18
■ cracking trigger point (2.75%) (years)	7.7	13.2	15.8	14.6	19.8
□ rutting trigger point (1.2 in.) (years)	22.8	20.5	27.8	27.8	29.8

Figure 5-20. Resurfacing trigger points associated with various load spectra (typical HMA)

Step 7: Perform an Additional Sensitivity Analysis with the *2002 Design Guide*

An additional sensitivity analysis was conducted by including the load spectra associated with the stations in Table 5-1 with a medium thickness pavement structure—e.g., 4-in. AC (PG 64-28), 8-in. granular base (40-ksi) on top of subgrade (14-ksi). Daily traffic of 1,000 Class 9 vehicles, without annual growth, were the only traffic included in the analysis. The chosen daily traffic was significantly less than the traffic analyzed in Step 6; however, it was more than adequate for this pavement thickness (given the AASHTO 93 design equation).

As in Step 6, figures 5-21 through 5-23 show the pavement damage criteria used with the employed load spectra. Figure 5-23 shows that the *2002 Design Guide* is not sensitive to changes in IRI (as before). Thus, the primary factors used to evaluate the sensitivity of the *2002 Design Guide* were again rutting and fatigue cracking.

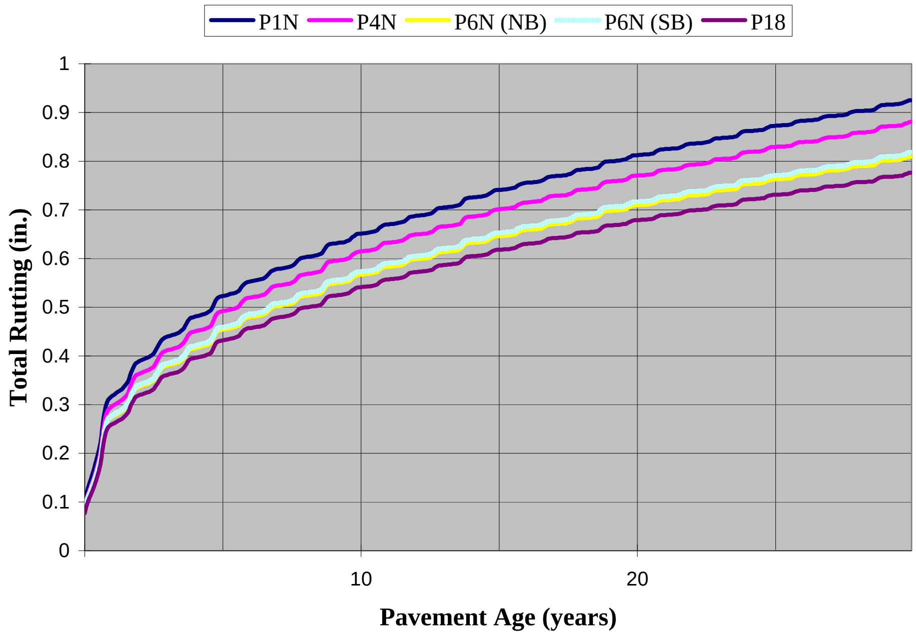


Figure 5-21. Total rutting associated with the various load spectra (medium thickness HMA)

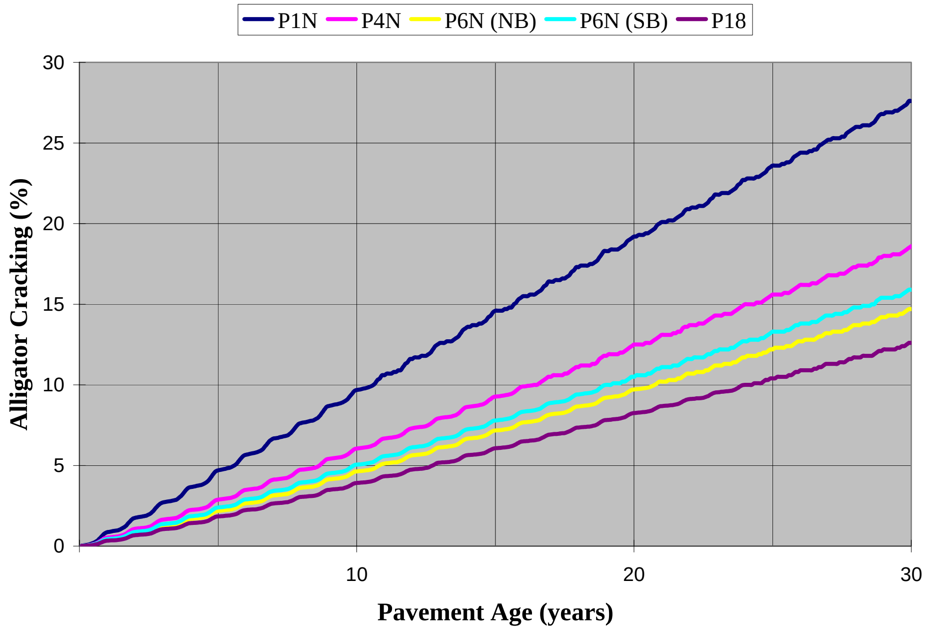


Figure 5-22. Bottom up fatigue cracking damage associated with the various load spectra (medium thickness HMA)

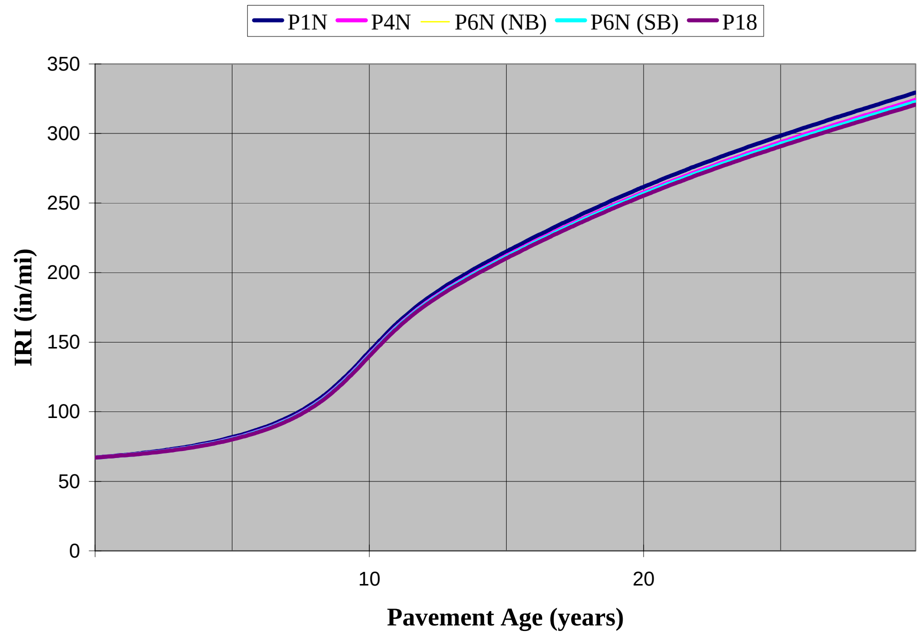
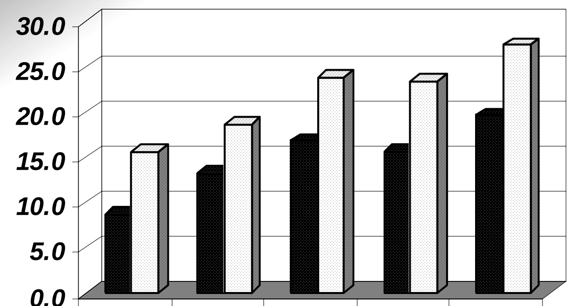


Figure 5-23. IRI (in/mi) associated with the various load spectra (medium thickness HMA)

The chosen cracking damage percentage associated with the ideal load spectrum (i.e., Station P4N) at approximately 13 years was 8 percent, while the trigger point for rutting at 20 years was 0.75 inches (see figures 5-21 and 5-22). On the basis of these rehabilitation trigger points (i.e., 8 percent and 0.75 in.) and the two-year standard deviation proposed in Step 6, Figure 5-24 shows that the *2002 Design Guide* is notably sensitive to significantly overestimated and underestimated load spectra (i.e., the rehabilitation trigger points for stations P1N and P18 differed from Station P4N by 5-7 years) and is moderately sensitive to slightly underestimated load spectra (i.e., the rehabilitation trigger points Stations P6 (NB and SB) differed from Station P4N by 2.5-3.5 years).

These findings corroborate the initial recommendation in Chapter 4 regarding the exclusion of moderately and significantly overestimated and underestimated load spectra. Therefore, only load spectra that fit the criteria in Chapter 4 should be used.



	P1N	P4N	P6N (NB)	P6N (SB)	P18
■ cracking trigger point (8%) (years)	8.7	13.3	16.8	15.7	19.7
□ rutting trigger point (0.75 in.) (years)	15.7	18.7	23.9	23.5	27.5

Figure 5-24. Resurfacing trigger points associated with various load spectra (medium thickness HMA)

STATISTICAL ANALYSIS

Having performed a sensitivity analyses, the next step was to correlate its results with statistical testing. The single axle load spectra in figures 5-6 through 5-10 appeared normally distributed; therefore, t-tests and ANOVAs could be employed to determine whether the spectra differed statistically. However, the difference in single axle ESALs is insignificant from the standpoint of pavement design, making that such tests unnecessary (see Table 5-1).

The tandem axle load spectra in figures 5-11 through 5-15 were non-normally distributed; therefore, a non-parametric test equivalent to the t-test and ANOVA (i.e., Mann-Whitney and Kruskal-Wallis) could be used to determine whether the spectra differed significantly. Non-parametric tests use the rank of data, rather than their values, to calculate the statistic. As such, they are not as powerful as the t-test and the ANOVA.

Consultations with the Department of Statistics at the University of Washington determined that statistical tests based on ranking (i.e., the Mann-Whitney and Kruskal-Wallis) would be inappropriate. As an alternative, the Bootstrap method was suggested for determining whether two load spectra are significantly different.

The Bootstrap method was used to evaluate distinct GVW distributions from stations P4N and P1N and revealed a significant difference between the two stations (see Appendix F). To determine the sensitivity of the Bootstrap method, the GVW distribution for Station P1N was replicated and slightly modified. The modification consisted of increasing the number of trucks that weighed 95 kips from 1,200 to 1,250. Such an increase is relatively insignificant; however, the Bootstrap method found a clearly significant difference. The conclusion is that statistical testing may *not* be used to determine whether two stations and/or months have significantly different load spectra or GVW distributions.

This excerpt from a report prepared by the Department of Statistics at the University Washington summarizes the conclusions of the statistical testing:

> The Bootstrap method is a powerful tool to explore potential variability of summary statistics in wide range of applications. However, in this case, it does not help you to make the decision as whether to aggregate load spectra from different sources, because a small difference in load spectra that cannot be identified visually can be statistically significant. The limitation is not just for the Bootstrap method since the cause comes from large sample size. Methods or criteria other than statistics should be explored in order to make reasonable decision.

The complete report is supplied in Appendix F.

CHAPTER 6: LOAD SPECTRA DEVELOPMENT

The sensitivity analyses described in Chapter 5 showed that the *2002 Design Guide* is particularly sensitive to significantly overestimated and underestimated load spectra and is moderately sensitive to slightly underestimated load spectra. Therefore, WIM stations with load spectra that fit the criteria described in Chapter 4 (i.e., with ideal, or acceptable but not ideal, GVW distributions) were the only stations included in the rest of this study. The effects of excluding the WIM stations that did not fit the criteria in Chapter 4 are discussed below.

INVALID DATA EVALUATION

Fifty-two WIM stations in Washington State were evaluated. Out of the 52 stations, the following are the percentages of valid data stations in each region (see Table 6-1):

- 8 out of 24 in Western Washington
- 2 out of 26 in Eastern Washington
- 1 out of 2 in the Olympic Peninsula.

Table 6-1 shows that three of the selected stations possessed valid yearly data, whereas the remaining stations contained invalid monthly data. Consequently, the first step was to determine the effects of excluding the invalid months (i.e., with extremely or slightly underestimated or overestimated GVWs). The effects of such exclusions were determined by analyzing the combined valid monthly GVW versus the whole yearly GVW distributions. The valid months for each selected WIM station are shown in Table

6-1. The selected year for each WIM station typically possessed the greatest number of valid months (see Table 6-1).

Table 6-1. List of valid data months for the selected WIM stations

WIM station	Location	State Route	Roadway Classification	Geographic Location	Year	Valid months
B03 (both directions)	Pasco	SR-395	Rural	East	2002	7, 8, 9, 10
B04 (both directions)	Cle Elum	I-90	Rural	East	2002	1, 2, 12
P1N	Seattle	I-5	Urban	West	2002	1, 2, 3, 4, 10, 11, 12
P1S	Seattle	I-5	Urban	West	2000	All
P3N	Seattle	I-5	Urban	West	2000	3, 4, 5, 6, 7, 8, 12
P3S	Seattle	I-5	Urban	West	2001	1, 2, 3, 4, 5, 9, 10, 12
P4N	Olympia	I-5	Urban	West	2002	All
P6N	Seattle	I-5	Urban	West	2000	2, 3, 4, 5, 9, 10, 11, 12
P6S	Seattle	I-5	Urban	West	2000	All
P04 (both directions)	Ferndale	I-5	Rural	West	2001	1, 2, 12
P18 (NB)	Hoodsport	SR-101	Rural	Olympic Peninsula	2002	1, 2, 3, 4, 11, 12
P18 (SB)						1, 2, 3, 5, 6, 10, 11, 12

No significant seasonal variations were associated with the selected stations. This trend is evident in the stations with valid yearly data (see figures 6-1, 6-2, and Appendix A). In addition, the criteria for excluding the months with extremely and slightly overestimated or underestimated GVW distributions resulted in matching load patterns. Consequently, the monthly GVW distributions and load spectra were consolidated into yearly distributions.

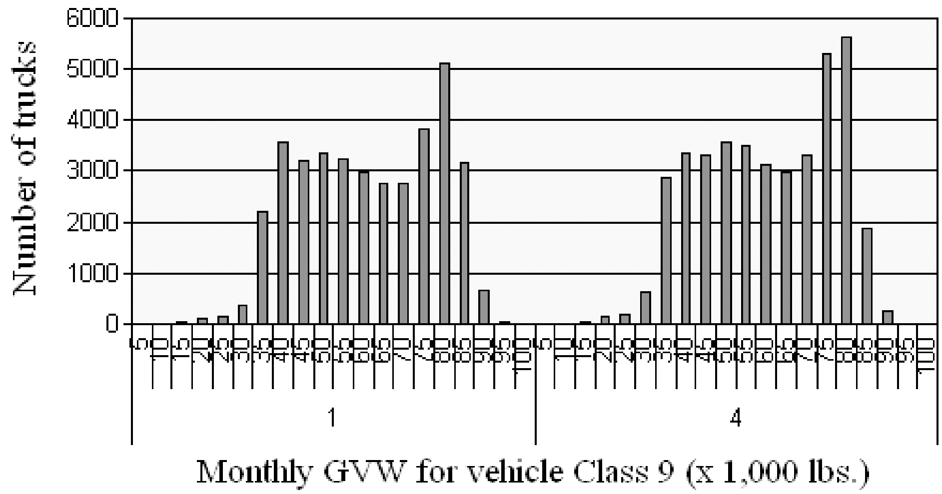


Figure 6-1. Monthly GVW distributions for Class 9 vehicles (Station P4N-2002-January, April)

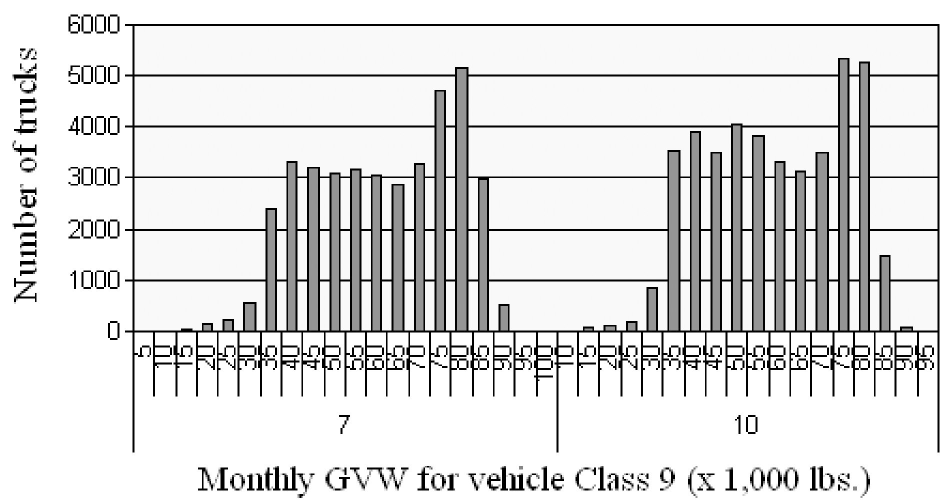


Figure 6-2. Monthly GVW distributions for Class 9 vehicles (Station P4N-2002-July, October)

The process of excluding invalid months resulted in the following three scenarios:

1. Stations not affected by the exclusion of the invalid months that produced adequate GVW distributions (e.g., see figures 6-3 and 6-4). The remaining stations are in Appendix B.
2. Stations not affected by the exclusion of the invalid months that produced inadequate GVW distributions (see figures 6-5 and 6-6).

3. Stations significantly affected by the exclusion of the invalid months that resulted in enhanced GVW distributions (i.e., resulted in a GVW distribution similar to the ideal plot) (see figures 6-7 and 6-8). The remaining stations are in Appendix B.

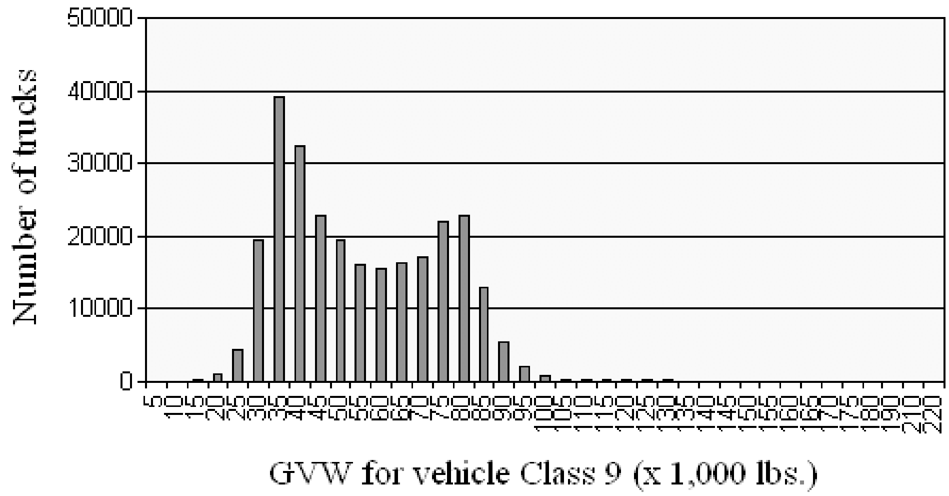


Figure 6-3. Yearly GVW distributions for Class 9 vehicles (Station P3S-2001) (total months)

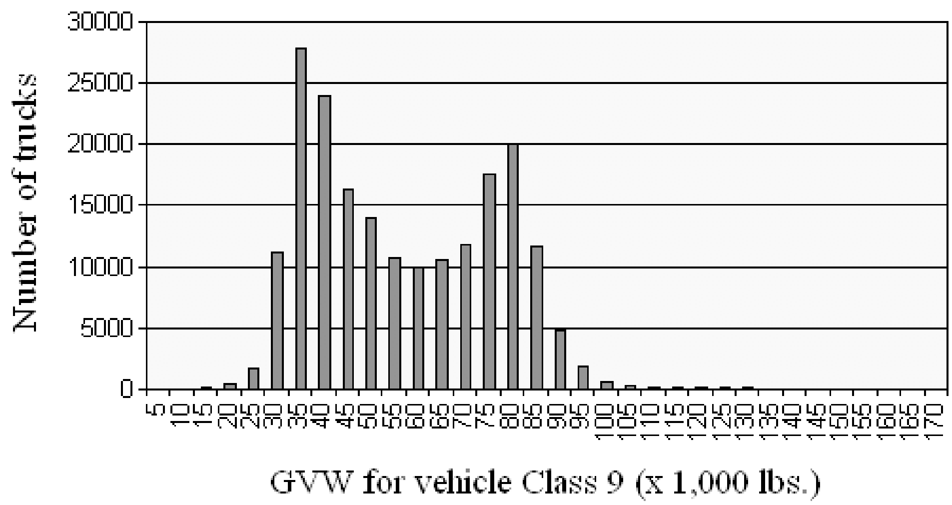


Figure 6-4. Yearly GVW distributions for Class 9 vehicles (Station P3S-2001) (valid months)

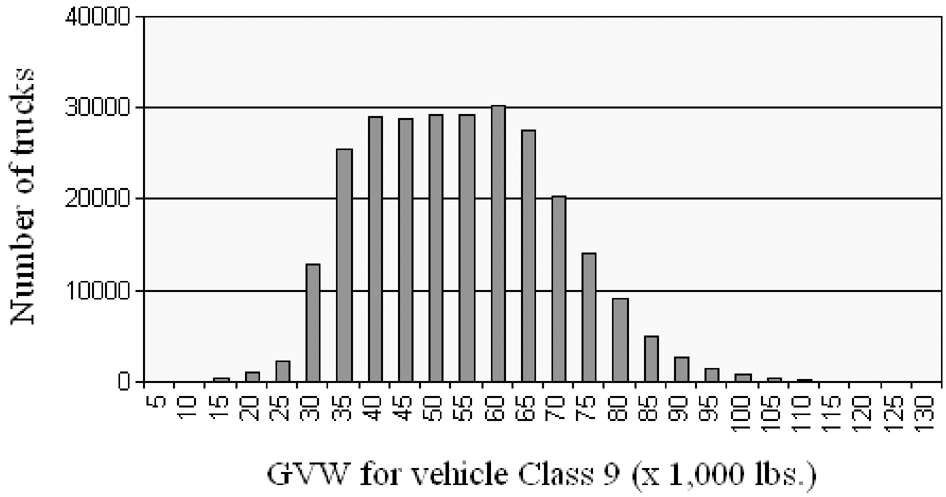


Figure 6-5. Yearly GVW distributions for Class 9 vehicles (Station P04-NB-2001) (total months)

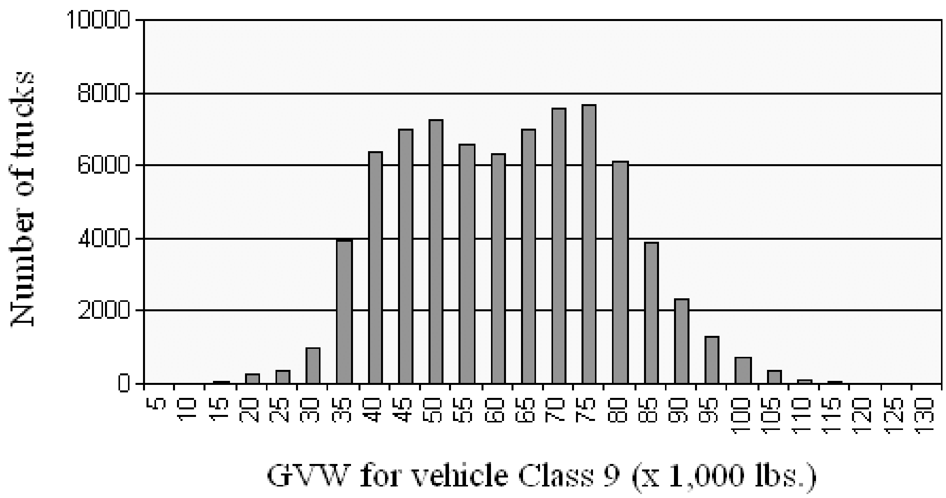


Figure 6-6. Yearly GVW distributions for Class 9 vehicles (Station P04-NB-2001) (valid months)

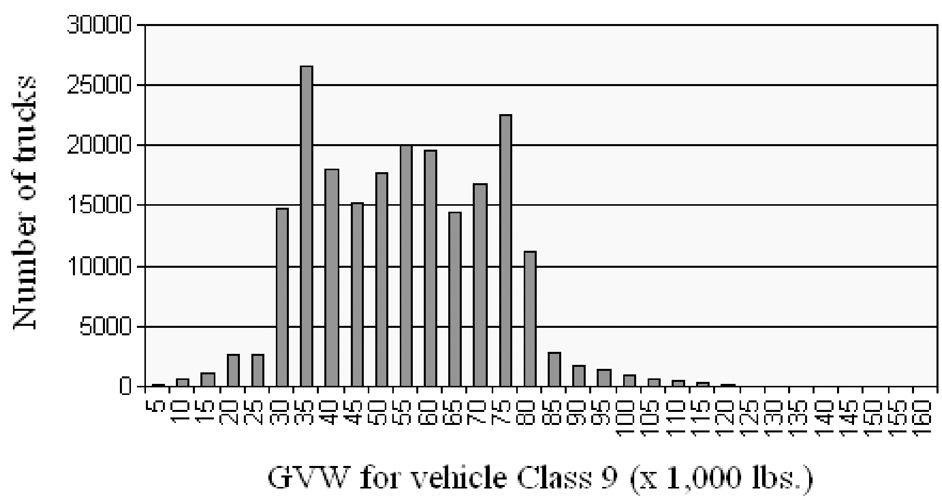


Figure 6-7. Yearly GVW distributions for Class 9 vehicles (Station B03-NB-2002) (total months)

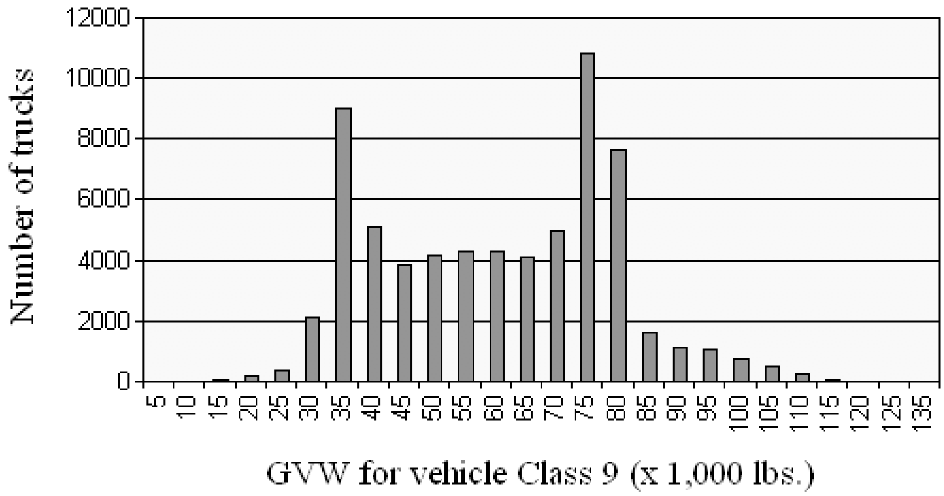


Figure 6-8. Yearly GVW distributions for Class 9 vehicles (Station B03-NB-2002) (valid months)

The resulting conclusion was that no consistent effect is associated with the exclusion of invalid months from each WIM station. However, it is clear that excluding such months will either improve the quality of analyzed data (i.e., result in GVW distributions similar to the ideal plot) or maintain its preexisting condition (i.e., result in no significant change to the GVW distributions). The resulting decision was to exclude invalid months from all analyses leading to the development of the load spectra.

WIM STATION EXPLORATION

The analyses discussed in Chapter 5 showed that neither statistical analyses nor average ESAL values are suitable for determining the difference between GVW distributions. Therefore, the GVW distributions were differentiated with respect to the GVW peak values associated with empty and fully loaded trucks, in conjunction with the percentages of trucks at those peaks.

The GVW distributions for the selected WIM stations, arranged in order of increasing percentage of fully loaded trucks, are shown in figures 6-9 through 6-20. The stations exhibited one of the following characteristics:

- The number of empty trucks was significantly greater than fully loaded trucks (e.g., Stations P04 (SB), B04, P3N, P6N, P1N, P6S).
- The number of empty trucks was greater than fully loaded trucks (e.g., stations P18 (SB), and P18 (NB), P1S, and P3S).
- The numbers of empty and fully loaded trucks were comparable (e.g., Station B03)
- The number of fully loaded trucks was greater than empty trucks (e.g., Station P4N).

Figures 6-9 through 6-20 show that the selected WIM stations typically had two peaks, one associated with empty Class 9 vehicles at approximately 35 to 40 kips and one associated with fully loaded Class 9 vehicles at 75 to 80 kips. However, the percentages of empty and fully loaded trucks varied among the selected WIM stations. To determine whether such variability could be reduced, the selected WIM stations were grouped with respect to the following classifications:

- geographic location (i.e., Western vs. Eastern Washington, and Northwestern vs. Southwestern Washington)
- urban versus rural roadways
- Interstate versus non-Interstate roadways (e.g., I-5 and I-90 vs. SR 395 and SR101).

No distinguishing trends resulted from the creation of any of these groups. That is, grouping the stations in figures 6-9 through 6-20 with respect to these geographic and roadway classifications did not reduce the variability associated with empty and fully loaded truck percentages. Therefore, the stations were treated as samples from a single population with consistent GVW peak values and varying percentages of empty and fully loaded trucks.

The tandem axle load spectra typically followed the shape of the GVW distributions, with peaks at 14 to16 kips and 30 to34 kips (see Appendix C). Therefore, the conclusions drawn regarding GVW distributions would be equally valid for tandem axle load spectra. The only exception was Station P04 (NB), which significantly differed from the remaining stations, having less pronounced GVW and/or tandem axle load spectra peaks (see Figure 6-21).

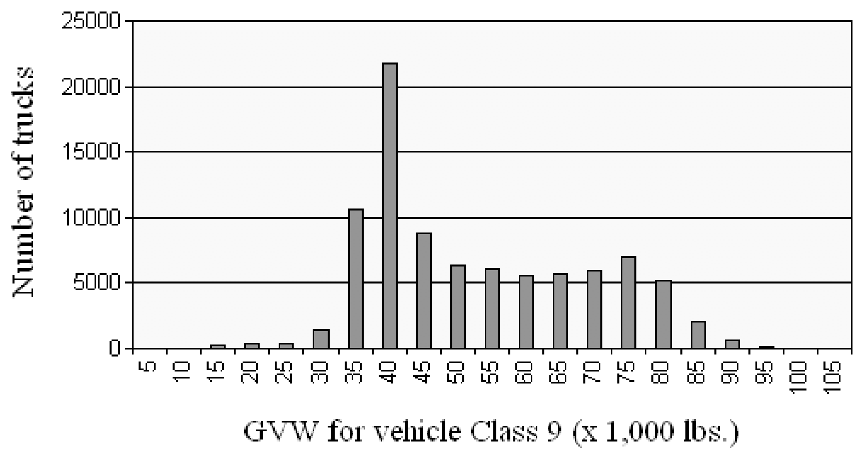


Figure 6-9. Yearly GVW distributions for Class 9 vehicles (Station P04-SB-2001)

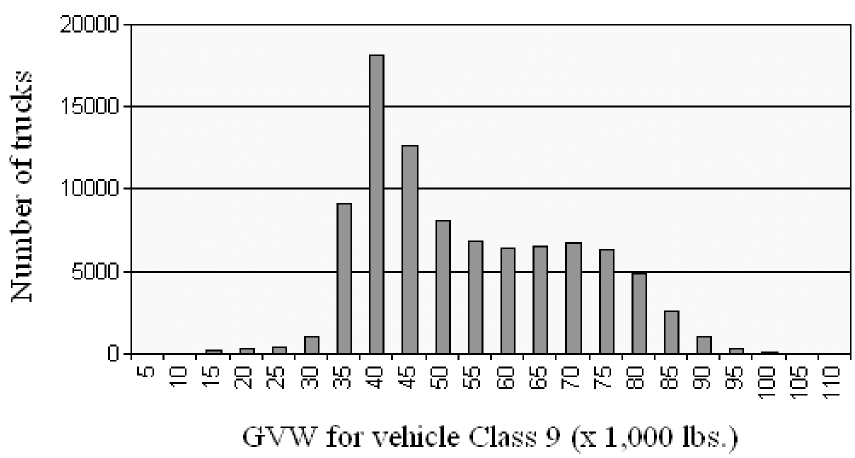


Figure 6-10. Yearly GVW distributions for Class 9 vehicles (Station B04-SB-2002)

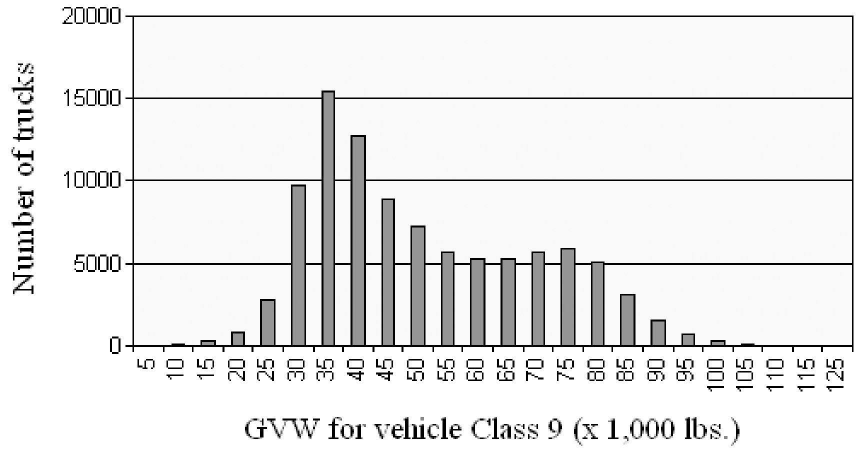


Figure 6-11. Yearly GVW distributions for Class 9 vehicles (Station P3N-2000)

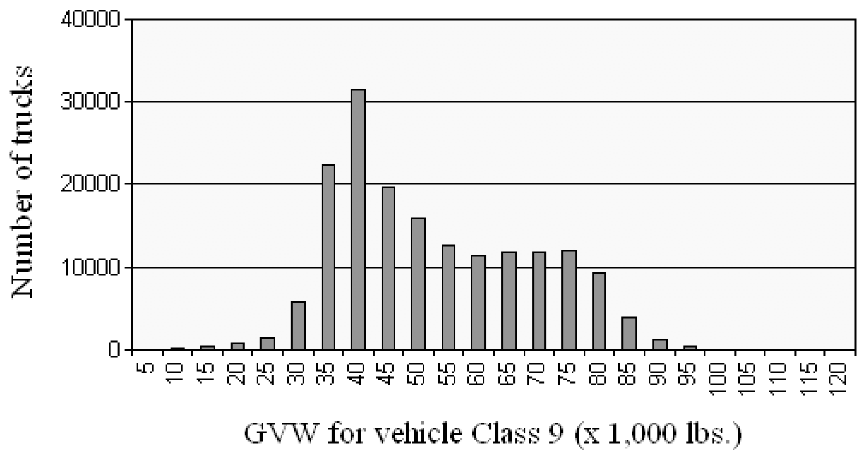


Figure 6-12. Yearly GVW distributions for Class 9 vehicles (Station P6N-2002)

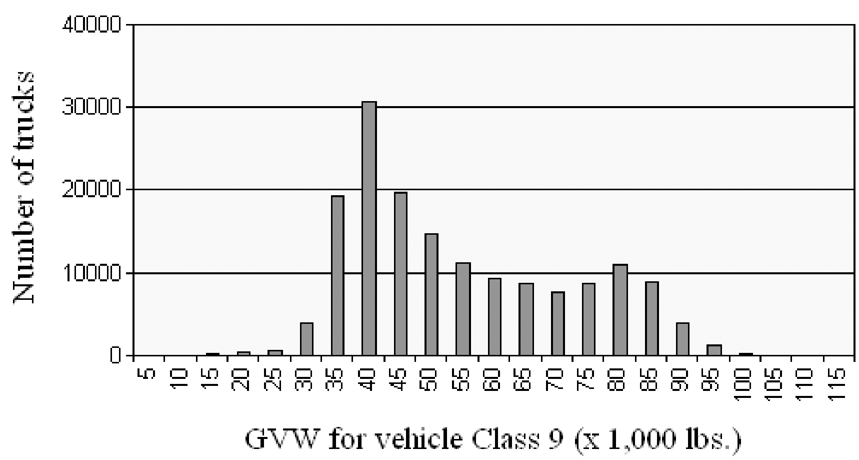


Figure 6-13. Yearly GVW distributions for Class 9 vehicles (Station P1N-2002)

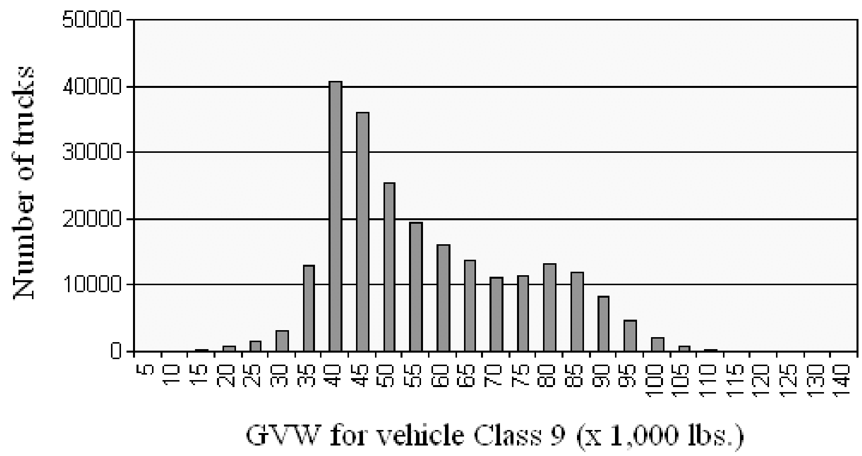


Figure 6-14. Yearly GVW distributions for Class 9 vehicles (Station P6S-2000)

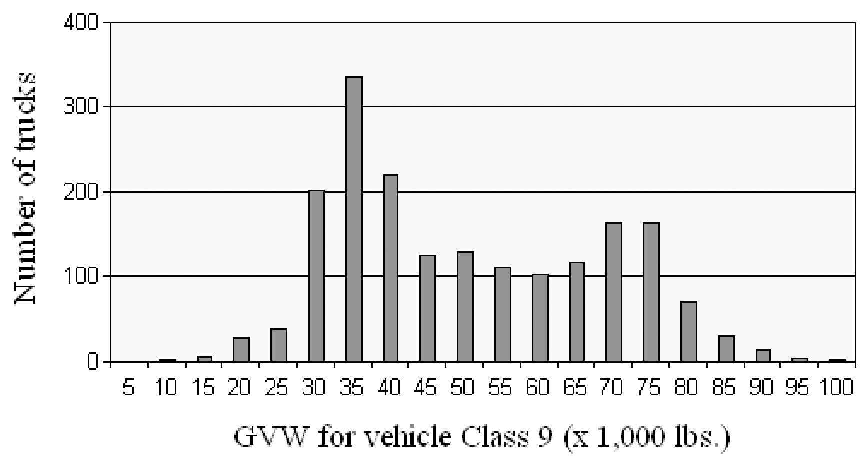


Figure 6-15. Yearly GVW distributions for Class 9 vehicles (Station P18-SB-2002)

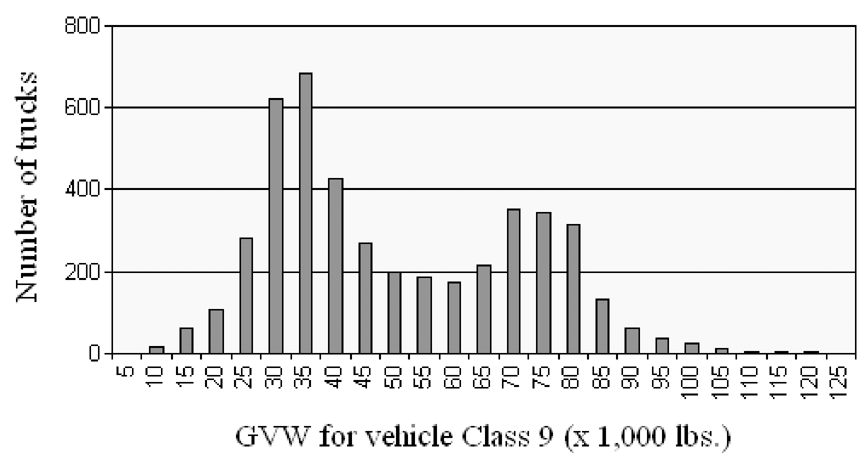


Figure 6-16. Yearly GVW distributions for Class 9 vehicles (Station P18-NB-2002)

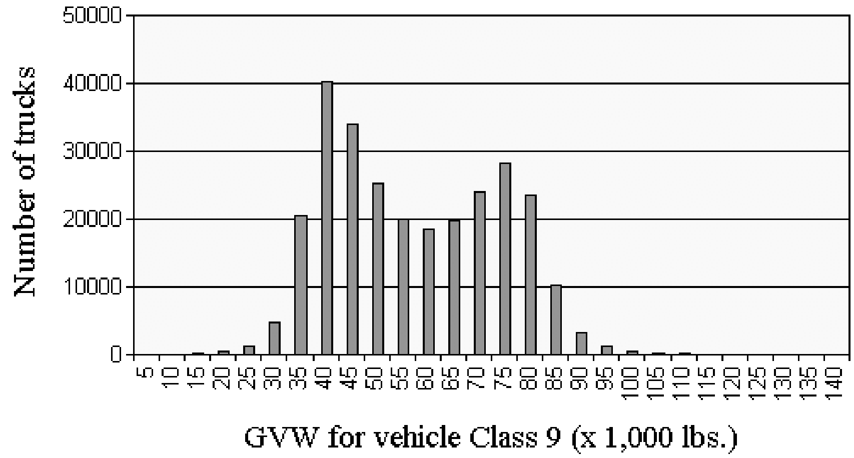


Figure 6-17. Yearly GVW distributions for Class 9 vehicles (Station P1S-2000)

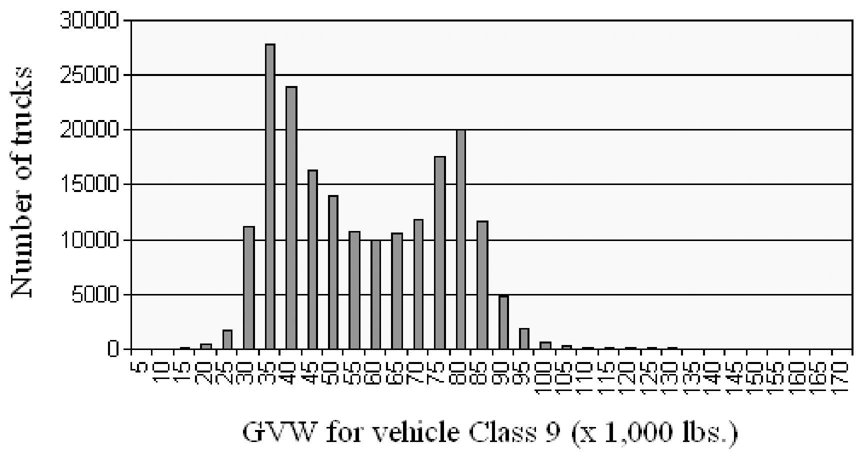


Figure 6-18. Yearly GVW distributions for Class 9 vehicles (Station P3S-2001)

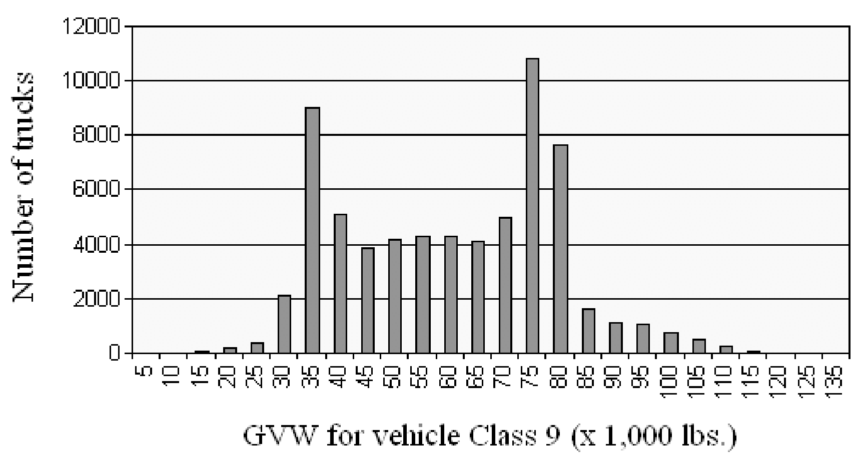


Figure 6-19. Yearly GVW distributions for Class 9 vehicles (Station B03-NB-2002)

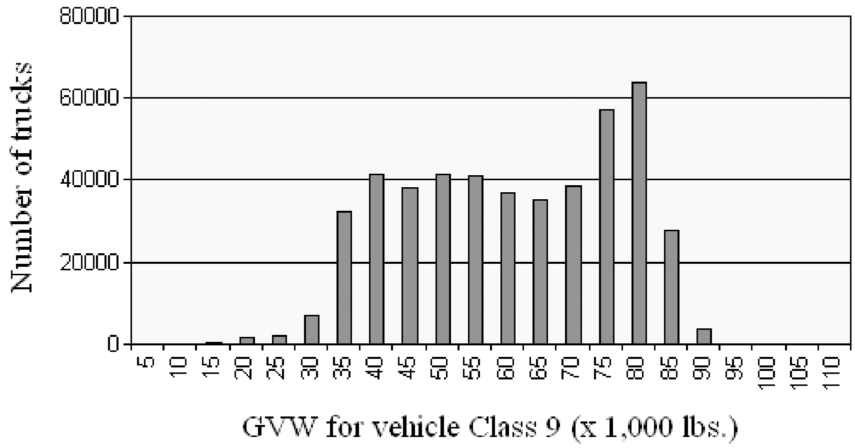


Figure 6-20. Yearly GVW distributions for Class 9 vehicles (Station P4N-2002)

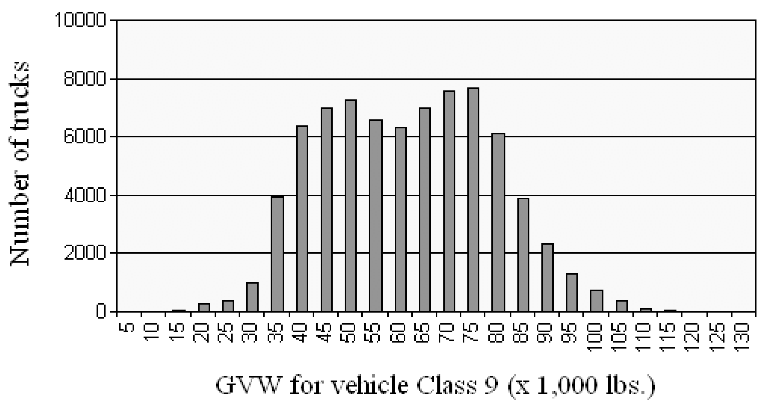


Figure 6-21. Yearly GVW distributions for Class 9 vehicles (Station P04-NB-2001)

SPECTRA DEVELOPMENT

As discussed above, all selected WIM stations, except for Station P04 (NB), could be treated as samples from a single population with consistent GVW peak values and varying percentages of empty and fully loaded trucks. However, the preceding analyses were based on Class 9 vehicles because of their fairly consistent loading pattern. Replicating such analyses for the remaining vehicle classes is not recommended because of their lack of consistency. Instead, either the most conservative load spectra or the average load spectra should be used. As a result, the developed load spectra for each vehicle class should be based on actual data from the selected WIM stations. The following alternatives are proposed:

1. Develop the load spectra with data from the station that possesses the greatest percentage of heavy tandem axles (i.e., 30- to 34-kip tandem axles associated with fully loaded Class 9 vehicles) among all evaluated WIM stations (e.g., Station P4N) (see Figure 6-22).

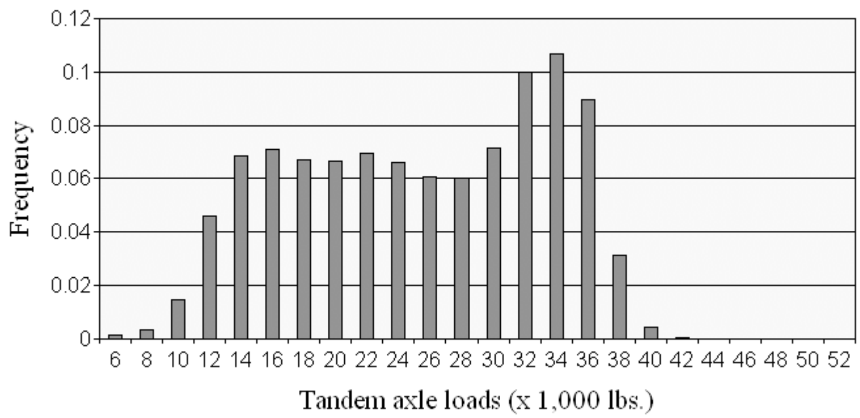


Figure 6-22. Tandem axle load spectrum for Class 9 vehicles (Station P4N-2002)

2. Develop the load spectra with data from a station that has a slightly greater percentage of light axles (i.e., 14- to16-kip axles associated with empty Class 9 vehicles) than heavy axles associated with fully loaded Class 9 vehicles (e.g., Station P1S) (see Figure 6-23). The majority of evaluated WIM stations had a greater percentage of light axles (see Appendix C).

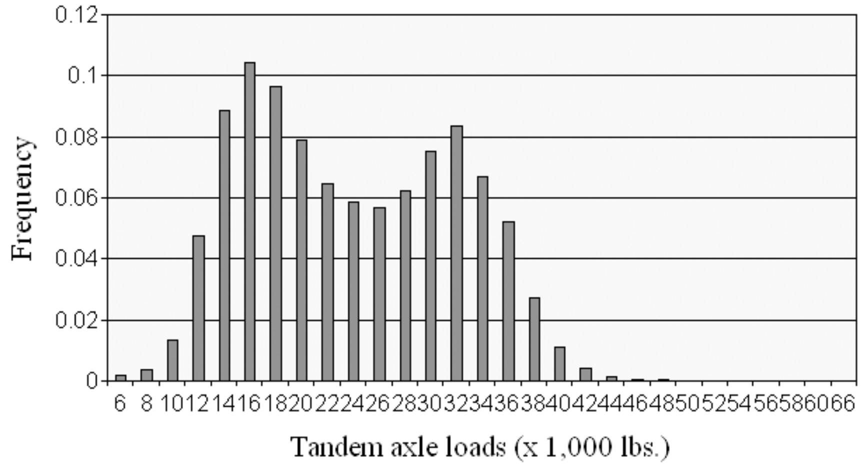


Figure 6-23. Tandem axle load spectrum for Class 9 vehicles (Station P1S-2002)

<u>Single Axles</u>

The most predominant truck axles per vehicle class were

- single axles associated with vehicle classes 5 and 9 (see figures 6-24 and 6-25)
- tandem axles associated with vehicle classes 9, 10, and 13 (see figures 6-32 and 6-33).
- tridem axles associated with vehicle classes 10, and 13 (see figures 6-42 and 6-43).

Therefore, the next section discusses vehicle classes 4 through 13, with added emphasis on the primary vehicle classes related to single, tandem, and tridem axles. The analyses include the number of axles associated with each vehicle class. However, to simplify the comparisons, the load spectra for each vehicle class are shown with frequencies of axle weights.

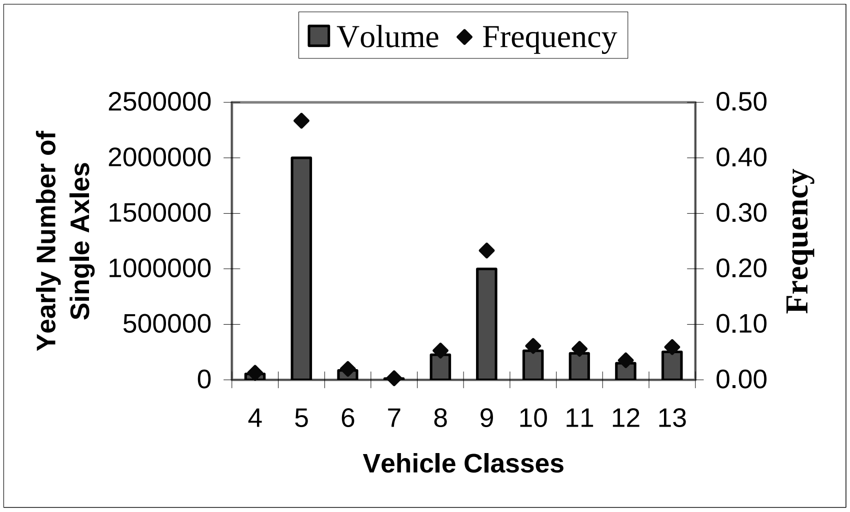


Figure 6-24. Yearly single axles per vehicle class (Station P4N-2002)

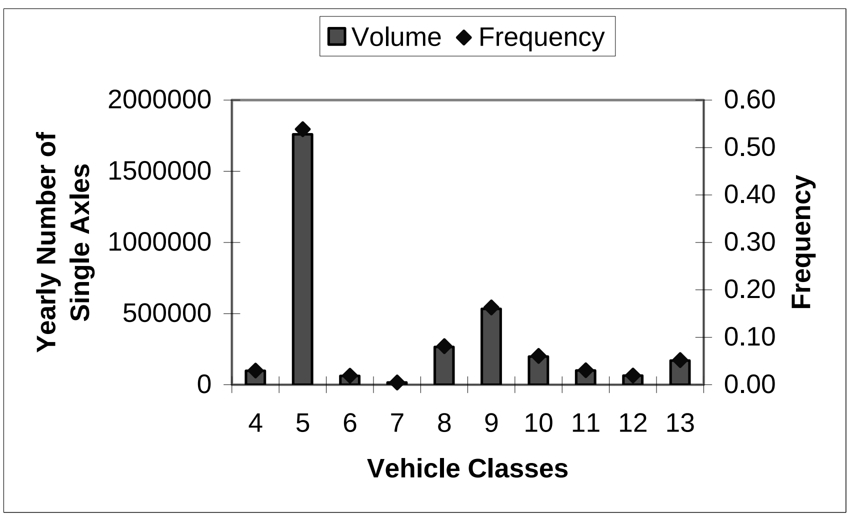


Figure 6-25. Yearly single axles per vehicle class (Station P1S-2000)

The combined single axle load spectra for vehicle classes 4 through 13, shown in figures 6-26 and 6-27 for stations P4N and P1S, were similar with respect to their predominant axle weights (i.e., 3 to 4 kips and 9 to 11 kips). These predominant weights were attributed primarily to vehicle classes 5 and 9, respectively (see figures 6-28 through 6-31). The load spectra for each vehicle class associated with stations P4N and P1S were also compared. Figures 6-28 through 6-31 show that the load spectra for both stations, and for vehicle classes 5 and 9, were similar. The percentages of their predominant weights differed slightly; however, their overall distribution shapes were similar. In addition, comparing the remaining vehicle classes (in Appendix D) associated with both stations resulted in similar load spectra. Therefore, it was concluded that the use of either of the two stations would result in similar single axle load spectra for all vehicle classes.

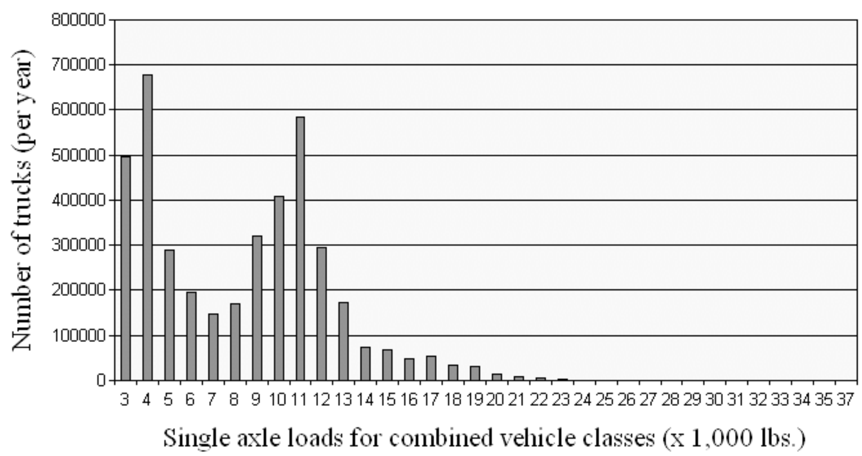


Figure 6-26. Single axle load spectrum for combined vehicle classes (Station P4N-2002)

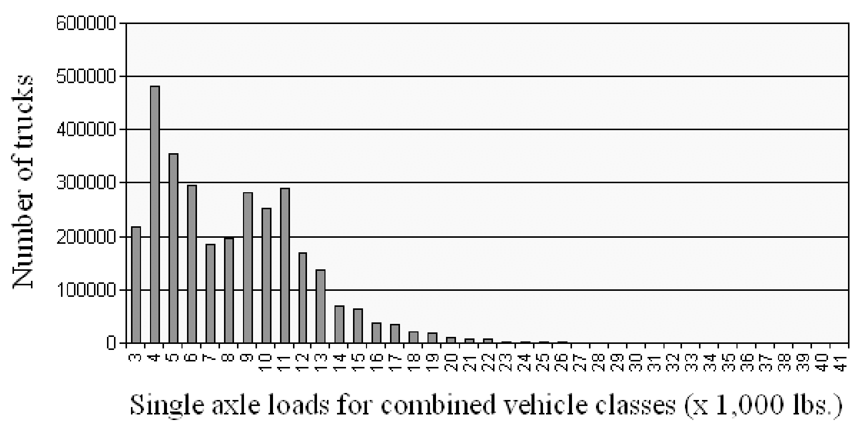


Figure 6-27. Single axle load spectrum for combined vehicle classes (Station P1S-2000)

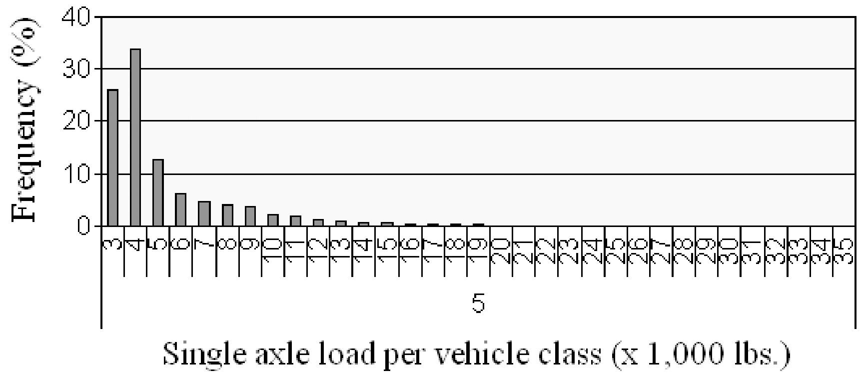


Figure 6-28. Single axle load spectrum for Class 5 vehicles (Station P4N-2002)

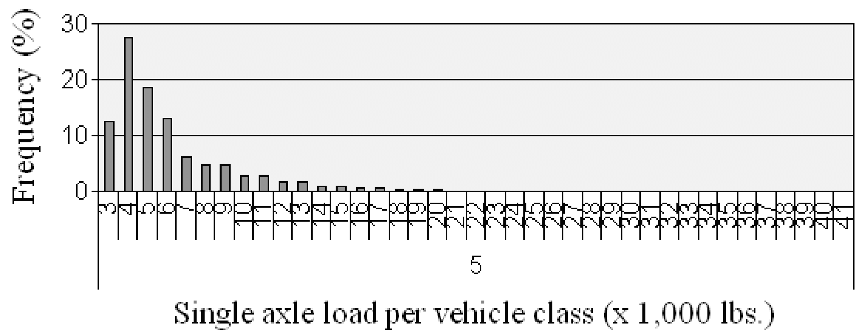


Figure 6-29. Single axle load spectrum for Class 5 vehicles (Station P1S-2000)

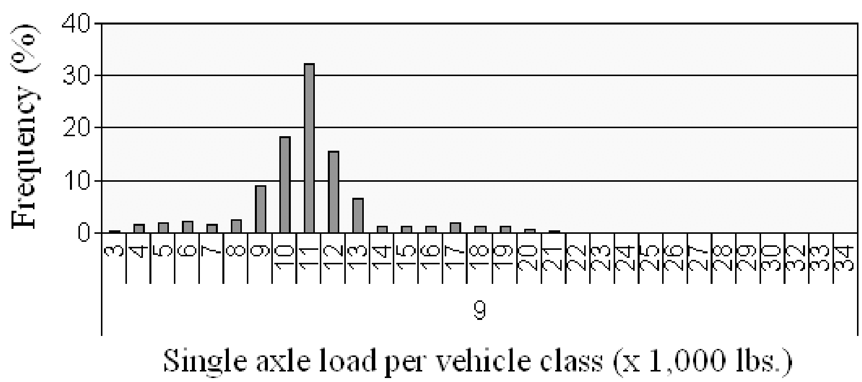


Figure 6-30. Single axle load spectrum for Class 9 vehicles (Station P4N-2002)

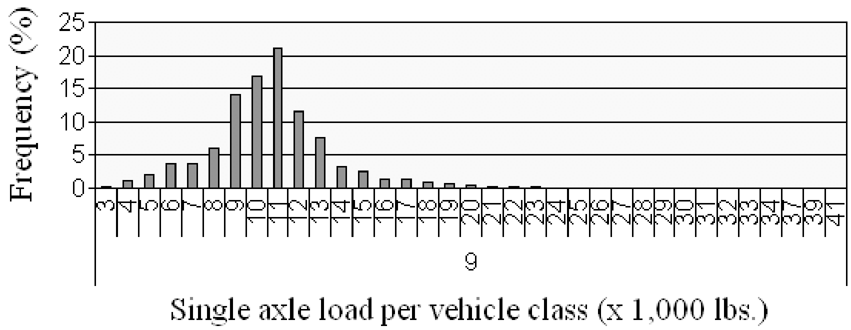


Figure 6-31. Single axle load spectrum for Class 9 vehicles (Station P1S-2000)

Tandem Axles

The majority of tandem axles (i.e., 60 to 70 percent) in stations P4N and P1S were associated with Class 9 vehicles (see figures 6-32 and 6-33). Therefore, the combined tandem axle load spectra for vehicle classes 4 through 13, shown in figures 6-34 and 6-35, were significantly influenced by the load spectra for Class 9 vehicles. As noted earlier, the tandem axle load spectrum for Class 9 vehicles and Station P4N had a greater percentage of heavier axles (i.e., 30 to 34 kips associated with fully loaded trucks) than light axles (i.e., 14 to16 kips associated with empty trucks), and vice versa for Station P1S (see figures 6-36 and 6-37).

Vehicle classes 10 and 13 occupied second and third position for tandem axles (see figures 6-32 and 6-33). The tandem axle load spectra associated with these vehicle classes did not exhibit the same pattern as that exhibited by Class 9 vehicles (i.e., the percentage of heavy axles was greater than light axles for Station P4N and vice versa for Station P1S). Nonetheless, Station P4N had a greater percentage of heavier axles for both vehicle classes than Station P1S (see figures 6-38 through 41).

The evaluations of vehicle classes 8 and 12 also showed that Station P4N had a greater percentage of heavier axles than Station P1S (see Appendix D). However, the load spectra associated with the remaining vehicle classes were similar for both stations (see Appendix D).

Thus, in contrast to the conclusions for single axles, it was concluded that the use of Station P4N would result in significantly heavier tandem axle load spectra associated with the predominant vehicle classes.

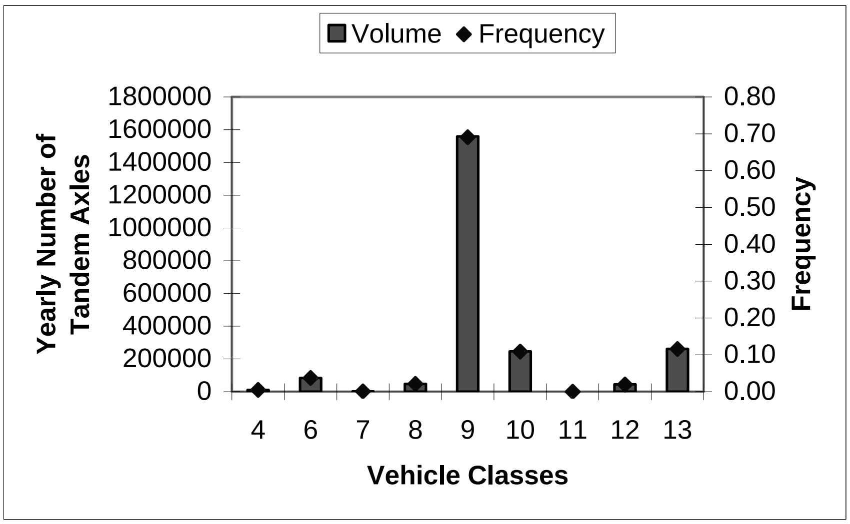


Figure 6-32. Yearly tandem axles per vehicle class (Station P4N-2002)

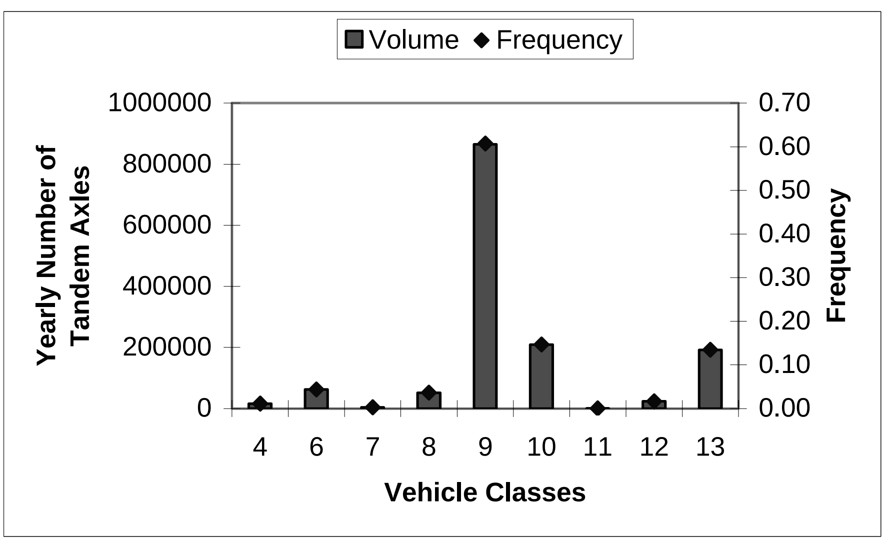


Figure 6-33. Yearly tandem axles per vehicle class (Station P1S-2000)

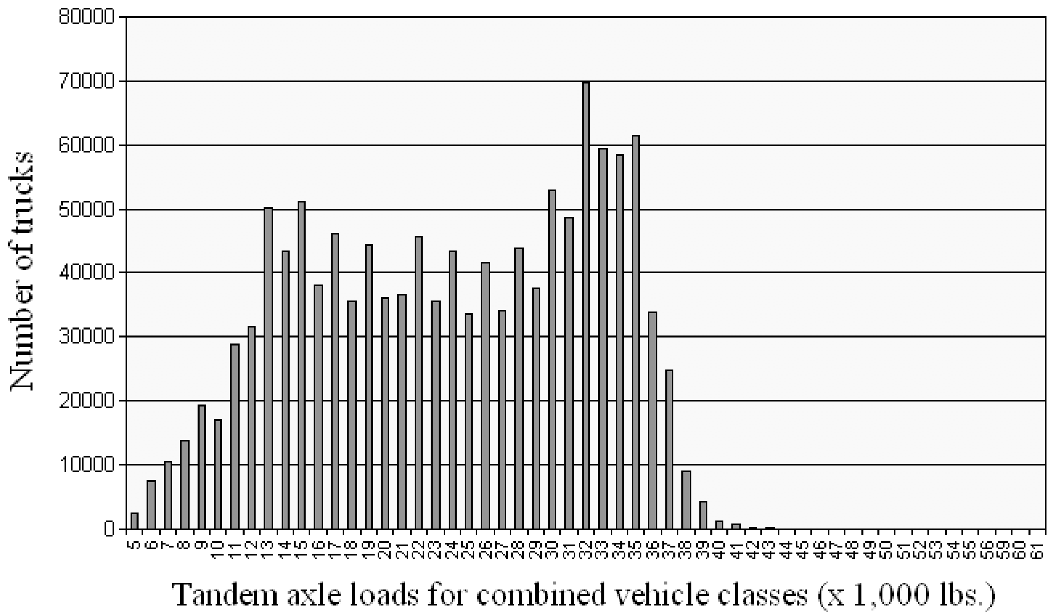


Figure 6-34. Tandem axle load spectrum for combined vehicle classes (Station P4N-2002)

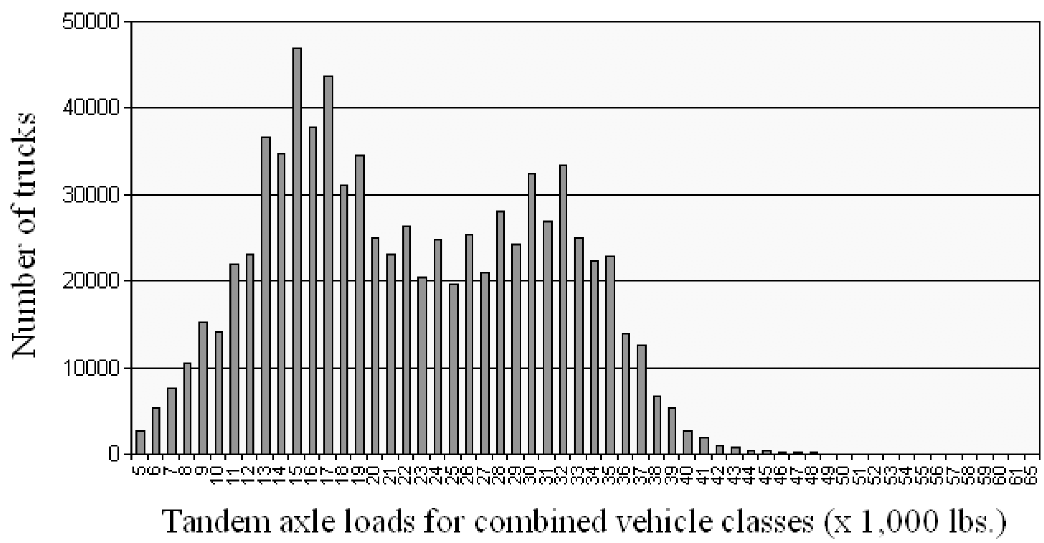


Figure 6-35. Tandem axle load spectrum for combined vehicle classes (Station P1S-2000)

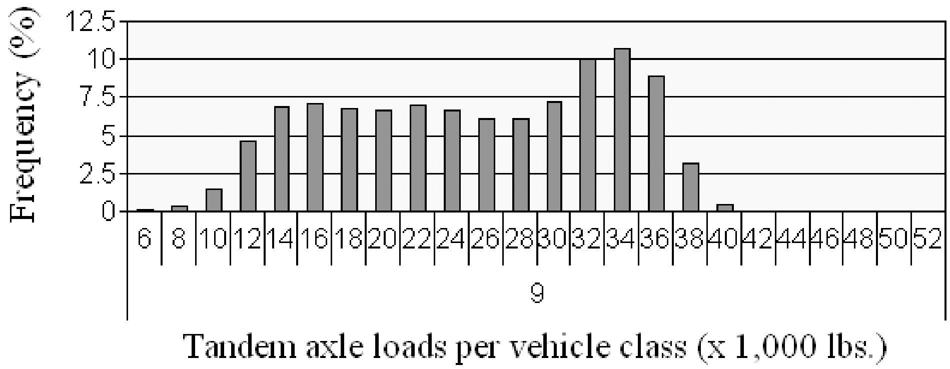


Figure 6-36. Tandem axle load spectrum for Class 9 vehicles (Station P4N-2002)

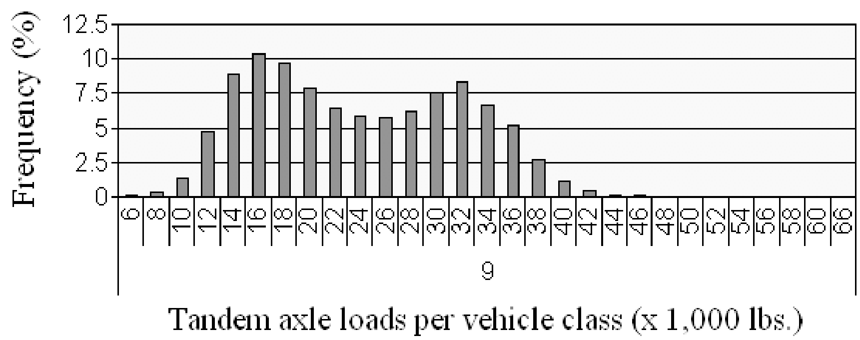


Figure 6-37. Tandem axle load spectrum for Class 9 vehicles (Station P1S-2000)

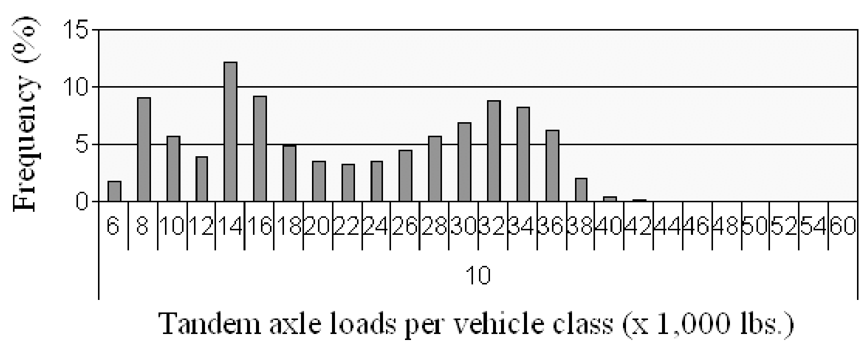


Figure 6-38. Tandem axle load spectrum for Class 10 vehicle (Station P4N-2002)

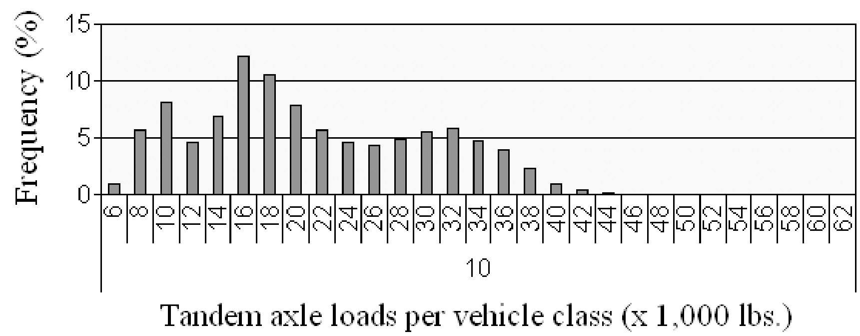


Figure 6-39. Tandem axle load spectrum for Class 10 vehicle (Station P1S-2000)

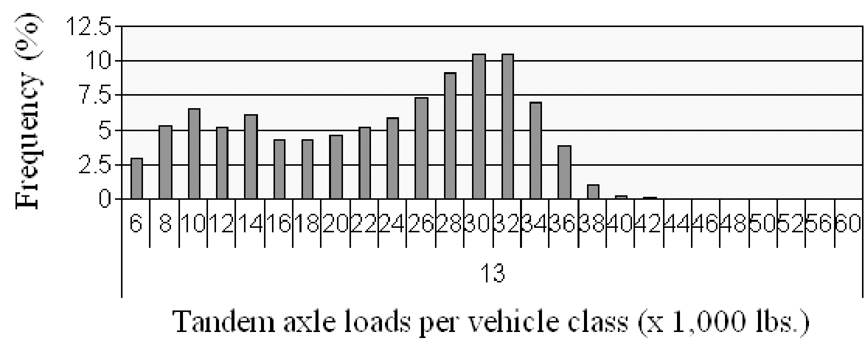


Figure 6-40 Tandem axle load spectrum for Class 13 vehicle (Station P4N-2002)

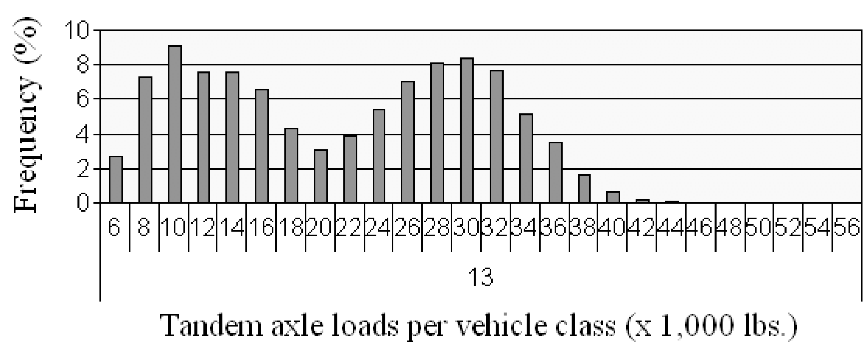


Figure 6-41. Tandem axle load spectrum for Class 13 vehicle (Station P1S-2000)

Tridem Axles

The percentages of tridem axles at stations P4N and P1S associated with vehicle classes 10 and 13 were approximately 70 percent and 20 percent of all vehicle classes, respectively (see figures 6-42 and 6-43). The tridem axle load spectrum for the combined vehicle classes in Station P4N had a greater percentage of heavier axles (i.e., 39 to 42 kips associated with fully loaded trucks) than light axles (i.e., 15 to 18 kips associated with empty trucks) (see Figure 6-44). In contrast, Station P1S has comparable percentages of heavy and light tridem axles (see Figure 6-45).

Like the tandem axle load spectra for Class 9 vehicles (see above), the tridem axle load spectra for Class 10 vehicles and Station P4N had a greater percentage of heavier axles than light axles, and vice versa for Station P1S (see figures 6-46 and 6-47, respectively). On the other hand, the load spectra for Class 13 vehicles were fairly similar, although Station P4N had a slightly greater percentage of heavier axles (see figures 6-48 and 6-49).

The remaining vehicle classes were also examined at both stations but were not significantly different (see Appendix D).

Thus, it was concluded that the use of Station P4N would result in significantly heavier tridem axle load spectra associated with Class 10 vehicles but would not significantly affect the load spectra of the remaining vehicle classes. When the tridem axle load spectra associated with Class 10 vehicles in all the WIM stations in Table 6-1 were compared, it was evident that Station P4N had the heaviest tridem axle load spectrum (see Appendix E).

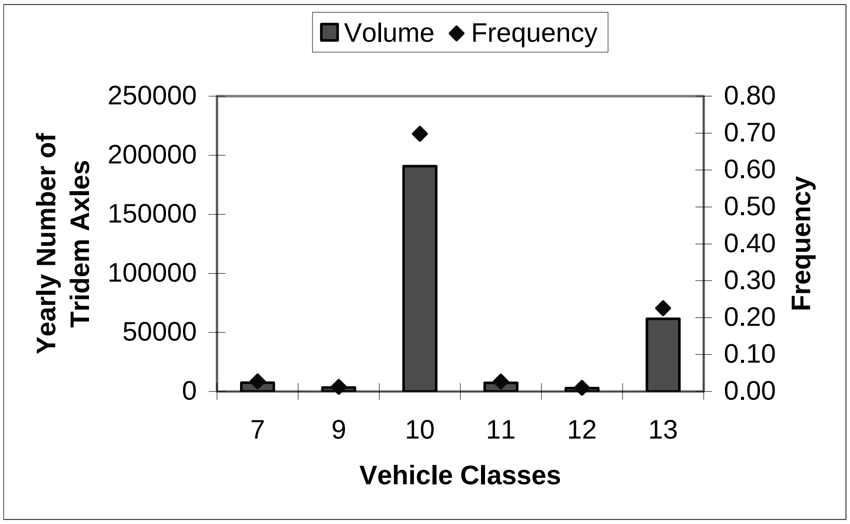


Figure 6-42. Yearly tridem axle count per vehicle class (Station P4N-2002)

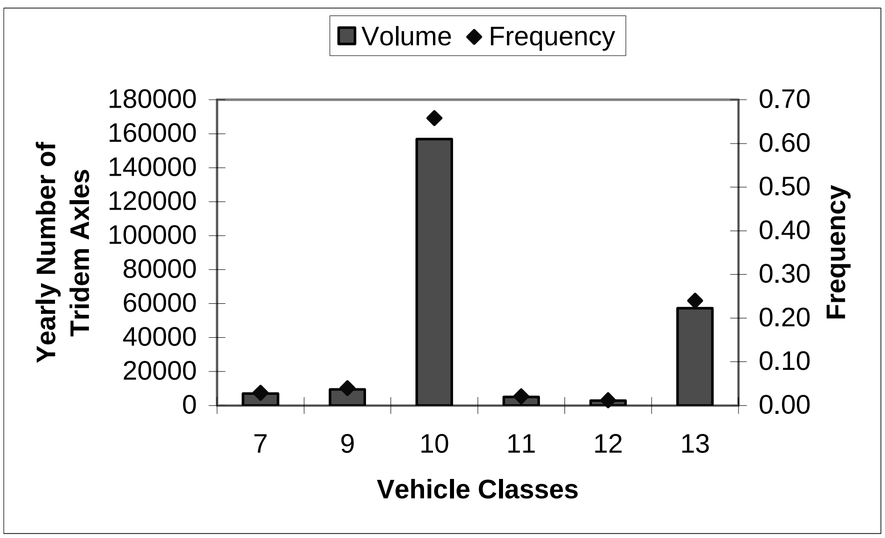


Figure 6-43. Yearly tridem axle count per vehicle class (Station P1S-2000)

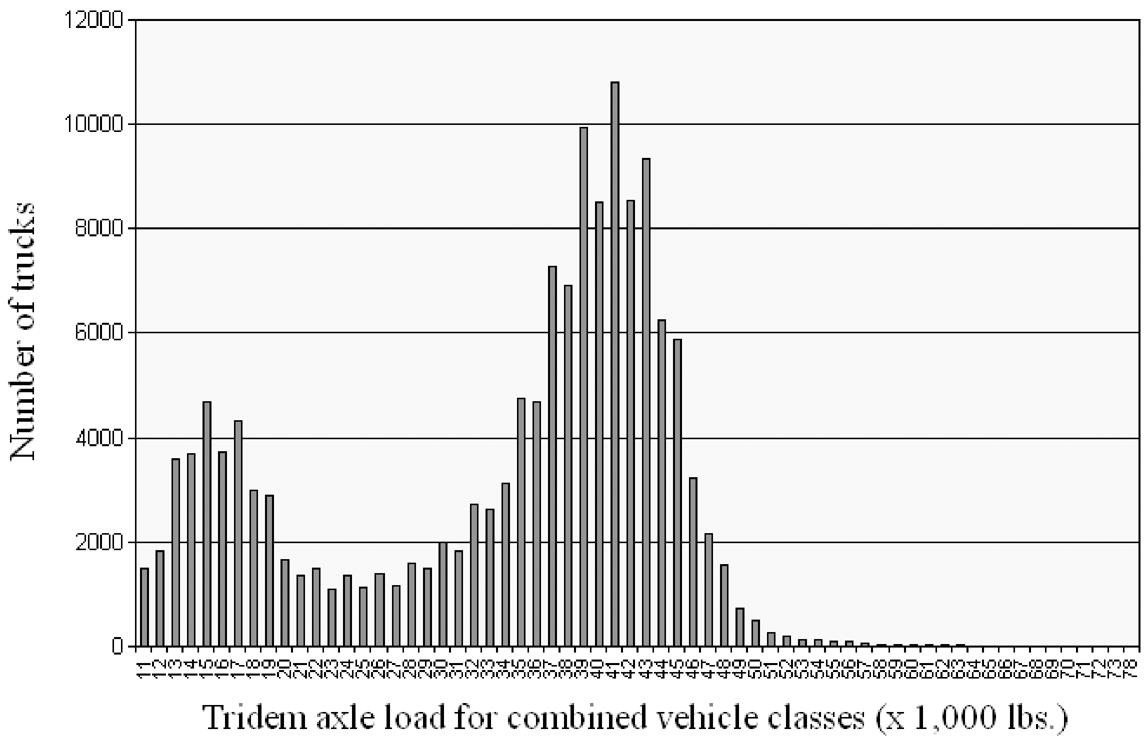


Figure 6-44. Tridem axle load spectrum for combined vehicle classes (Station P4N-2002)

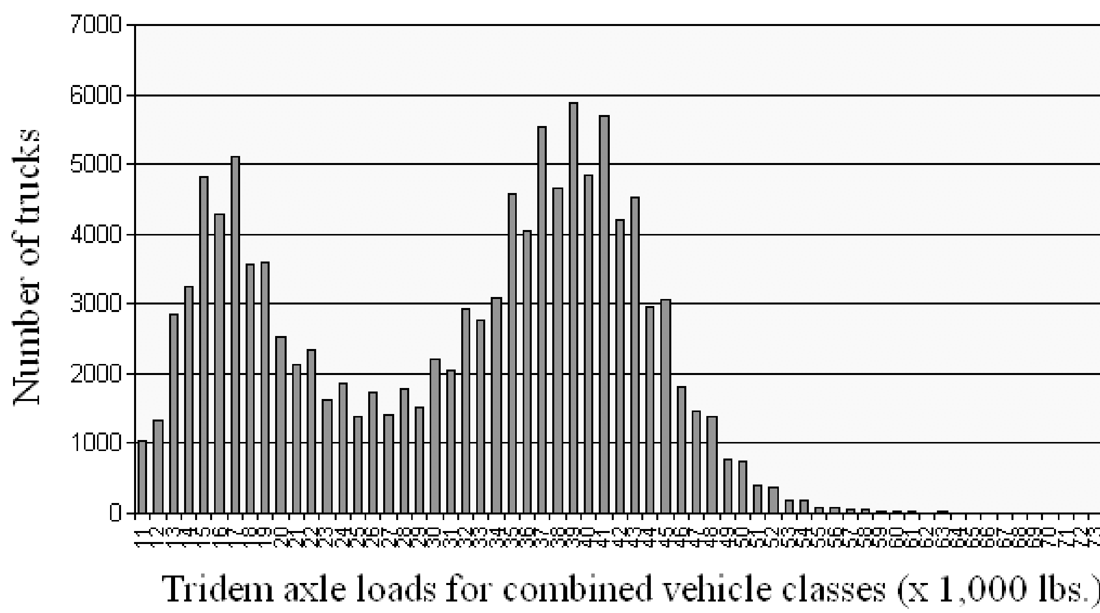


Figure 6-45. Tridem axle load spectrum for combined vehicle classes (Station P1S-2000)

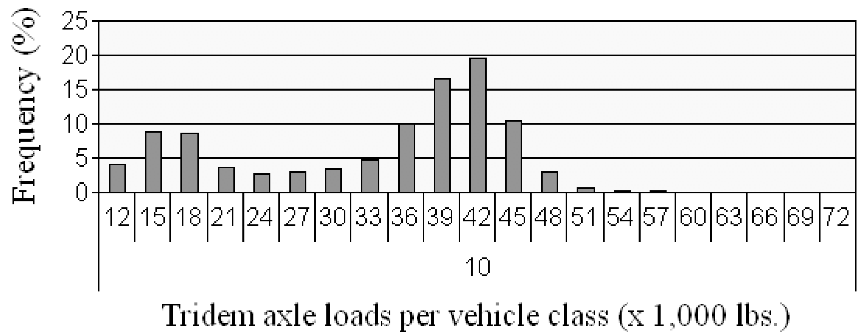


Figure 6-46. Tridem axle load spectrum for Class 10 vehicles (Station P4N-2002)

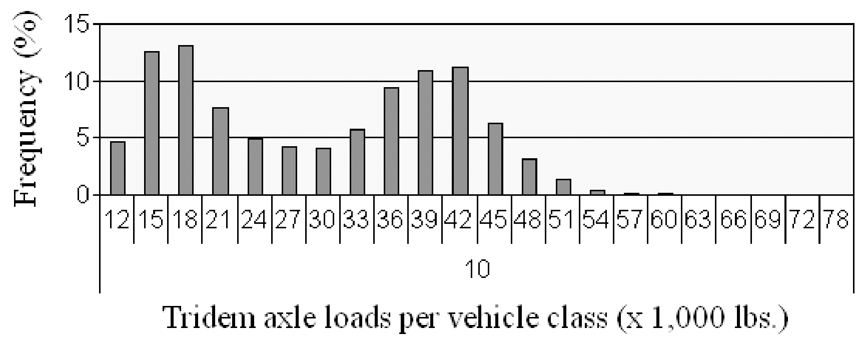


Figure 6-47. P1S Tridem axle load spectrum for Class 10 vehicles (Station P1S-2000)

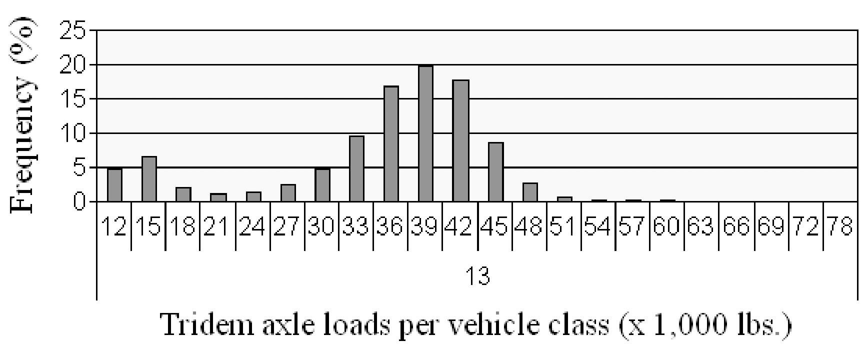


Figure 6-48. Tridem axle load spectrum for Class 13 vehicles (Station P4N-2002)

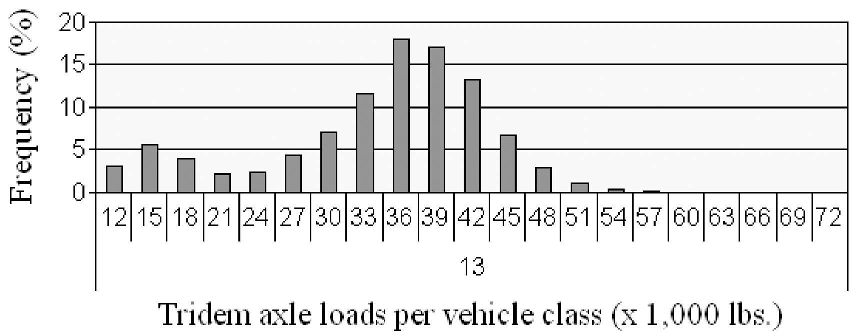


Figure 6-49. Tridem axle load spectrum for Class 13 vehicles (Station P1S-2000)

Load Spectra Development Preliminary Conclusions

The selected WIM stations were arranged in order of increasing number of fully loaded Class 9 vehicles and/or percentage of heavier tandem axles. In this arrangement, Station P4N had the most conservative tandem axle loads. The analyses described above compared stations P4N and P1S to determine whether this conclusion was equally valid for the remaining vehicle classes in conjunction with single, tandem, and tridem axles. The following conclusions were drawn:

- Stations P4N and P1S resulted in similar single load spectra for all vehicles classes. Therefore, it appears that single axle load spectra are not influenced by the tandem axle load spectrum for Class 9 vehicles.
- Station P4N had a greater percentage of heavier tandem axles associated with its most predominant vehicle classes than did Station P1S. Furthermore, Station P4N had the greatest percentage of heavier tandem axles among the selected WIM stations associated with Class 9 vehicles (60 to 70 percent of all tandem axle vehicles were Class 9 vehicles). For that reason, the initial conclusion, that Station P4N was the most conservative WIM station, appeared equally valid for the predominant vehicle classes associated with tandem axles.

- Of all the selected WIM stations, Station P4N had the greatest percentage of heavier tridem axles associated with it most predominant vehicle class (70 percent of all tridem axle vehicles were Class 10). Furthermore, Station P4N had a slightly greater percentage of heavier tridem axles for Class 13 vehicles (20 percent of all tridem axles vehicles were Class 13) than did Station P1S. Thus, the selected order of WIM stations—which resulted in Station P4N being the most conservative—appeared equally valid for the predominant vehicle classes associated with tridem axles.

Therefore, the use of Station P4N is recommended to produce the most conservative load spectra for tandem and tridem axles for their predominant vehicle classes.

RESULT VALIDATION

To assure the validity of the developed load spectra, they were compared with load spectra from [1] the *2002 Design Guide* defaults and [2] the Minnesota Department of Transportation Office of Material and Road Research (MnROAD). In addition, the ESALs associated with the developed load spectra were compared with WSDOT's 1993 ESALs.

The comparisons associated with the *2002 Design Guide* defaults focused on the predominant vehicles classes for single axles (i.e., classes 5 and 9), tandem axles (i.e., Class 9), and tridem axles (i.e., Class 10).

The MnROAD load spectra were developed for combined vehicle classes for steering axles and tandem axles. Therefore, the MnROAD steering axle load spectrum were compared with the single axle load spectrum developed for combined vehicle classes.

2002 Design Guide Defaults

Single Axles

The overall spectrum shapes of the *2002 Design Guide* defaults and the developed load spectra for Class 5 vehicles are somewhat comparable (see figures 6-50 and 6-51). Although the majority of axles in both distributions weigh 3 to 5 kips, there is a major difference in the percentages of the 3- and 4-kip axle weights. However, the pavement damage associated with these axle weights is minimal, so the difference may not be of great significance. In contrast, although the *2002 Design Guide's* Class 9 vehicles' load spectra have a similar overall shape (see figures 6-52 and 6-53), the percentages of the predominant axle weights (i.e., 10 to 12 kips) differ only slightly.

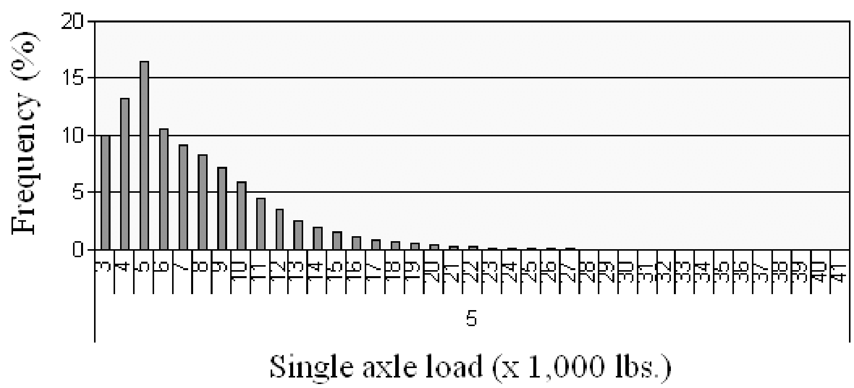


Figure 6-50. Single axle load spectrum for Class 5 vehicles (2002 DESIGN GUIDE)

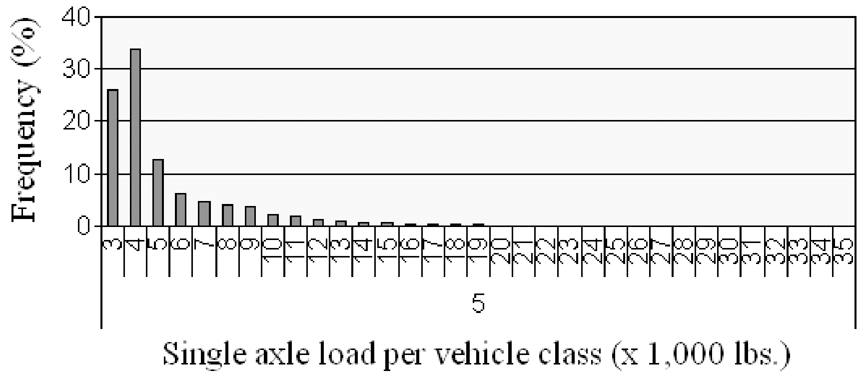


Figure 6-51. Single axle load spectrum for Class 5 vehicles (Station P4N-2002)

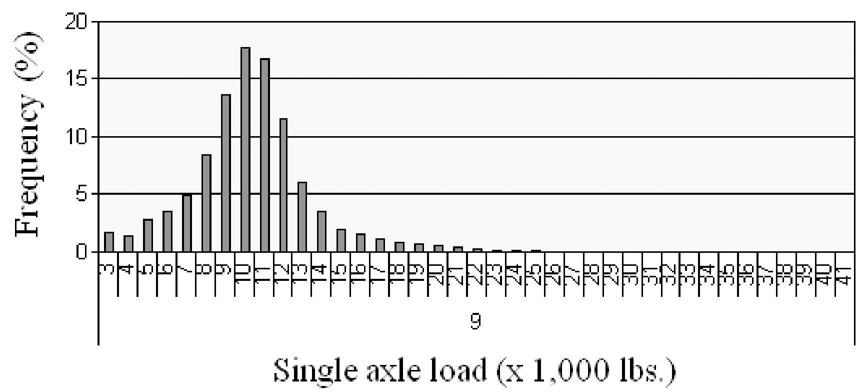


Figure 6-52. Single axle load spectrum for Class 9 vehicles (2002 DESIGN GUIDE)

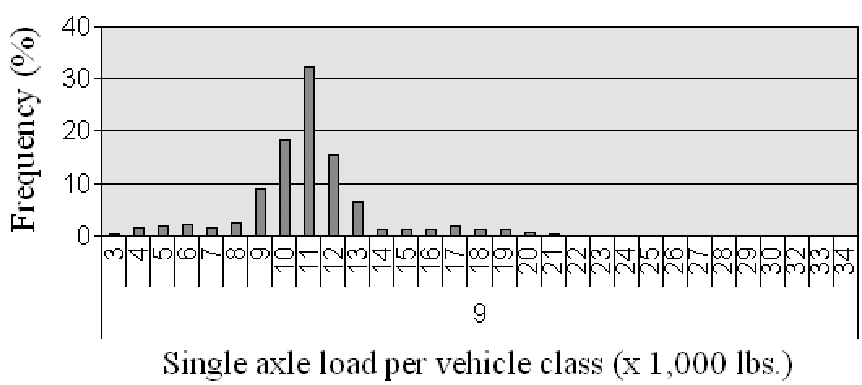


Figure 6-53. Single axle load spectrum for Class 9 vehicles (Station P4N-2002)

Tandem Axles

The *2002 Design Guide* defaults and the developed load spectra for Class 9 vehicles are shown in figures 6-54 and 6-55, respectively. The *2002 Design Guide* default spectrum is similar to the spectrum associated with Station P1S (see above and Figure 6-56). Thus, the *Design Guide* and the developed load spectra have two peaks at 14 to16 kips and 30 to 34 kips, which are associated with empty and fully loaded trucks. However, the developed load spectrum has a greater percentage of heavier axles than light axles, whereas the *2002 Design Guide* default spectrum has a greater percentage of light axles.

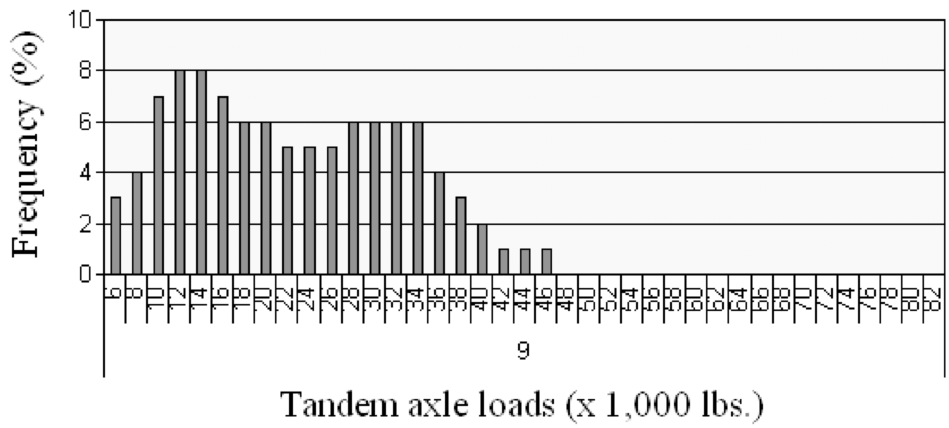


Figure 6-54. Tandem axle load spectrum for Class 9 vehicles (2002 DESIGN GUIDE)

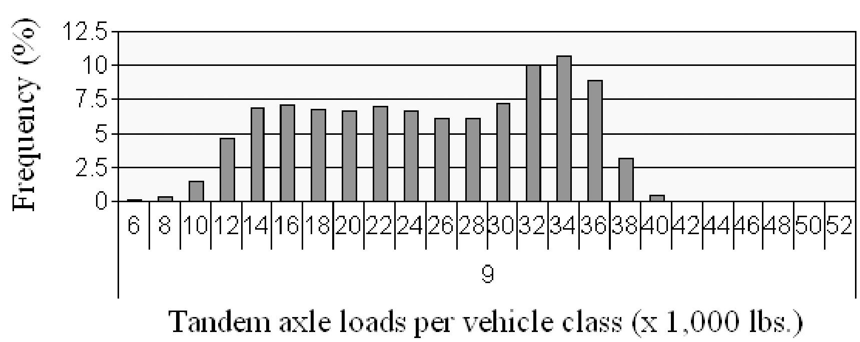


Figure 6-55. Tandem axle load spectrum for Class 9 vehicles (Station P4N-2002)

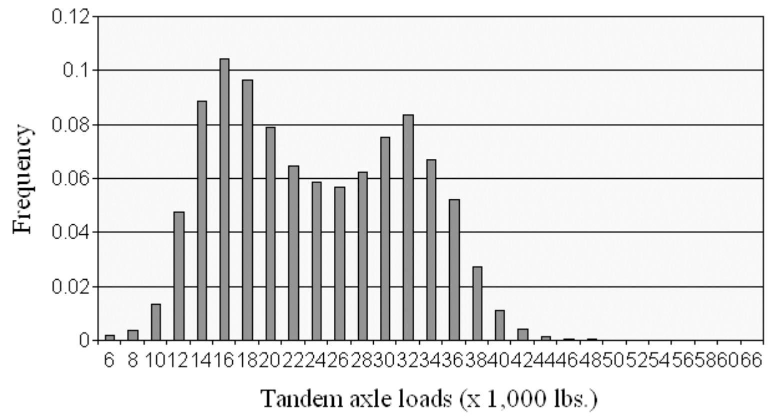


Figure 6-56. Tandem axle load spectrum for Class 9 vehicles (Station P1S-2002)

Tridem Axles

The *2002 Design Guide* default and the developed load spectra for Class 10 vehicles are shown in figures 6-57 and 6-58. Like the tandem axle load spectra comparison, the *Design Guide* and the developed load spectra have two peaks at 12 to 15 kips and 39 to 42 kips, each associated with empty and fully loaded trucks. However, the developed load spectrum has more heavier axles than light axles, whereas the *2002 Design Guide* default spectrum has more light axles. However, note that the *2002 Design Guide* defaults have some extremely heavy tridem axles (up to 81,000 lbs), whereas the developed load spectra do not. This needs further assessment.

The *2002 Design Guide* default and the developed load spectra, for Class 13 vehicles are shown in figures 6-59 and 6-60. The *2002 Design* Guide default spectrum for Class 13 vehicles is similar to that for Class 10 vehicles (see figures 6-57 and 6-59), as is the developed load spectrum for Class 13 vehicles and Class 10 vehicles (see figures 6-58 and 6-60). The conclusion pertaining to Class 10 vehicles is thus equally valid for Class 13 vehicles. However, the transitions between consecutive axle loads for the *2002 Design Guide* load spectrum are not as smooth as those for the developed load spectrum.

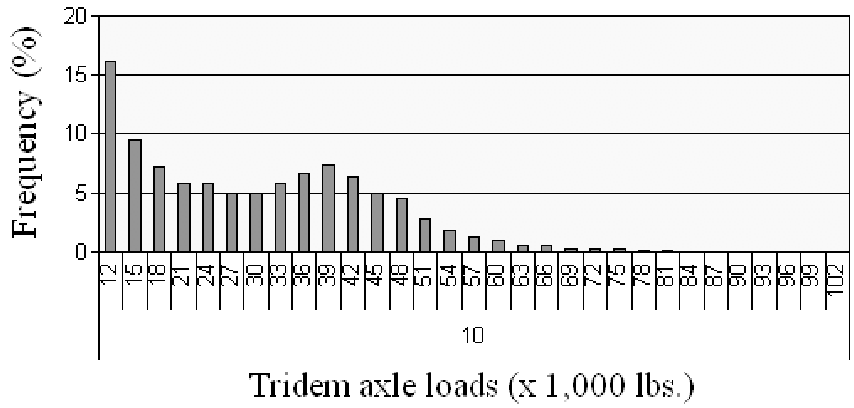


Figure 6-57. Tridem axle load spectrum for Class 10 vehicles (2002 DESIGN GUIDE)

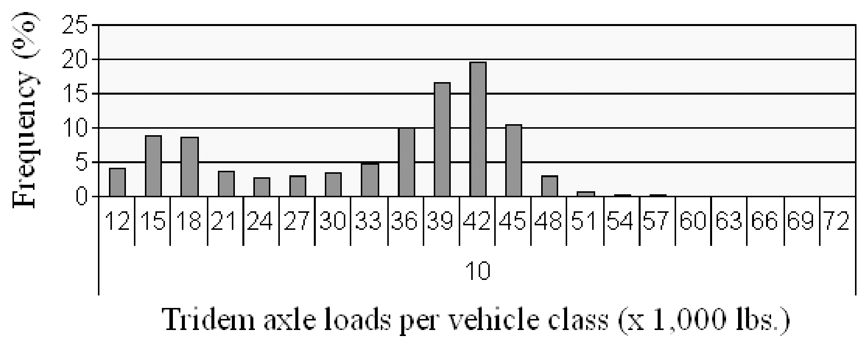


Figure 6-58. Tridem axle load spectrum for Class 10 vehicles (Station P4N-2002)

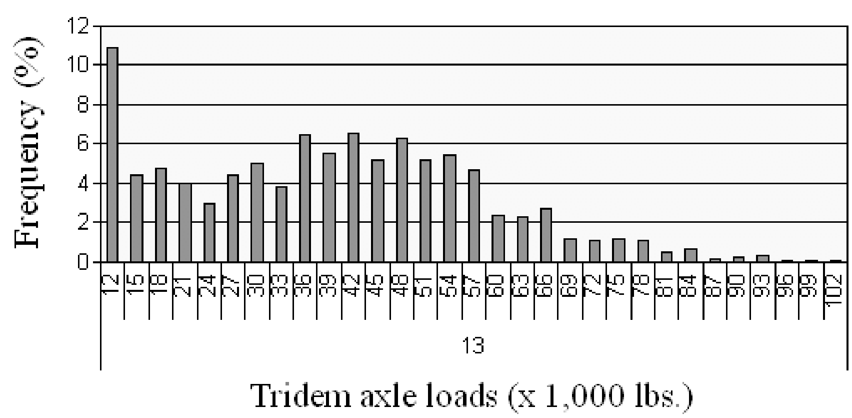


Figure 6-59. Tridem axle load spectrum for Class 13 vehicles (2002 DESIGN GUIDE)

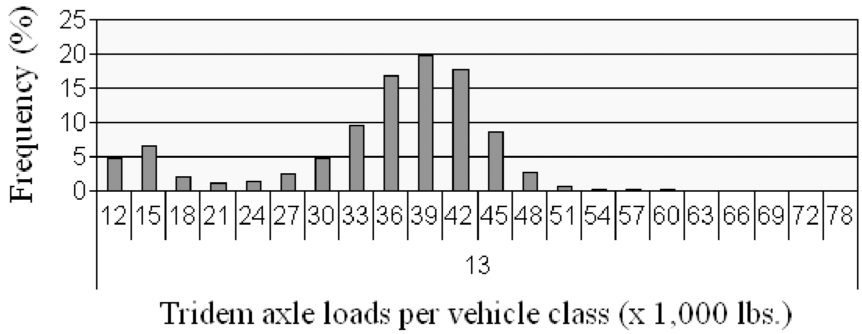


Figure 6-60. Tridem axle load spectrum for Class 13 vehicles (Station P4N-2002)

MnROAD Load Spectra

Single Axles

The MnROAD load spectra and the developed single axle load spectra for combined vehicle classes are shown in figures 6-61 and 6-62. The spectra are similar in having a load peak at 10 to 11 kips. Single axles associated with Class 5 vehicles principally weigh 3 to 4 kips. Therefore, the peak at 10 to 11 kips is associated with the remaining vehicle classes. Figure 6-61 shows that the MnROAD load spectrum has peaks at these approximate loads (i.e., 3 to 4 kips and 10 to 11 kips), but the percentage of Class 5 vehicles included in the MnROAD study appears to be significantly less than the percentage found at Station P4N.

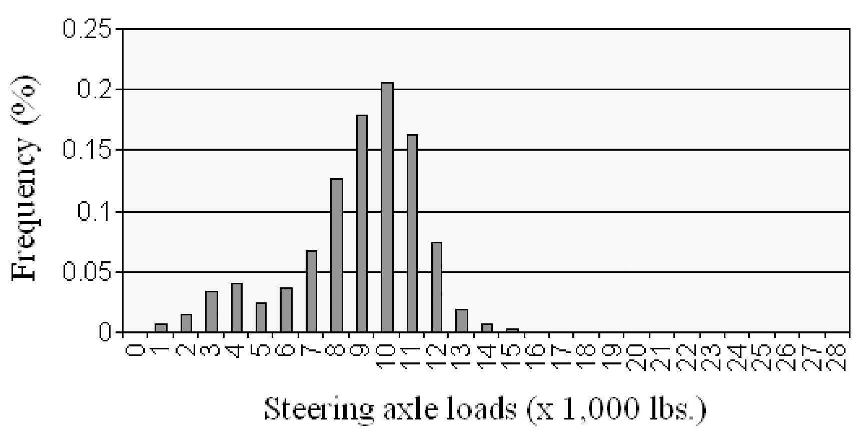


Figure 6-61. MnROAD steer axle load spectrum for combined vehicle classes

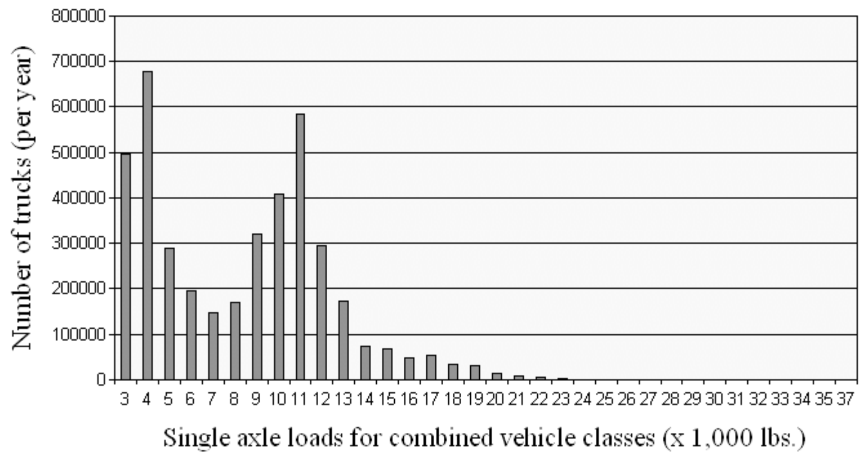


Figure 6-62. Single axle load spectrum for combined vehicle classes (Station P4N-2002)

Tandem Axles

The MnROAD load spectra and the developed tandem axle load spectra for the combined vehicle classes are shown in figures 6-63 and 6-64. The two spectra are similar in magnitude and the percentage of the peaks associated with empty and fully loaded trucks.

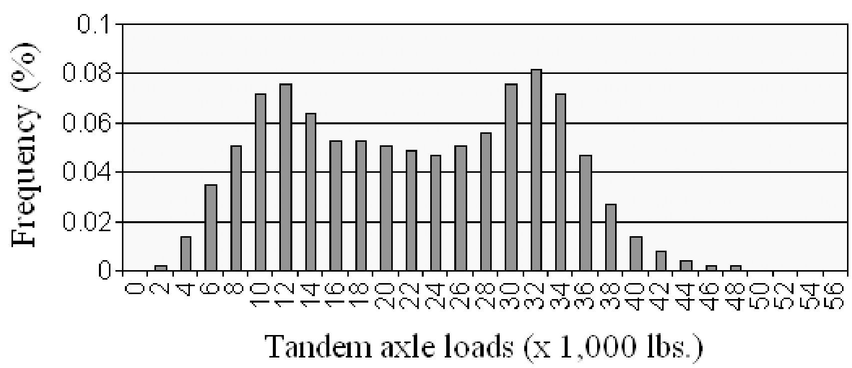


Figure 6-63. MnROAD tandem axle load spectrum for combined vehicle classes

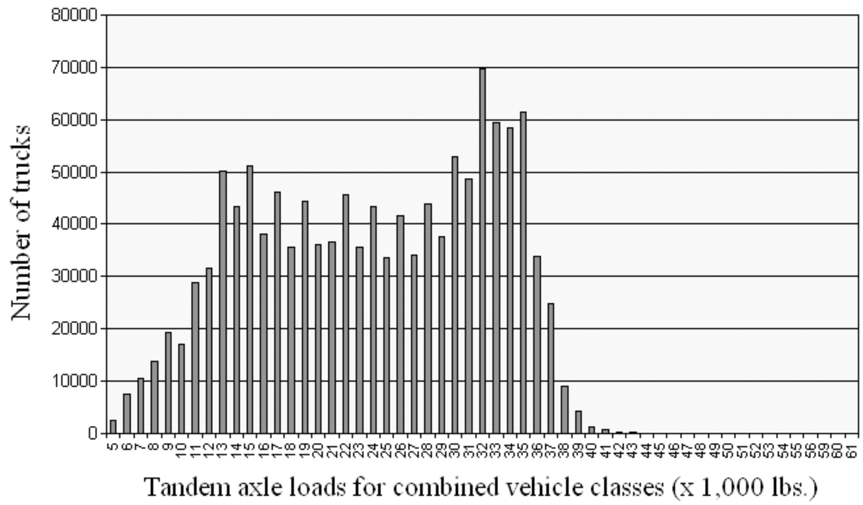


Figure 6-64. Tandem axle load spectrum for combined vehicle classes (Station P4N-2002)

ESALs

The average ESALs per axle per vehicle class associated with the developed load spectra are shown in tables 6-2 through 6-5. The single axle ESALs were obtained with the fourth power law, by dividing the single axle load spectra weights by 18 kips and raising the product to the fourth power. Consequently, the average ESALs are the sums of the product of the ESALs and their associated frequencies. The tandem and tridem ESALs were also calculated with the fourth power law. However, the tandem and tridem ESALs were obtained by dividing the tandem and tridem axle load spectra weights by 33.25 kips and 47.6 kips, respectively. The 33.25-kips and 47.6-kip values are the tandem and tridem axle weights that result in ESALs equal to 1. These ESALs were obtained with a Structural Number (SN) = 5 and Terminal Serviceability (p_t) = 2.5.

These average ESALs were compared with historical values developed in 1993 (Hallenbeck and Kim, 1993) (see Table 3-5). The average ESALs per vehicle class shown in Table 6-5 are the sums of the product of the *2002 Design Guide* default axles per vehicle class and the developed ESALs per axle (see Figure 6-65 and tables 6-2 through 6-4).

The developed ESALs are intended for agencies that do not use the *2002 Design Guide*. Table 6-5 shows a notable difference between the developed and historical average ESALs for vehicle classes 5, 7, 8, and 11. The historical and developed ESALs for the predominant vehicle classes associated with the tandem axles (i.e., classes 9, 10, and 13) and tridem axles (i.e., 10, and 13) are similar.

The conclusion is that the use of newly developed ESALs per vehicle will generally increase design ESALs. However, such an increase will be primarily due to the inclusion of less predominant vehicle classes (i.e., classes 4, 6, 7, 8, and 11).

Table 6-2. Average single axle average ESALs per vehicle class

Vehicle Class	Average ESAL
4	0.41
5	0.04
6	0.19
7	0.31
8	0.18
9	0.19
10	0.14
11	0.31
12	0.20
13	0.19

Table 6-3. Average tandem axle ESALs per vehicle class

Vehicle Class	Average ESAL
4	0.33
6	0.37
7	0.80
8	0.20
9	0.54
10	0.43
11	0.70
12	0.28
13	0.43

Table 6-4. Average tridem axle ESALs per vehicle class

Vehicle Class	Average ESAL
7	0.60
10	0.38
11	0.33
12	0.51
13	0.41

Table 6-5. Comparison of historical and developed ESALs per vehicle class

Vehicle Class	Developed average ESAL per vehicle Class	Historical average ESALs per vehicle Class*	Difference	% Difference
4	0.793	0.569	0.224	39
5	0.080	0.265	-0.185	-70
6	0.560	0.417	0.143	34
7	1.016**	0.417	0.599	144
8	0.562	0.304	0.258	85
9	1.257	1.2	0.057	5
10	0.974	0.932	0.042	4
11	1.532	0.816	0.716	88
12	1.054	1.061	-0.007	-1
13	1.468	1.39	0.078	6

* Hallenbeck and Kim (1993)
**1.016 = (1.0*0.31) + (0.26*0.8) + (0.83*0.6)

Number Axles/Truck | Axle Configuration | Wheelbase

	Single	Tandem	Tridem	Quad
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

Figure 6-65. 2002 Design Guide default number of axles per truck

Preliminary Conclusions: Comparisons with *Design Guide* and Minnesota Spectra

The developed load spectra, the MnROAD load spectra, and the *2002 Design Guide* spectra are similar in their overall location of peaks associated with empty and fully loaded trucks for the predominant vehicle classes for single, tandem and tridem axles. However, the percentages of axles within these peaks vary. Nonetheless, in most instances this variation is less than the variation among some of the selected WIM stations. Furthermore, the ESALs associated with the developed load spectra are similar to the historical ESALs for the predominant vehicle classes (i.e., classes 9, 10, and 13). The only exception is Class 5 vehicles, which have lower ESALs per vehicle.

Therefore, it is concluded that the developed load spectra are suitable. They are included in Appendix H.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The results of this study illustrate, to a certain extent, the significance of increased traffic data characterization on pavement design and performance enhancement. The project's objective was to develop load spectra for Washington State to be used with the *2002 Design Guide*. An examination of historical traffic data in Washington State (Chapter 3) resulted in the following conclusions:

- An analysis of historical ESALs (1960-1983) showed that
  - ESALs increased slightly throughout the years.
  - The increases in ESAL rates varied per vehicle class.
  - The increases in ESAL rates for the primary vehicle classes (i.e. classes 5, 9, 10, and multi trailers) on rural Interstate roadways appeared similar.
  - The increases in ESAL rates for the primary vehicle classes on urban Interstate roadways were more variable.
- An analysis of ESALs from WIM sites (1993) showed that
  - ESALs for vehicle classes 4 through 7 were consistent throughout the year.
  - ESALs for remaining vehicle classes changed in some months or seasons.

Before the load spectra could be developed, criteria for the selection and exclusion of WIM data were required. Consequently, ESAL analyses, and sensitivity and statistical testing (Chapter 5) were conducted with [1] extremely overestimated, [2] extremely underestimated, [3] ideal, and [4] slightly underestimated load spectra. The tests resulted in the following conclusions:

- ESAL analysis: ESALs associated with the five load spectra were within an order of two of the ideal station (Station P4N). Doubling the ESALs typically resulted in an increased pavement thickness equal to 1 inch or less. Therefore, the difference would have relatively modest impact on pavement design.
- A sensitivity analysis of the *2002 Design Guide* resulted in the following conclusions:
  - Utilizing significantly underestimated or overestimated load spectra yields rehabilitation trigger points within 5 to 7 years of the ideal load spectra.
  - Utilizing slightly underestimated load spectra yields rehabilitation trigger points within 2.5 to 4 years of the ideal load spectra.
  - The *2002 Design Guide* is especially sensitive to extreme load spectra (i.e., significantly underestimated or overestimated) and is moderately sensitive to slightly underestimated load spectra.
- Statistical analyses: Statistical testing may not be used to determine whether two load spectra are significantly different. It is recommended that methods or criteria other than statistics be used.

Because of these findings, the criteria for developing the load spectra were based solely on the sensitivity of the *2002 Design Guide*. Consequently, WIM sites with significantly and slightly underestimated and/or overestimated GVW distributions were excluded.

Fifty-two WIM sites were evaluated (Chapter 5) with the following results:

- Eleven out of 52 WIM stations possessed valid weight data, distributed as follows:

    - 8 out of 24 in Western Washington
    - 2 out 26 in Eastern Washington
    - 1 out of 2 in the Olympic Peninsula.
- Selected “valid” stations in Eastern Washington had the lowest number of valid months.

Analysis of the selected “valid” WIM stations (Chapter 6) resulted in the following conclusions:

- There are no significant seasonal variations. Consequently, ESALs throughout the year are constant.
- The consolidation of monthly GVW distributions into a yearly distribution is valid.
- The exclusion of invalid months will either improve the quality of analyzed data or maintain their preexisting condition.
- There are no evident trends that distinguish roadways with respect to
    - geographic location
    - urban versus rural
    - Interstate versus non-Interstate.
- All selected WIM stations, except for Station P04 (NB), may be treated as samples from a single population with consistent GVW peak values and varying percentages of empty and fully loaded trucks.

These analyses were based on Class 9 vehicles because of their consistent loading pattern. However, replicating the analyses for the remaining vehicle classes is not advisable because of their lack of consistency. Consequently, the developed load spectra are based on the WIM station with the most conservative load spectra (i.e., Station P4N).

To ensure the reliability of the developed load spectra, they were compared with the MnROAD and *2002 Design Guide* defaults. The developed load spectra were somewhat similar to the MnROAD and the *2002 Design Guide* spectra in their overall location of peaks associated with empty and fully loaded trucks for the predominant vehicle classes. The percentages of axles within these peaks varied. Nonetheless, in most instances this variation was less than the variation among some of the selected WIM stations.

The ESALs per vehicle class associated with the developed load spectra were compared with historical Washington State ESALs (1993). Both ESALs were similar for the predominant vehicle classes (i.e., 9, 10, and 13), except Class 5 vehicles, which had a lower ESAL value. Furthermore, the use of newly developed ESALs per vehicle will generally increase design ESALs. However, such an increase will be due primarily to the inclusion of the less predominant vehicle classes (i.e., 4, 6, 7, 8, and 11). Therefore, the developed load spectra are concluded to be reasonable.

RECOMMENDATIONS

The developed load spectra are based on analyses of 11 stations throughout Washington State. To assure the applicability of the research findings, the following are recommended:

- Calibrate the selected stations.
- Calibrate all or some of the excluded stations.

If the findings of this research are valid, the following is recommended:

- Focus future efforts on the selected WIM stations.
- Discard the majority of invalid WIM sites.
- Because seasonal variation is insignificant, the calibration efforts should be performed periodically on Station P4N for at least:
    - an entire month, four times a year or
    - an entire month, twice a year.
- Remaining stations should be periodically calibrated with weekly durations.

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CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

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APPENDIX A: MONTHLY GVW DISTRIBUTIONS

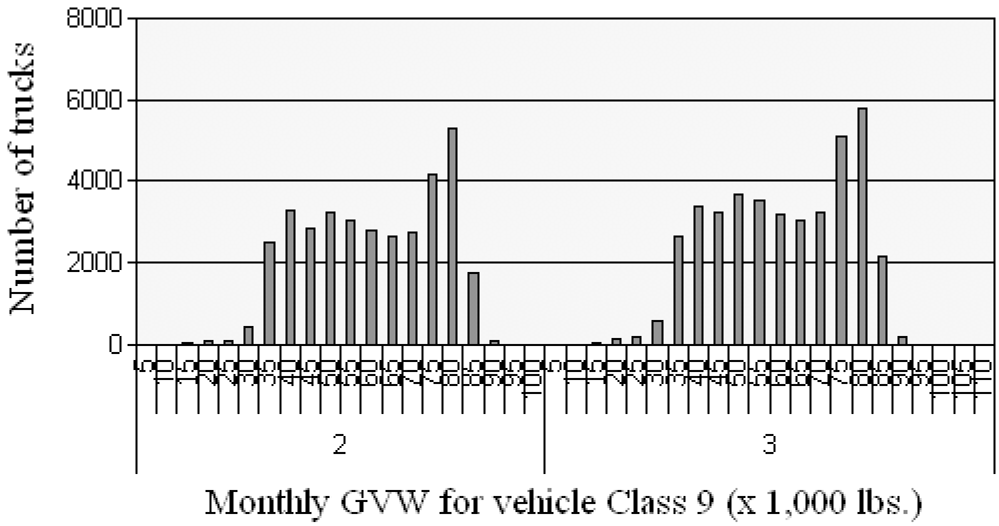

Figure A-1. Monthly GVW distributions for Class 9 vehicles (Station P4N-2002-February, March)

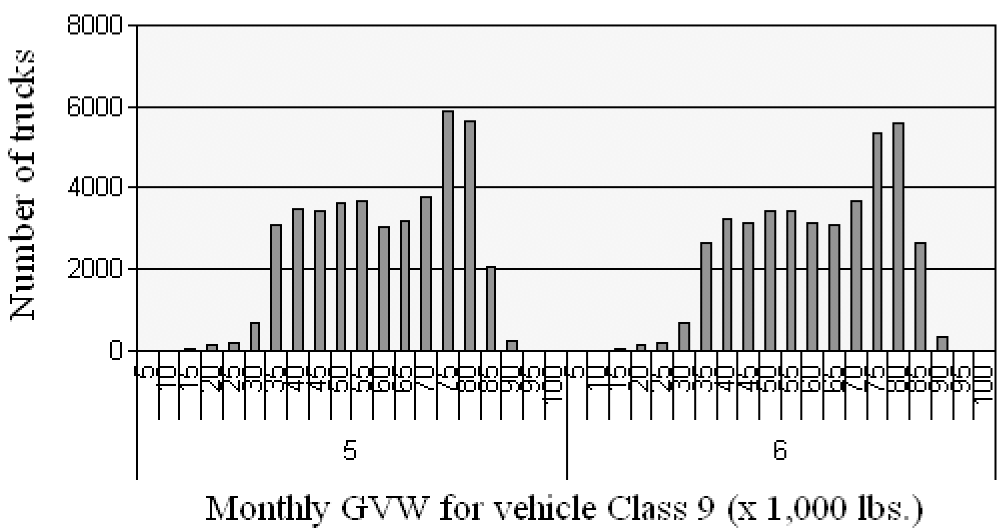

Figure A-2. Monthly GVW distributions for Class 9 vehicles (Station P4N-2002-May, June)

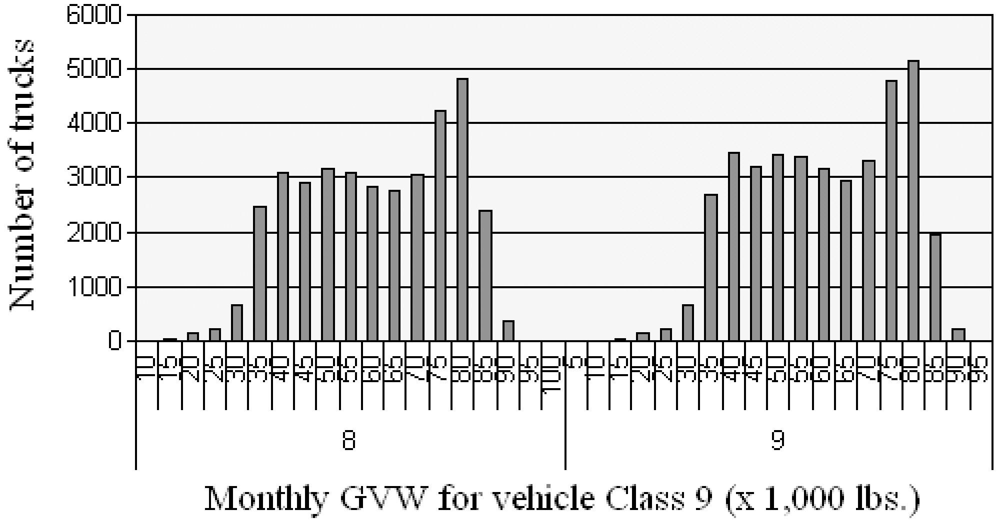

Figure A-3. Monthly GVW distributions for Class 9 vehicles (Station P4N-2002-August, September)

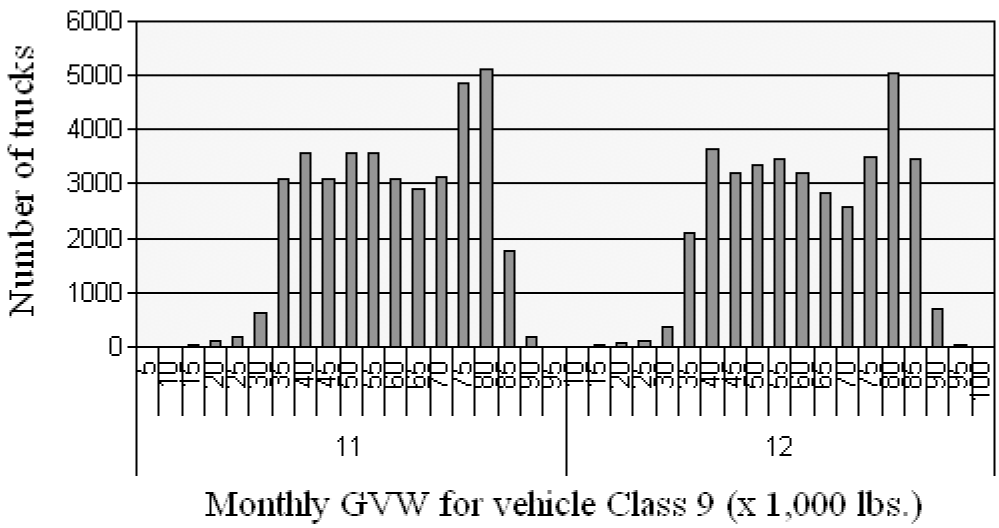

Figure A-4. Monthly GVW distributions for Class 9 vehicles (Station P4N-2002-November, December)

APPENDIX B: INVALID GVW DATA EVALUATION

Remaining stations not affected by the exclusion of the bad months, which produced adequate GVW distributions.

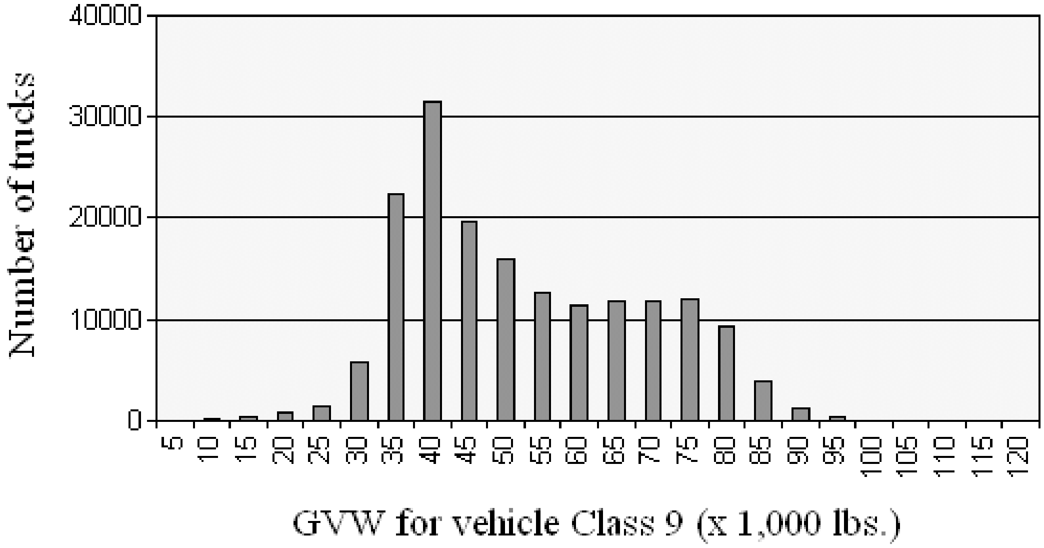

Figure B-1. Yearly GVW distributions for Class 9 vehicles (Station P6N-2000) (valid months)

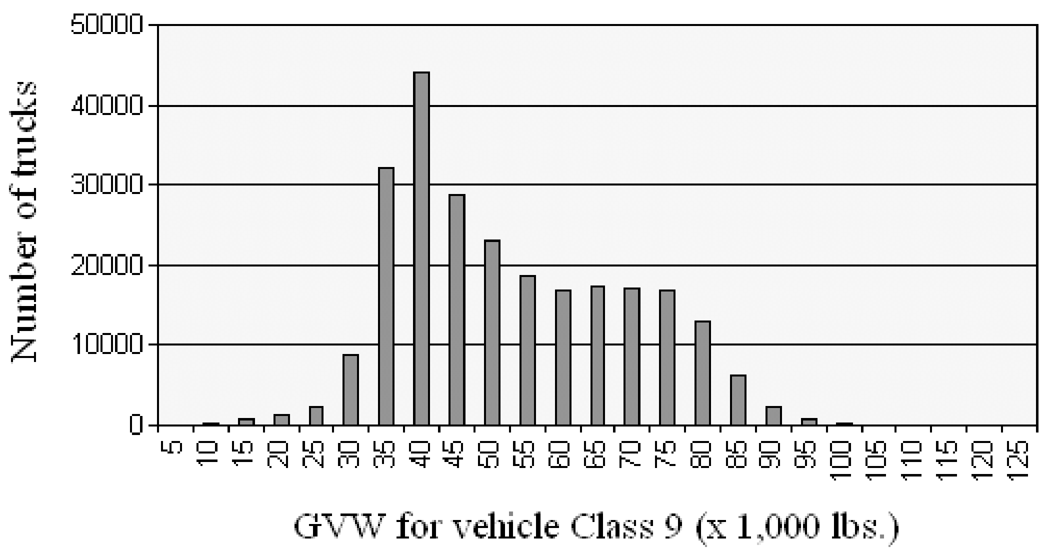

Figure B-2. Yearly GVW distributions for Class 9 vehicles (Station P6N-2000) (total months)

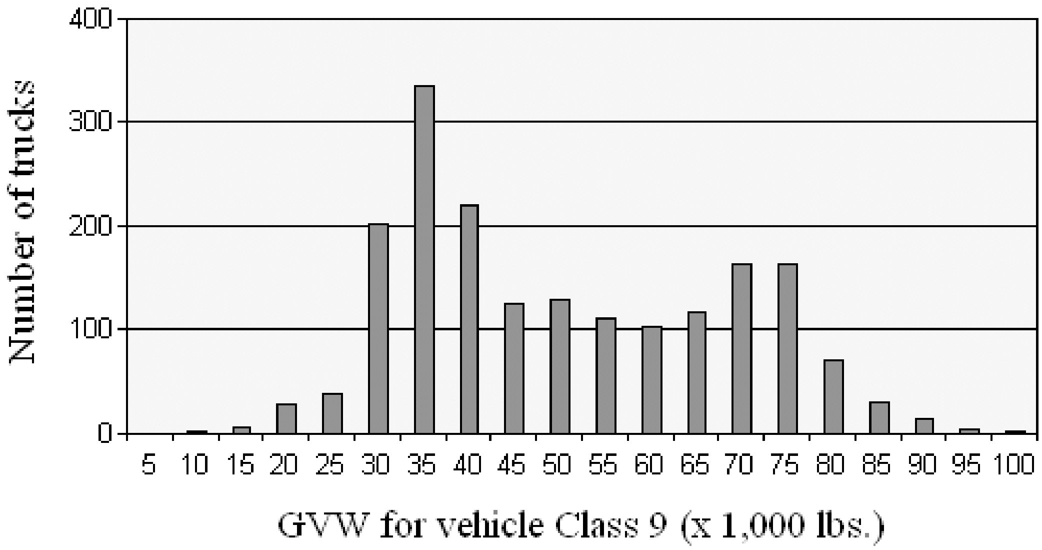

Figure B-3. Yearly GVW distributions for Class 9 vehicles (Station P18-SB-2002) (valid months)

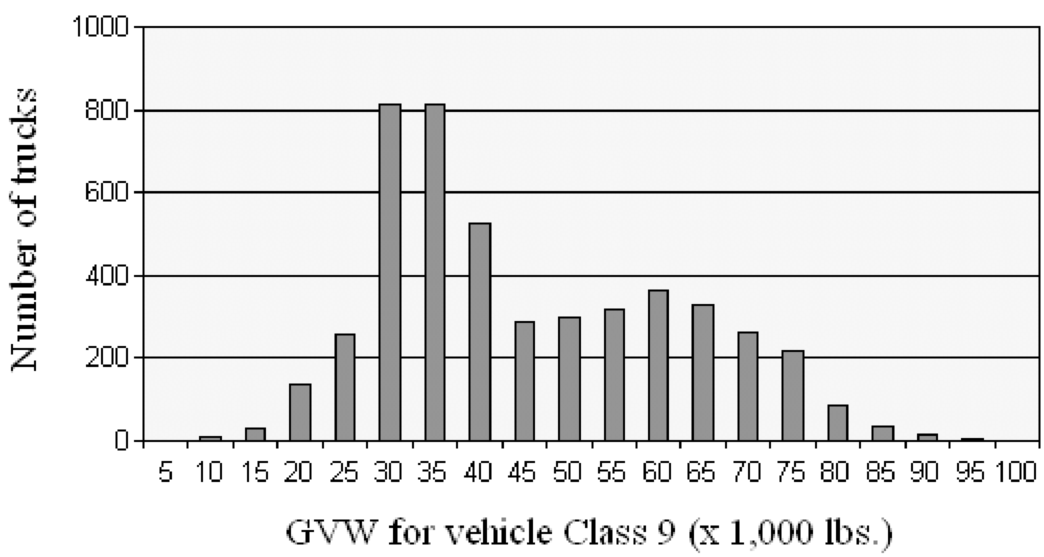

Figure B-4. Yearly GVW distributions for Class 9 vehicles (Station P18-SB-2002) (total months)

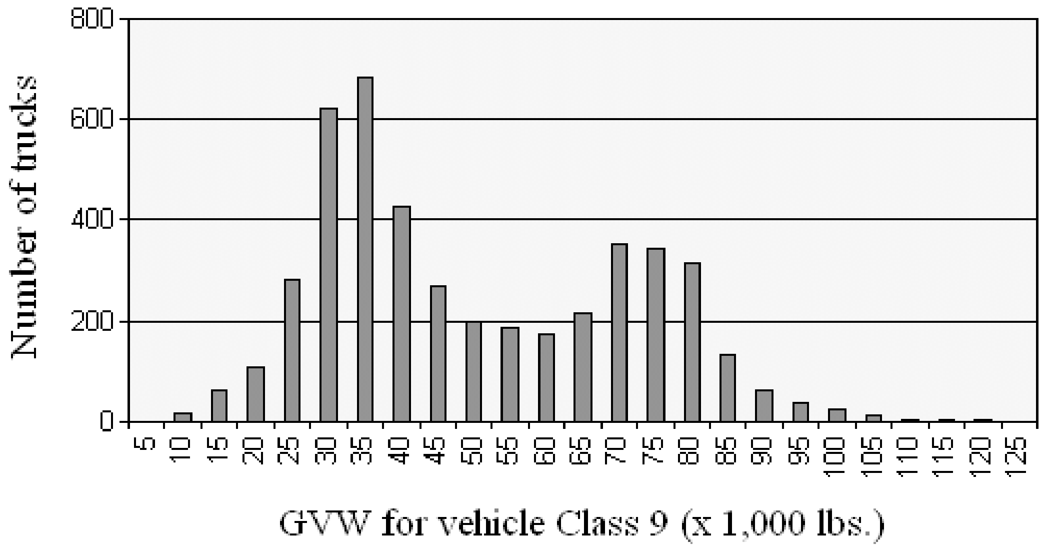

Figure B-5. Yearly GVW distributions for Class 9 vehicles (Station P18-NB-2002) (valid months)

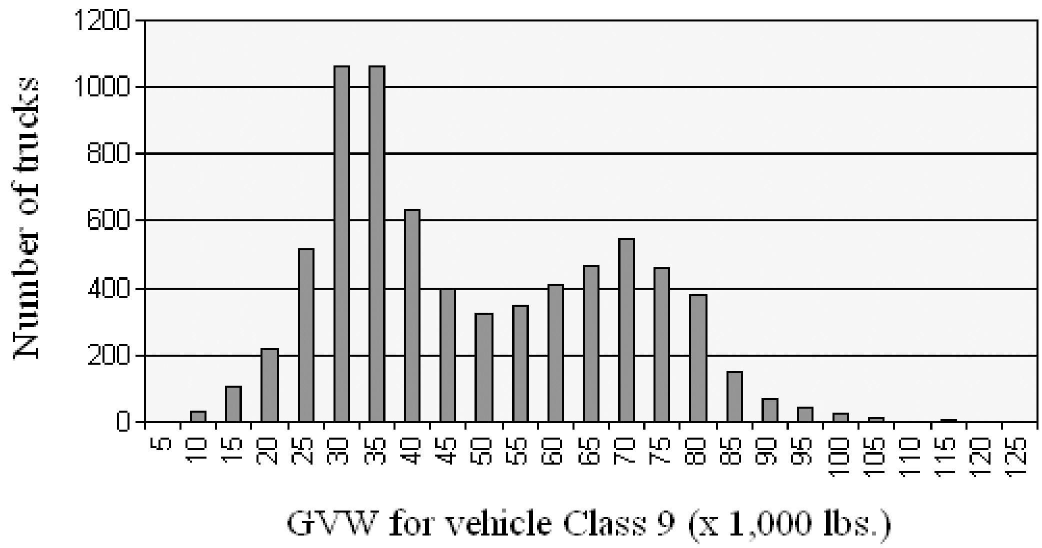

Figure B-6. Yearly GVW distributions for Class 9 vehicles (Station P18-NB-2002) (total months)

Remaining stations that were affected by the exclusion of the bad months.

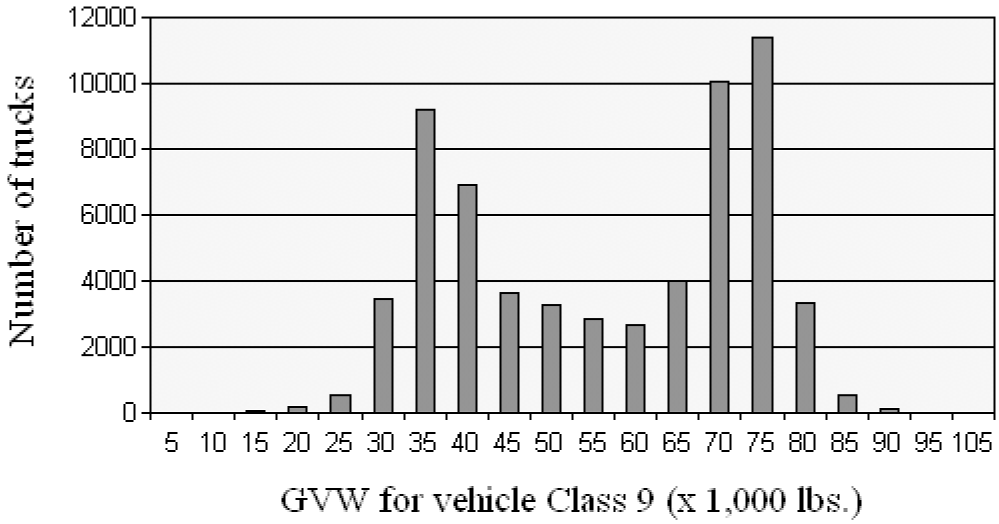

Figure B-7. Yearly GVW distributions for Class 9 vehicles (Station B03-SB-2002) (valid months)

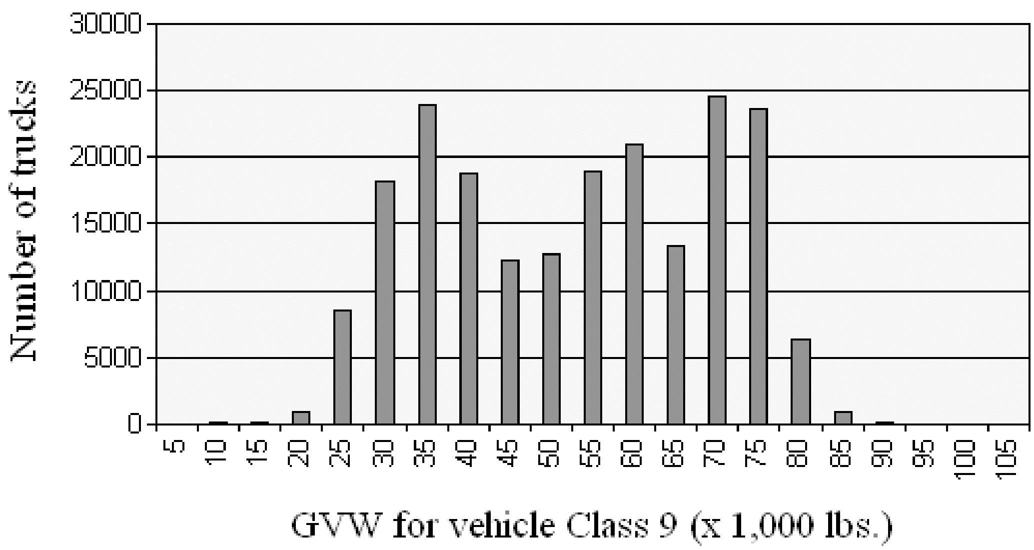

Figure B-8. Yearly GVW distributions for Class 9 vehicles (Station B03-SB-2002) (total months)

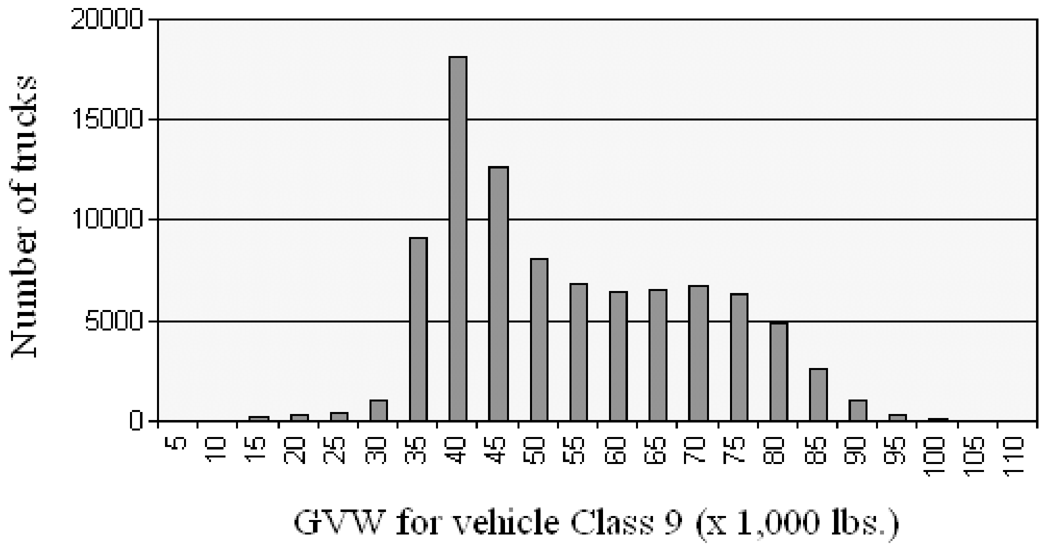

Figure B-9. Yearly GVW distributions for Class 9 vehicles (Station B04-SB-2002) (valid months)

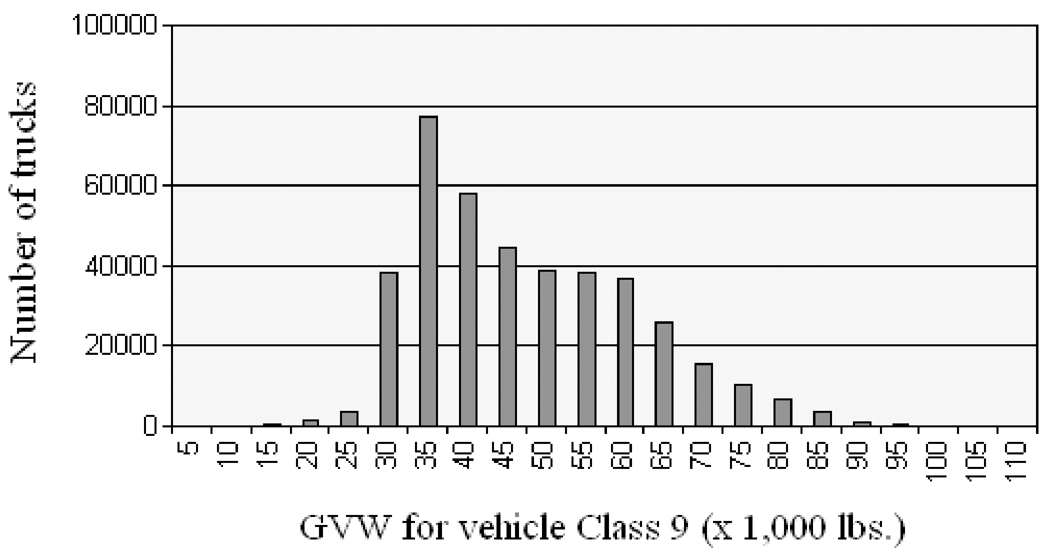

Figure B-10. Yearly GVW distributions for Class 9 vehicles (Station B04-SB-2002) (total months)

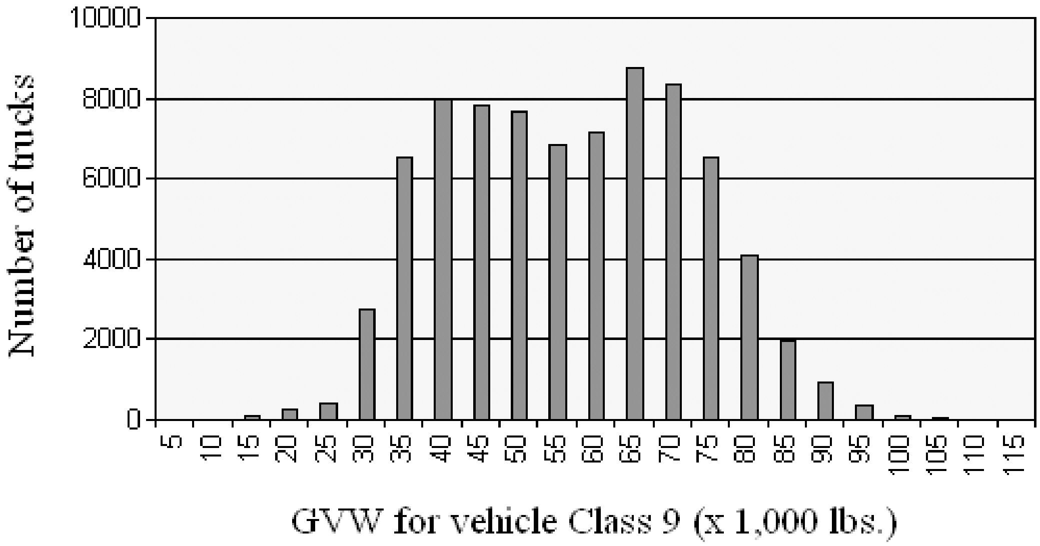

Figure B-11. Yearly GVW distributions for Class 9 vehicles (Station B04-NB-2002) (valid months)

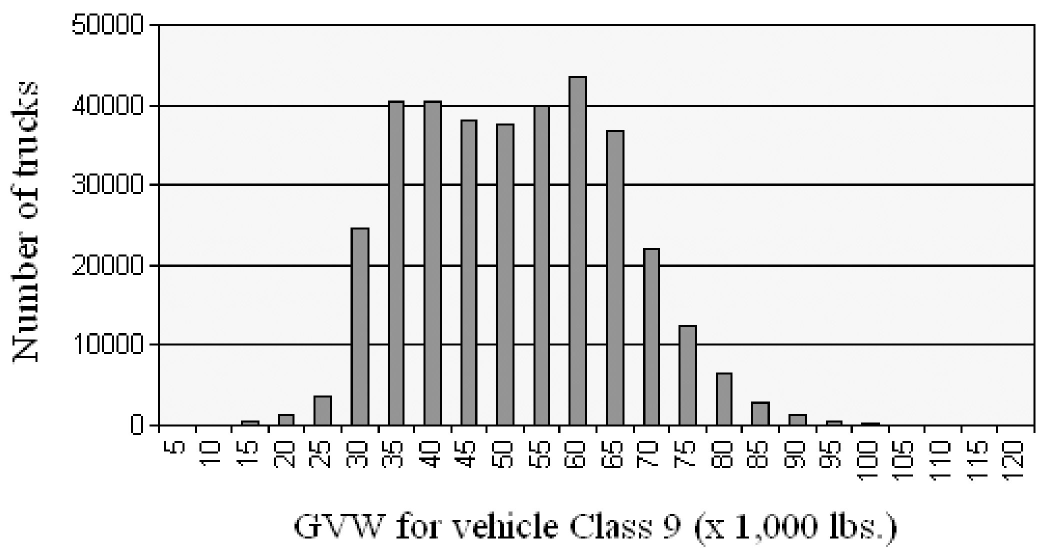

Figure B-12. Yearly GVW distributions for Class 9 vehicles (Station B04-NB-2002) (total months)

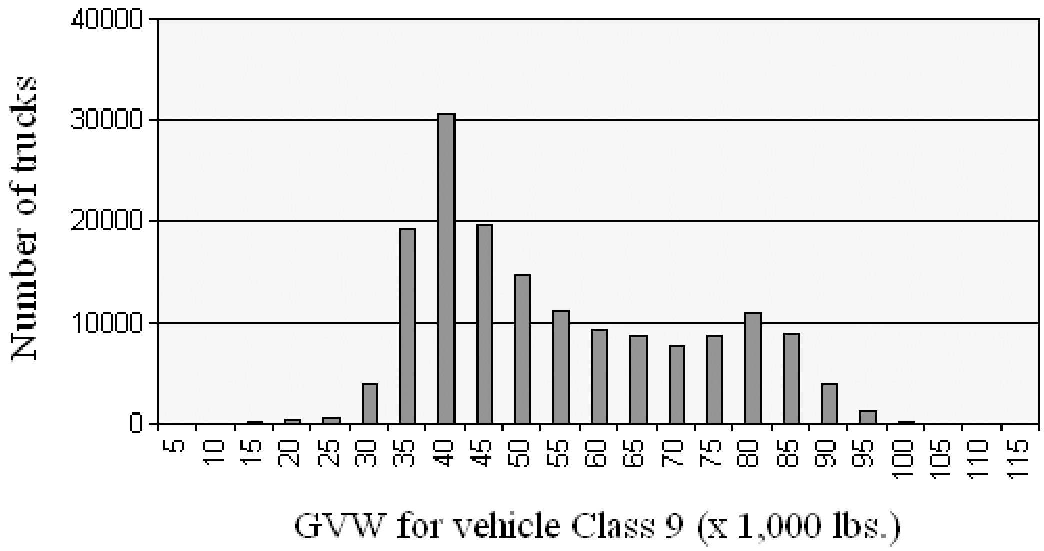

Figure B-13. Yearly GVW distributions for Class 9 vehicles (Station P1N-2002) (valid months)

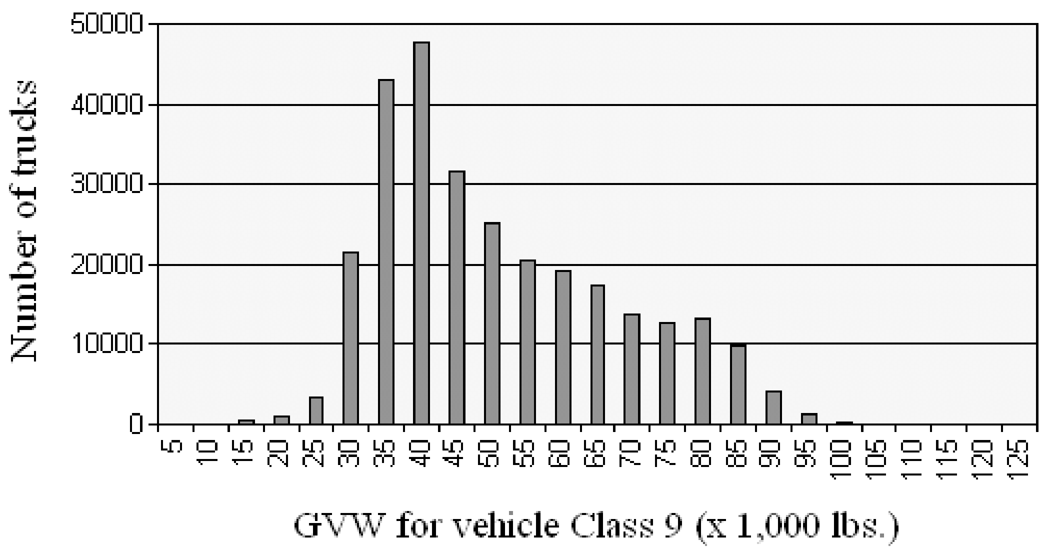

Figure B-14. Yearly GVW distributions for Class 9 vehicles (Station P1N-2002) (total months)

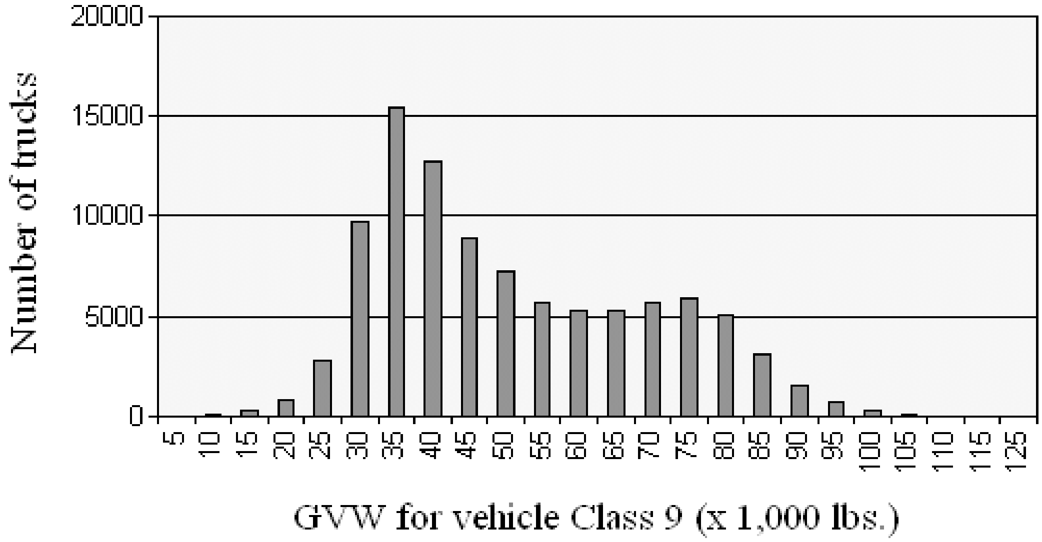

Figure B-15. Yearly GVW distributions for Class 9 vehicles (Station P3N-2000) (valid months)

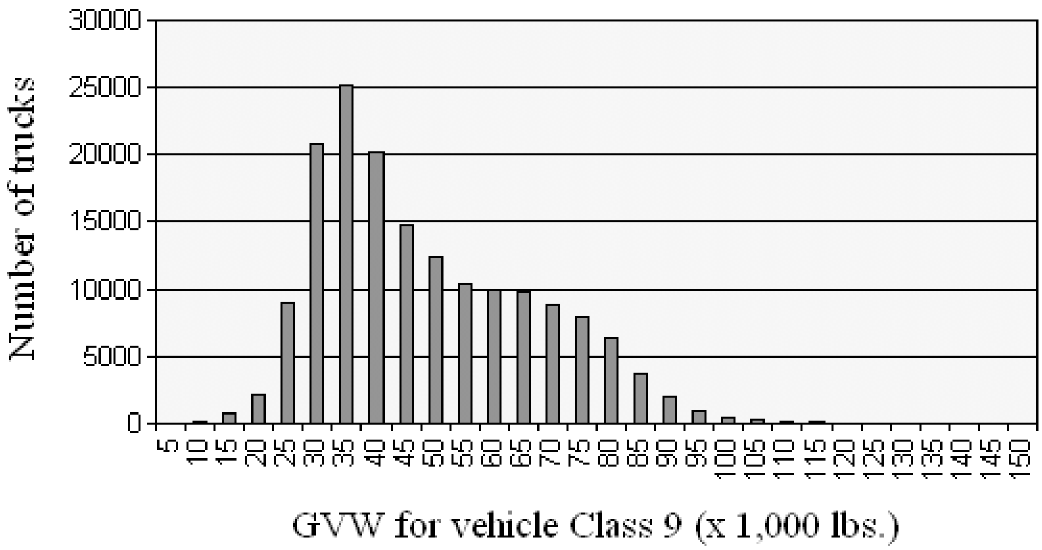

Figure B-16. Yearly GVW distributions for Class 9 vehicles (Station P3N-2000) (total months)

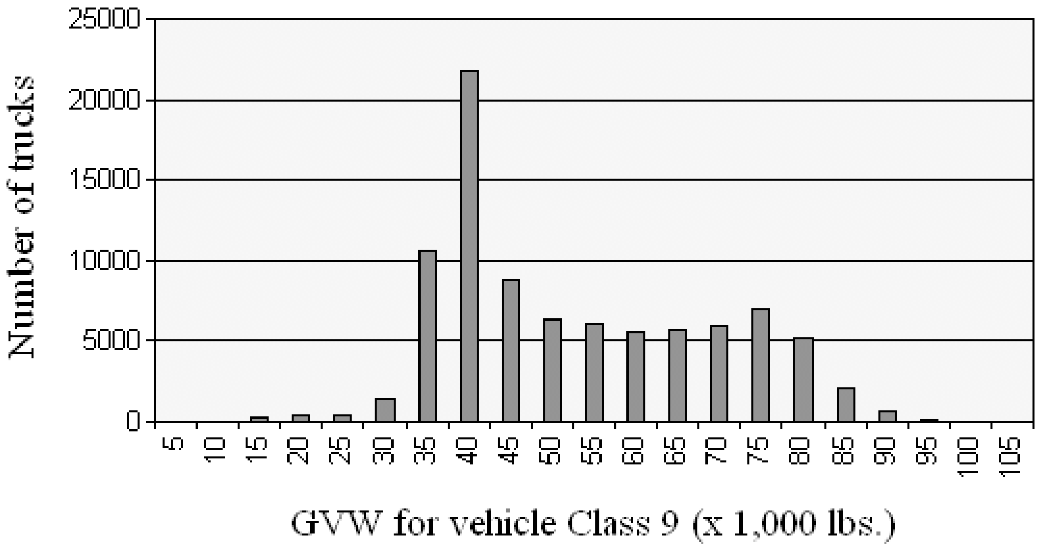

Figure B-17. Yearly GVW distributions for Class 9 vehicles (Station P04-SB-2001) (valid months)

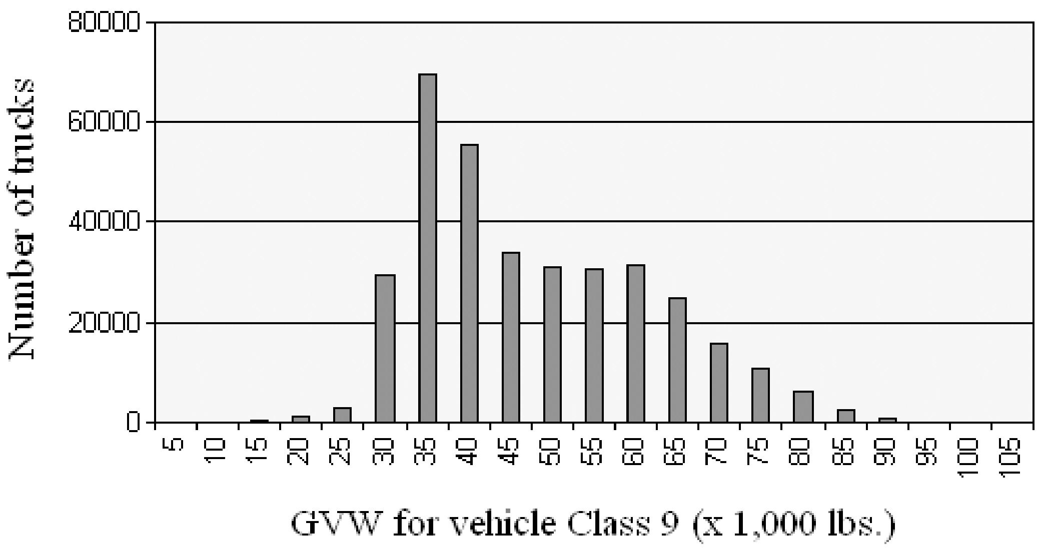

Figure B-18. Yearly GVW distributions for Class 9 vehicles (Station P04-SB-2001) (total months)

APPENDIX C: GVW AND TANDEM AXLE LOAD SPECTRA

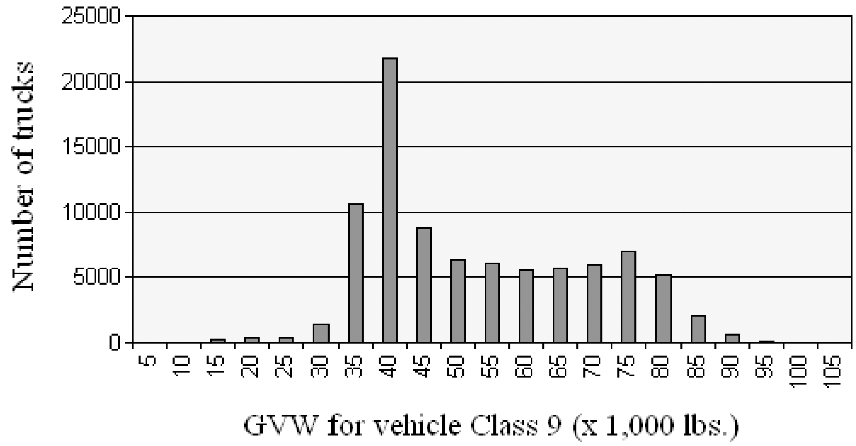

Figure C-1. Yearly GVW distributions for Class 9 vehicles (Station P04-SB-2001)

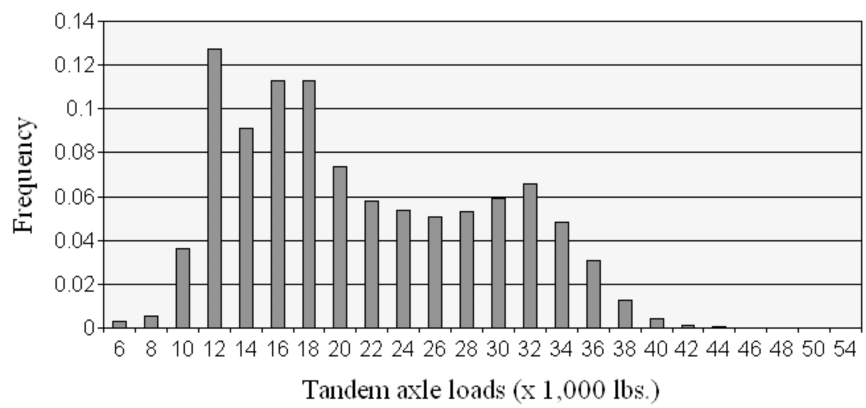

Figure C-2. Tandem axle load spectrum for Class 9 vehicles (Station P04-SB-2001)

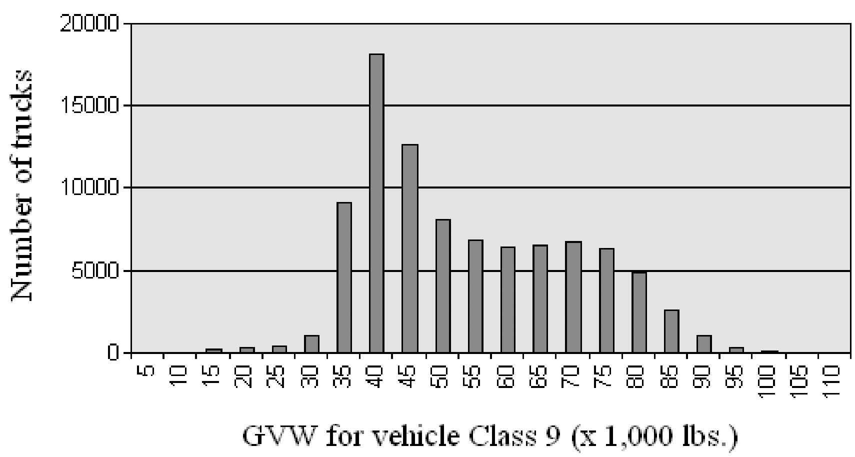

Figure C-3. Yearly GVW distributions for Class 9 vehicles (Station B04-SB-2002)

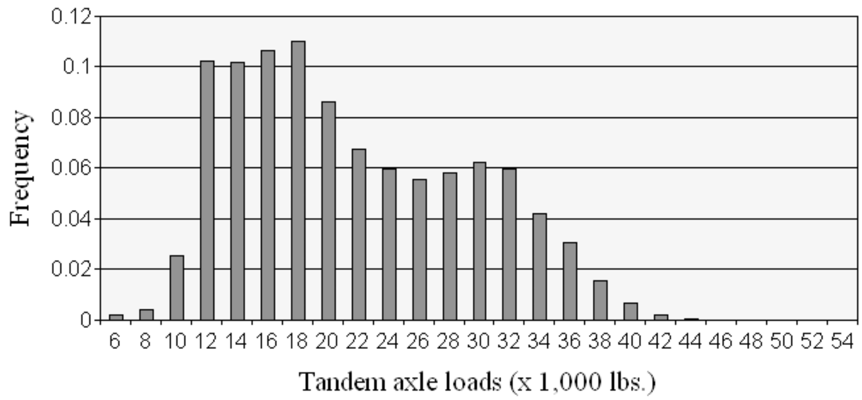

Figure C-4. Tandem axle load spectrum for Class 9 vehicles (Station B04-SB-2002)

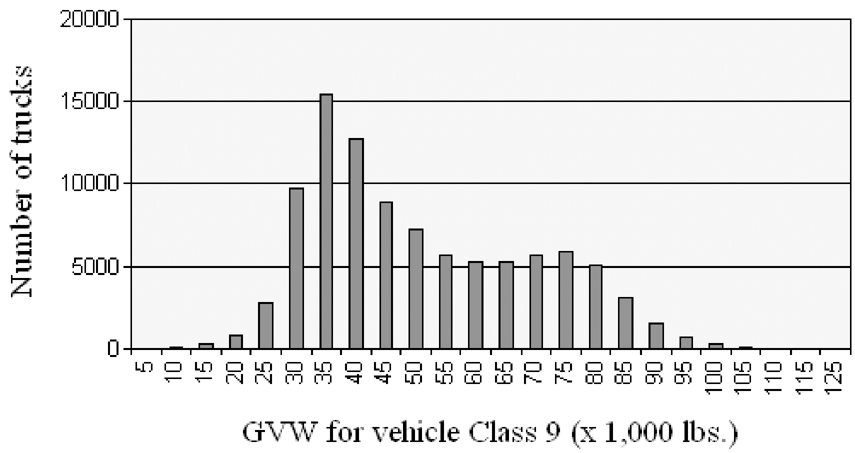

Figure C-5. Yearly GVW distributions for Class 9 vehicles (Station P3N-2000)

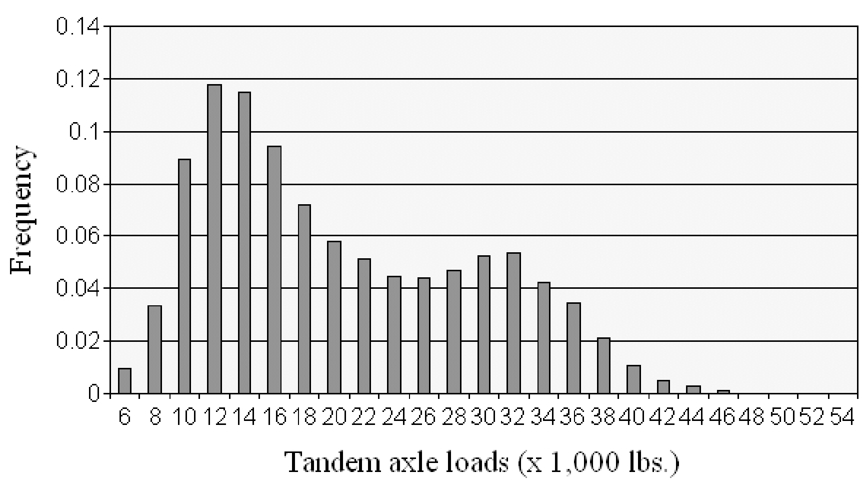

Figure C-6. Tandem axle load spectrum for Class 9 vehicles (Station P3N-2000)

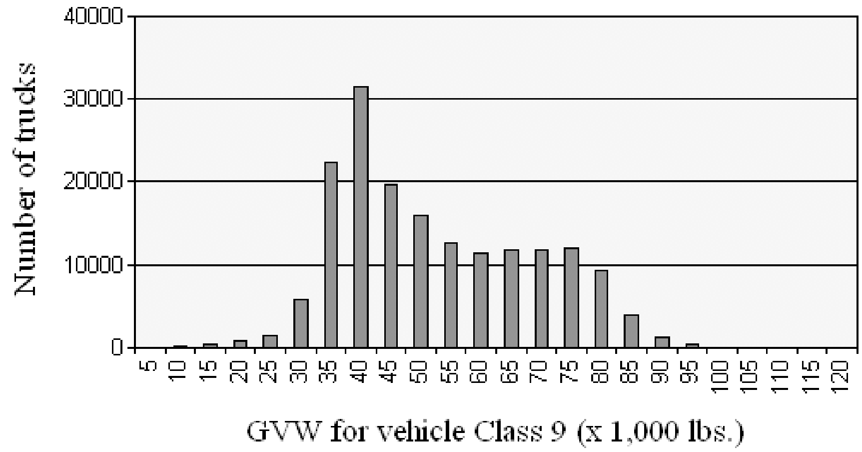

Figure C-7. Yearly GVW distributions for Class 9 vehicles (Station P6N-2002)

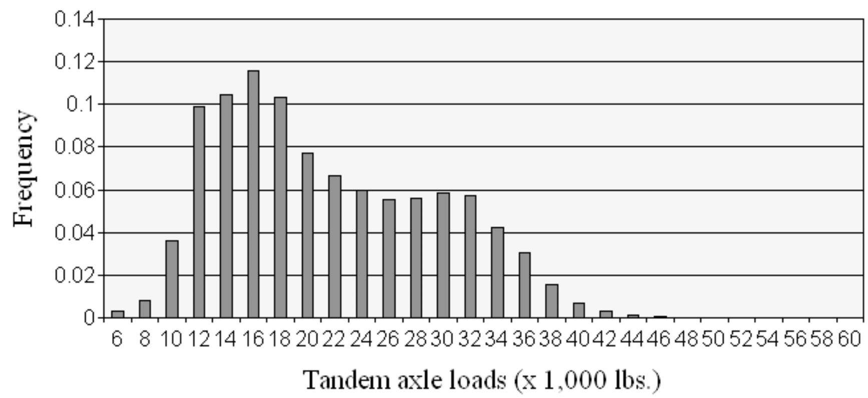

Figure C-8. Tandem axle load spectrum for Class 9 vehicles (Station P6N-2000)

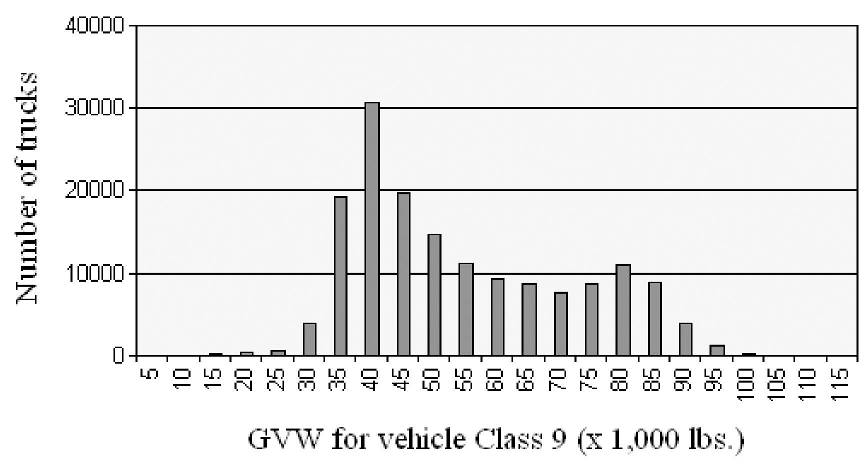

Figure C-9. Yearly GVW distributions for Class 9 vehicles (Station P1N-2002)

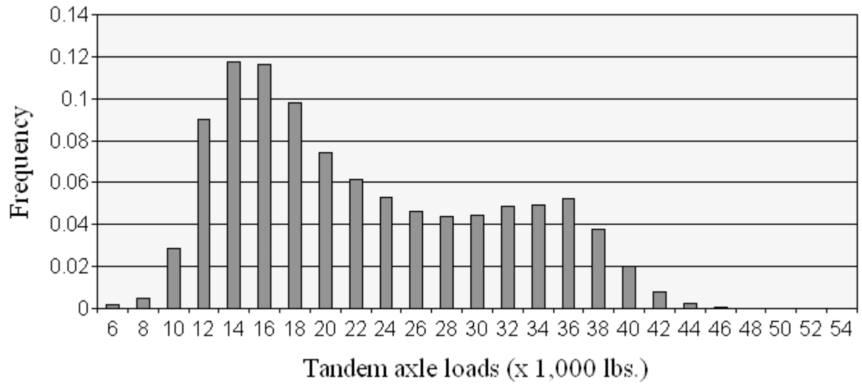

Figure C-10. Tandem axle load spectrum for Class 9 vehicles (Station P1N-2002)

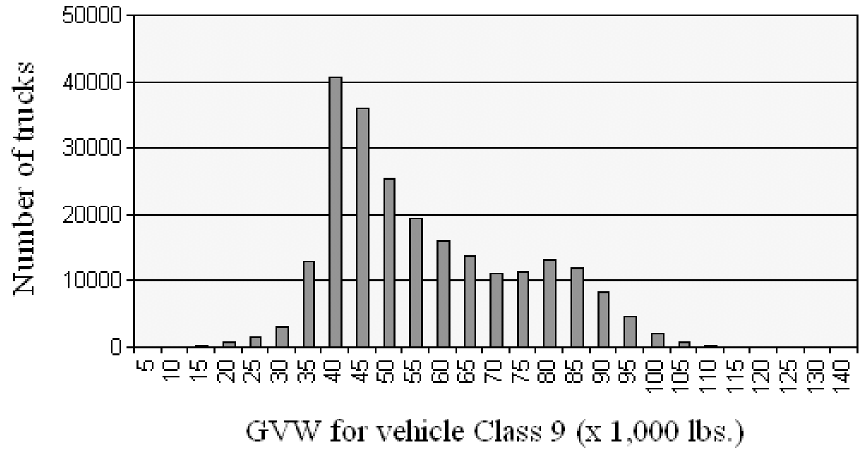

Figure C-11. Yearly GVW distributions for Class 9 vehicles (Station P6S-2000)

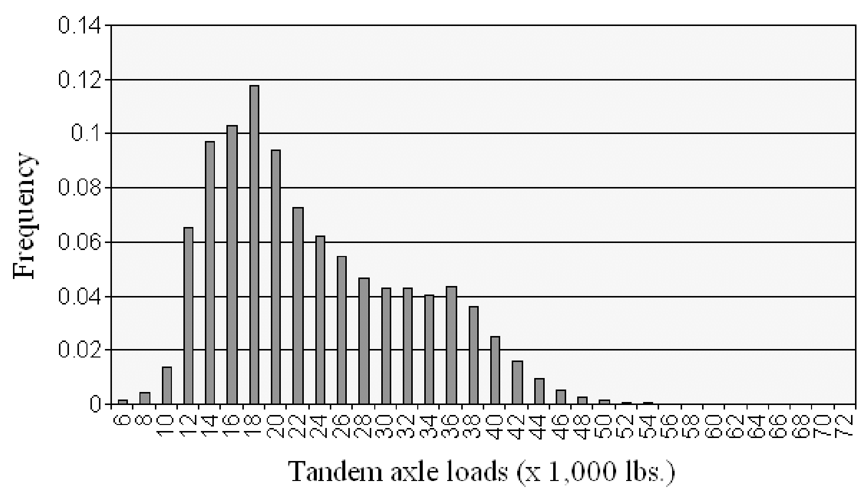

Figure C-12. Tandem axle load spectrum for Class 9 vehicles (Station P6S-2000)

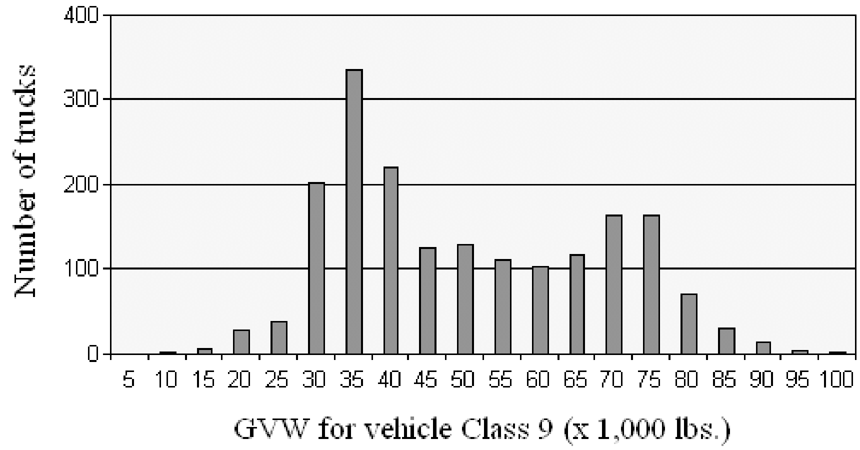

Figure C-13. Yearly GVW distributions for Class 9 vehicles (Station P18-SB-2002)

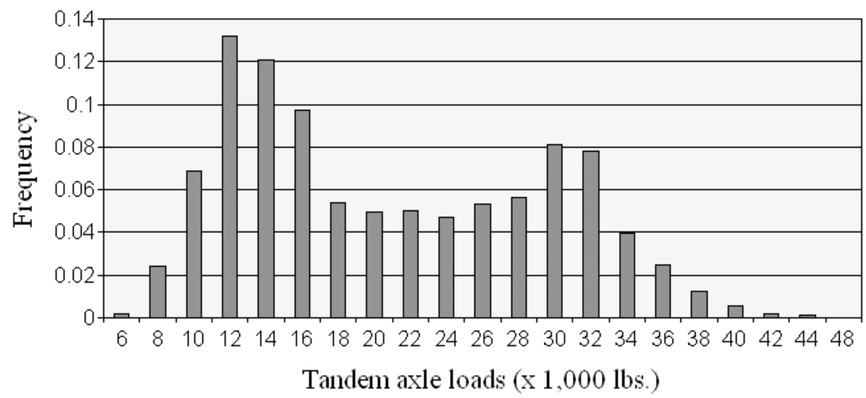

Figure C-14. Tandem axle load spectrum for Class 9 vehicles (Station P18-SB-2002)

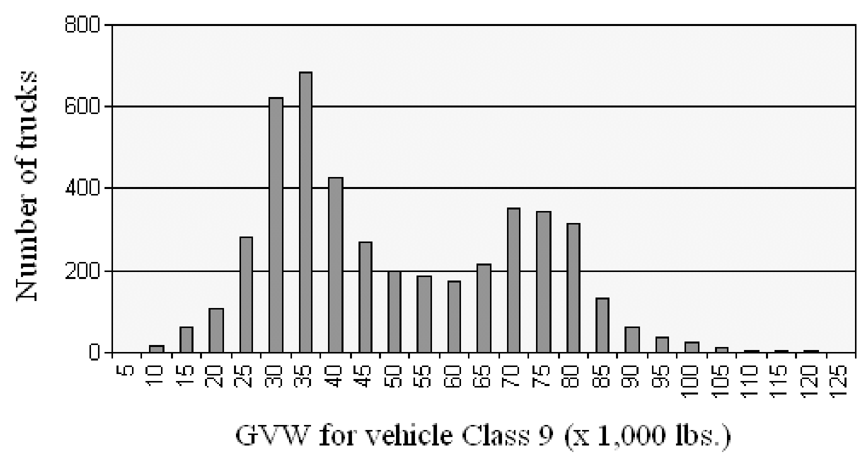

Figure C-15. Yearly GVW distributions for Class 9 vehicles (Station P18-NB-2002)

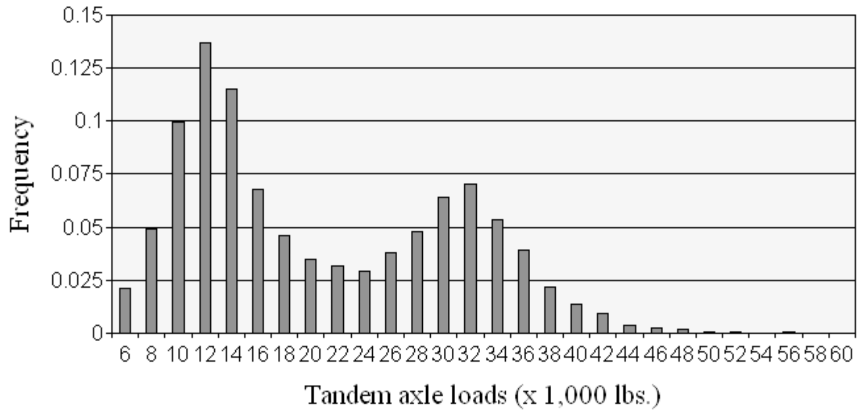

Figure C-16. Tandem axle load spectrum for Class 9 vehicles (Station P18-NB-2002)

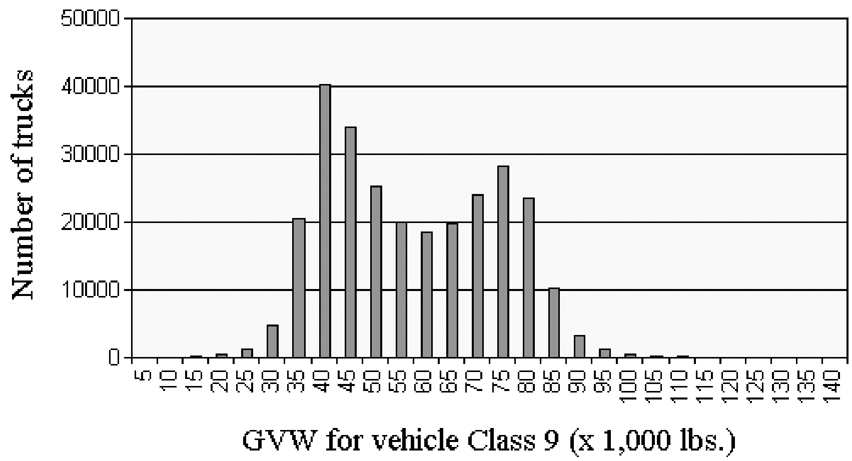

Figure C-17. Yearly GVW distributions for Class 9 vehicles (Station P1S-2000)

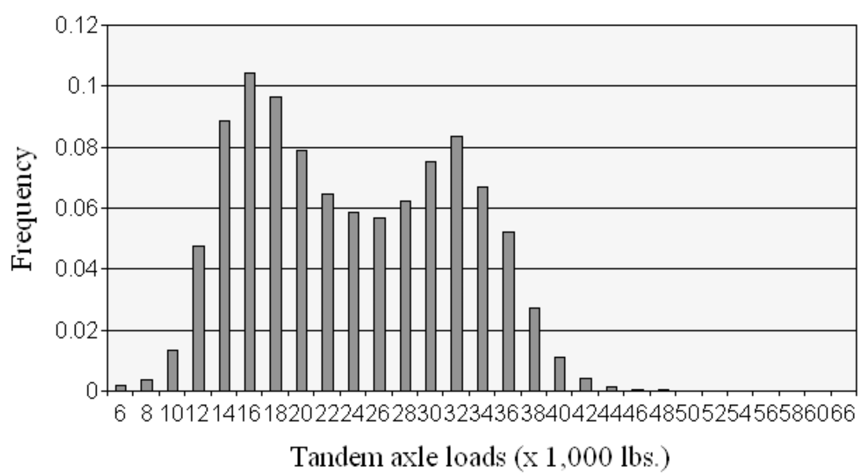

Figure C-18. Tandem axle load spectrum for Class 9 vehicles (Station P1S-2002)

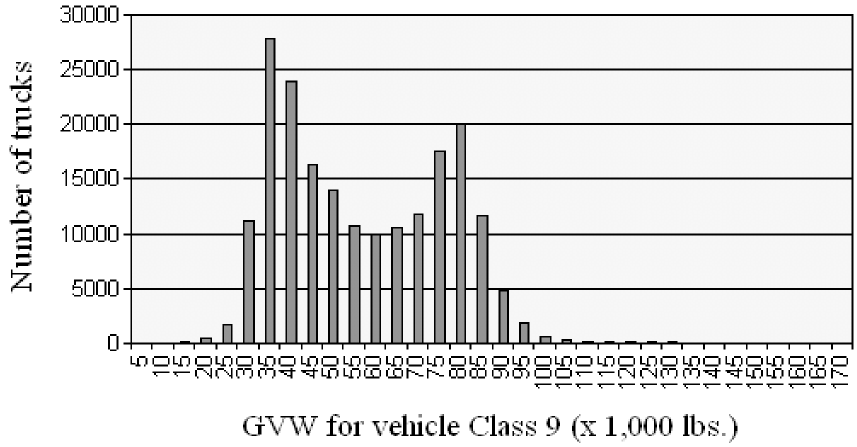

Figure C-19. Yearly GVW distributions for Class 9 vehicles (Station P3S-2001)

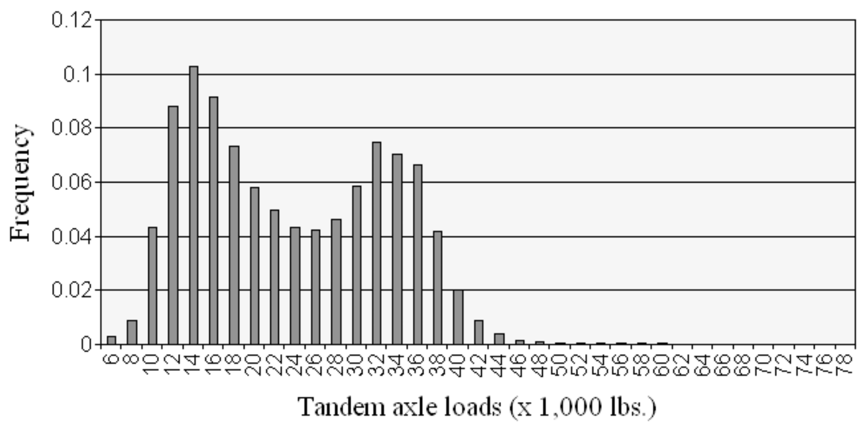

Figure C-20. Tandem axle load spectrum for Class 9 vehicles (Station P3S-2001)

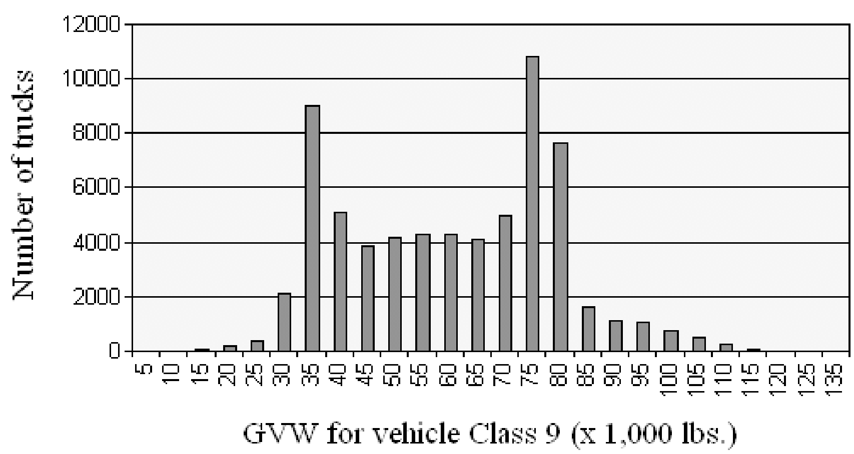

Figure C-21. Yearly GVW distributions for Class 9 vehicles (Station B03-NB-2002)

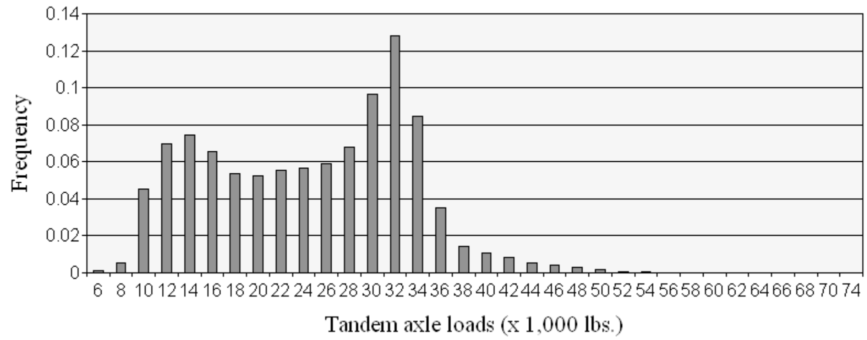

Figure C-22. Tandem axle load spectrum for Class 9 vehicles (Station B03-NB-2002)

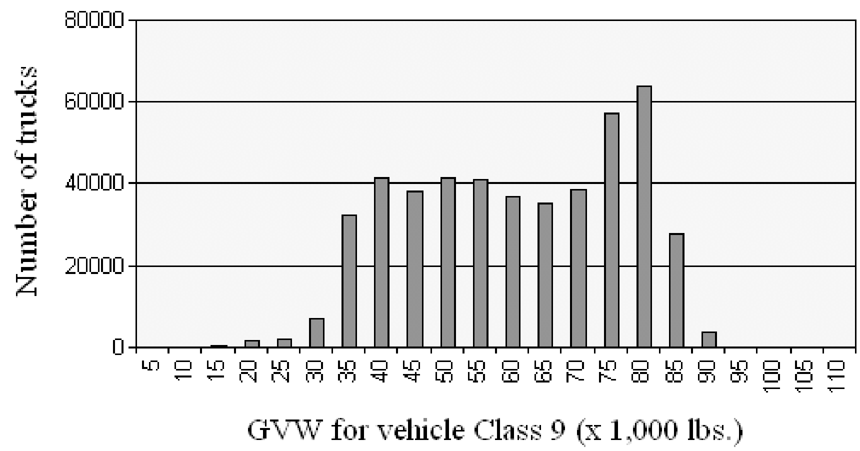

Figure C-23. Yearly GVW distributions for Class 9 vehicles (Station P4N-2002)

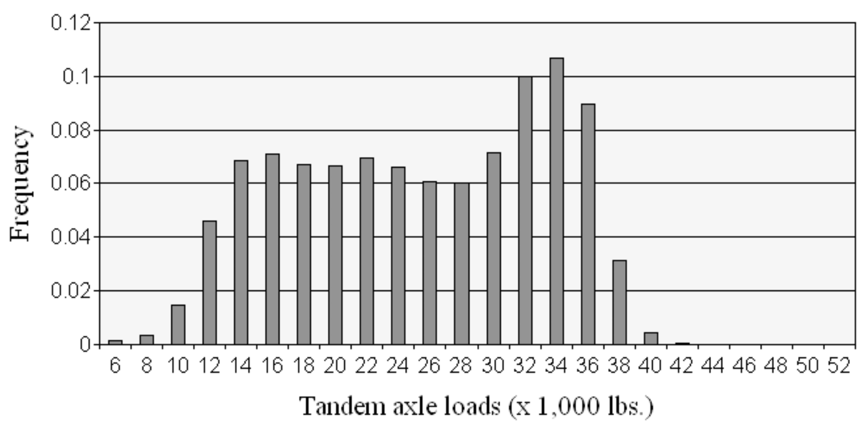

Figure C-24. Tandem axle load spectrum for Class 9 vehicles (Station P4N-2002)

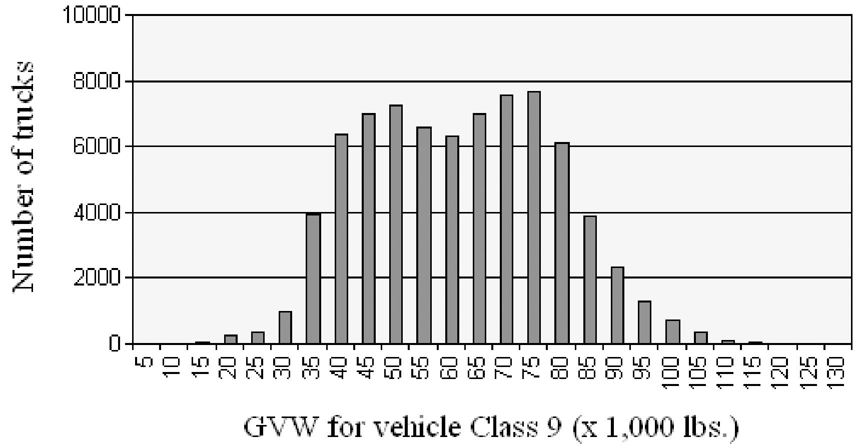

Figure C-25. Yearly GVW distributions for Class 9 vehicles (Station P04-NB-2001)

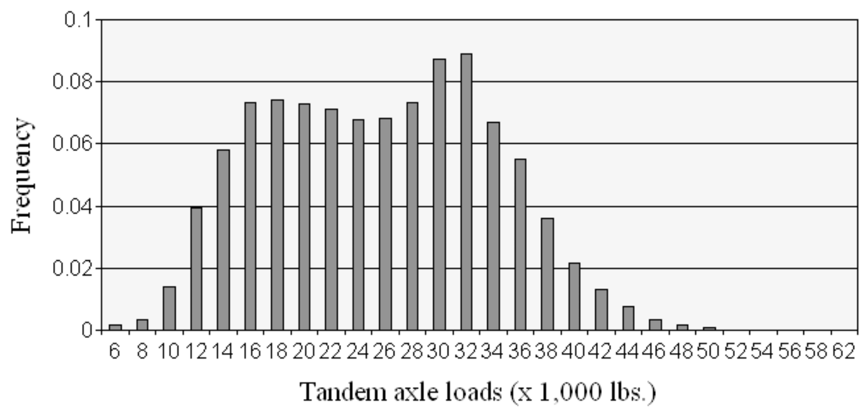

Figure C-26. Tandem axle load spectrum for Class 9 vehicles (Station P04-NB-2001)

APPENDIX D: LOAD SPECTRA (STATIONS P4N AND P1S)

Load spectra for Station P4N and remaining vehicle classes.

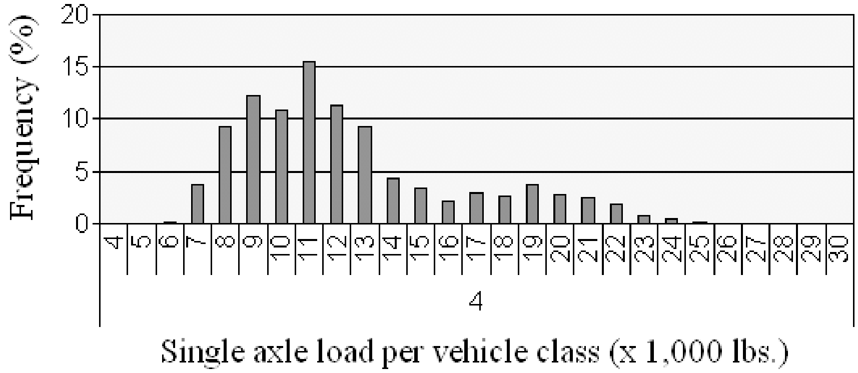

Figure D-1. Single axle load spectrum for Class 4 vehicles (Station P4N-2002)

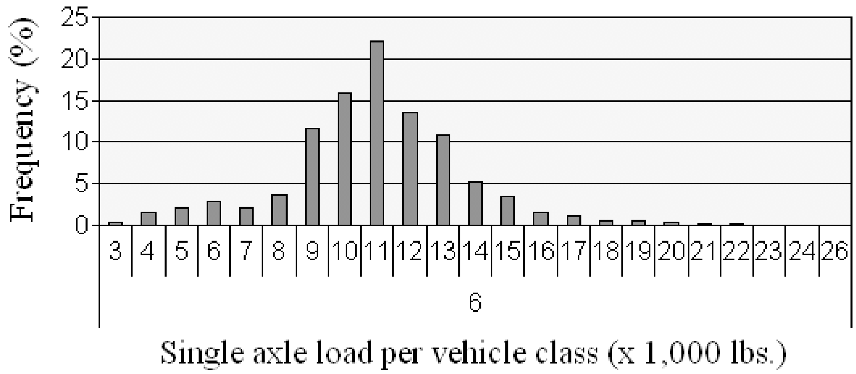

Figure D-2. Single axle load spectrum for Class 6 vehicles (Station P4N-2002)

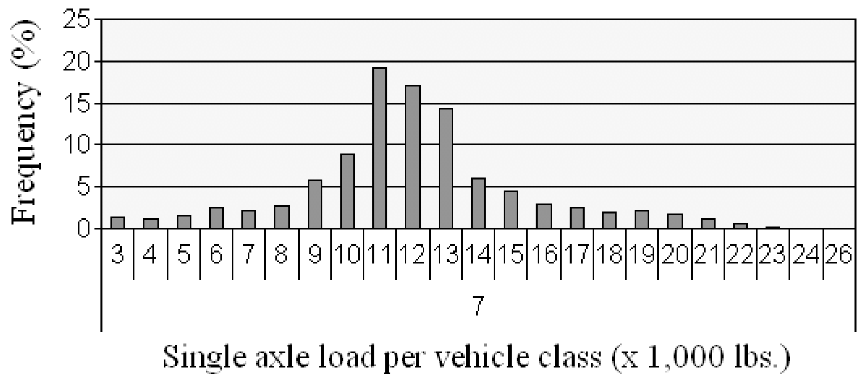

Figure D-3. Single axle load spectrum for Class 7 vehicles (Station P4N-2002)

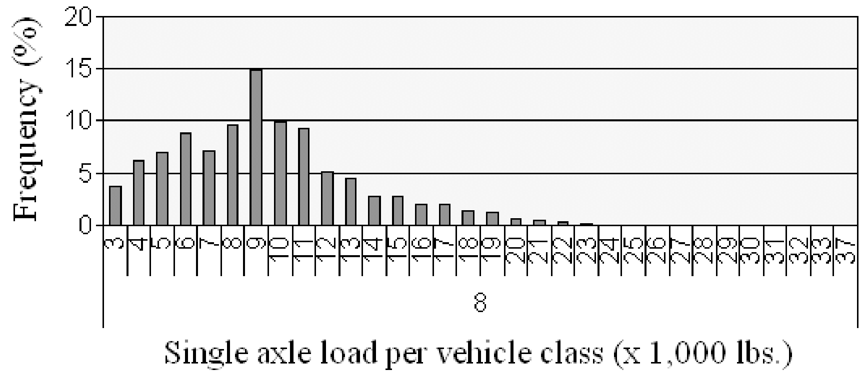

Figure D-4. Single axle load spectrum for Class 8 vehicles (Station P4N-2002)

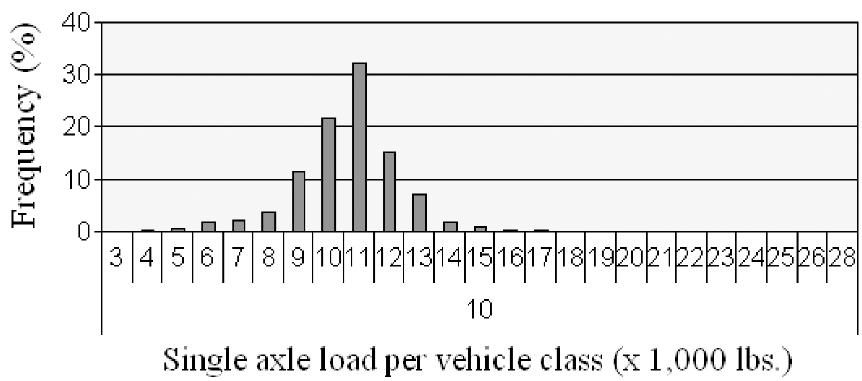

Figure D-5. Single axle load spectrum for Class 10 vehicles (Station P4N-2002)

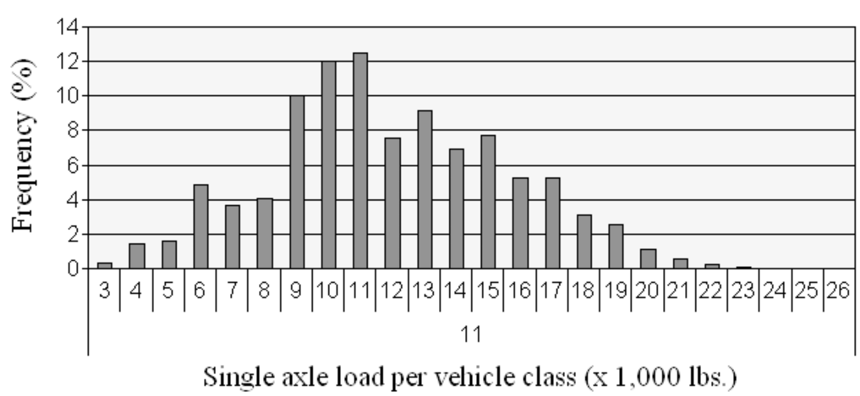

Figure D-6. Single axle load spectrum for Class 11 vehicles (Station P4N-2002)

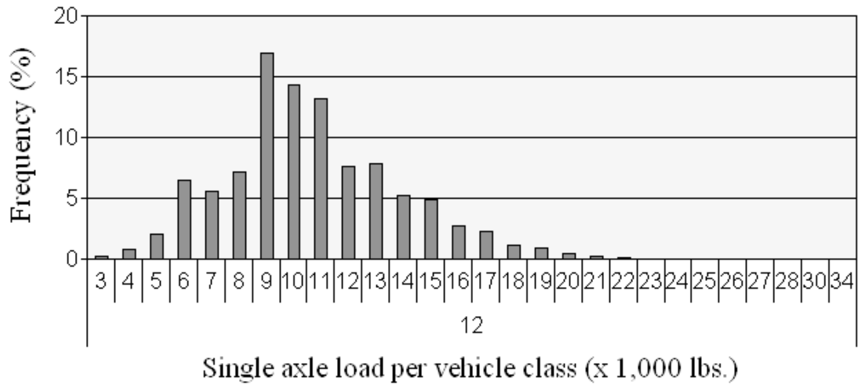

Figure D-7. Single axle load spectrum for Class 12 vehicles (Station P4N-2002)

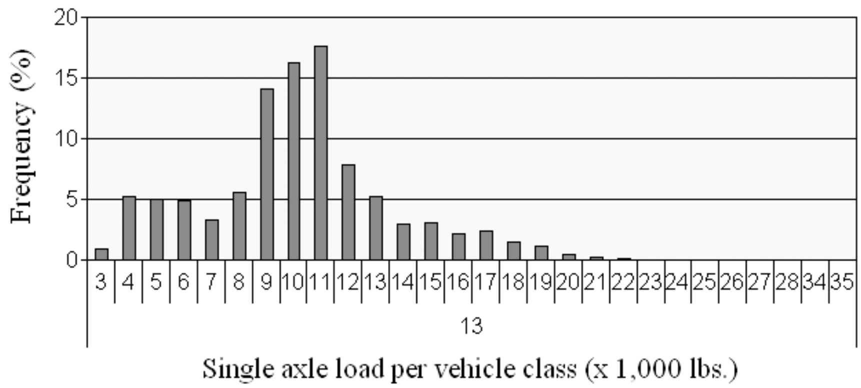

Figure D-8. Single axle load spectrum for Class 13 vehicles (Station P4N-2002)

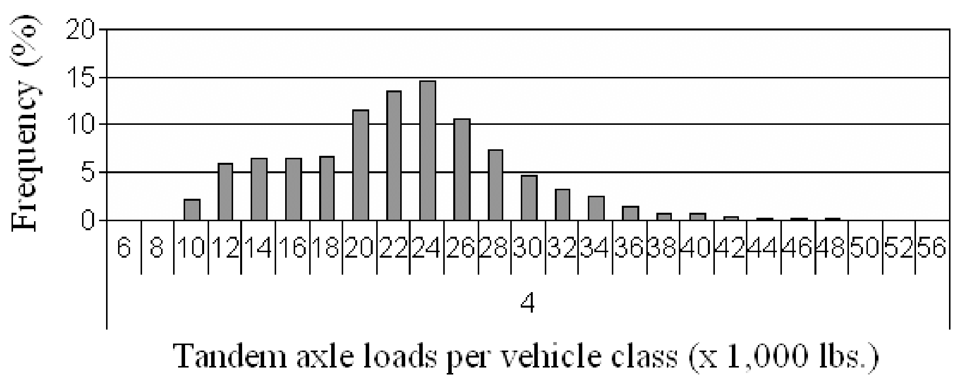

Figure D-9. Tandem axle load spectrum for Class 4 vehicles (Station P4N-2002)

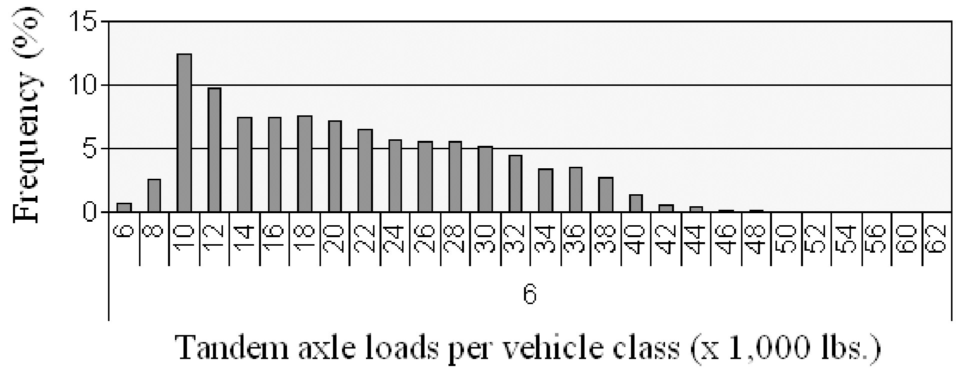

Figure D-10. Tandem axle load spectrum for Class 6 vehicles (Station P4N-2002)

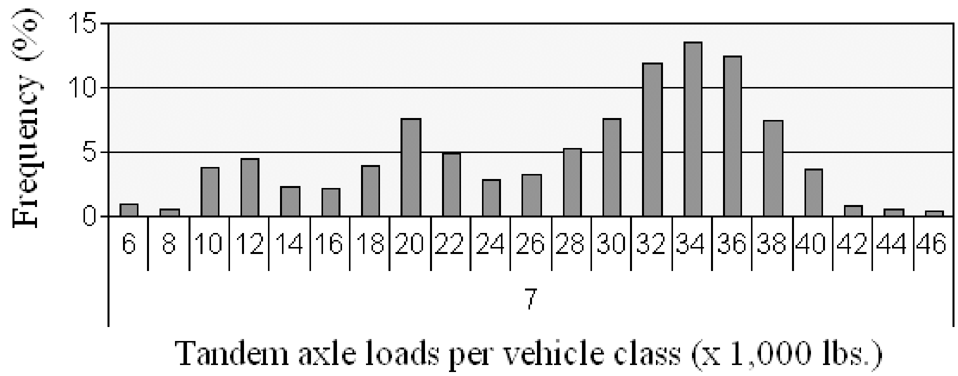

Figure D-11. Tandem axle load spectrum for Class 7 vehicles (Station P4N-2002)

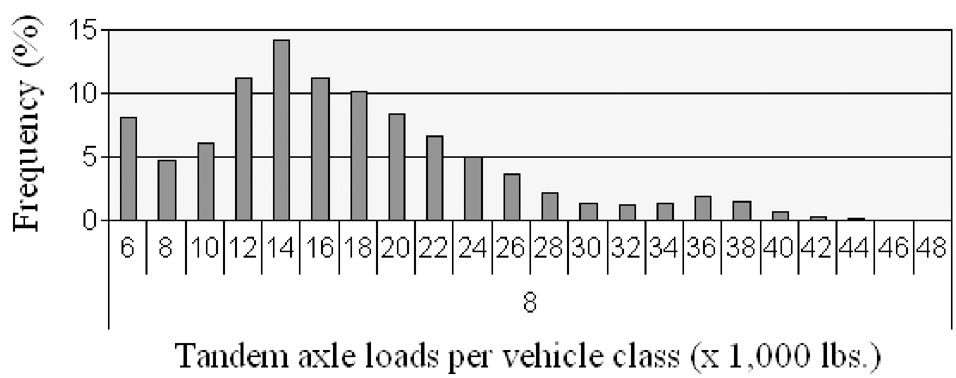

Figure D-12. Tandem axle load spectrum for Class 8 vehicles (Station P4N-2002)

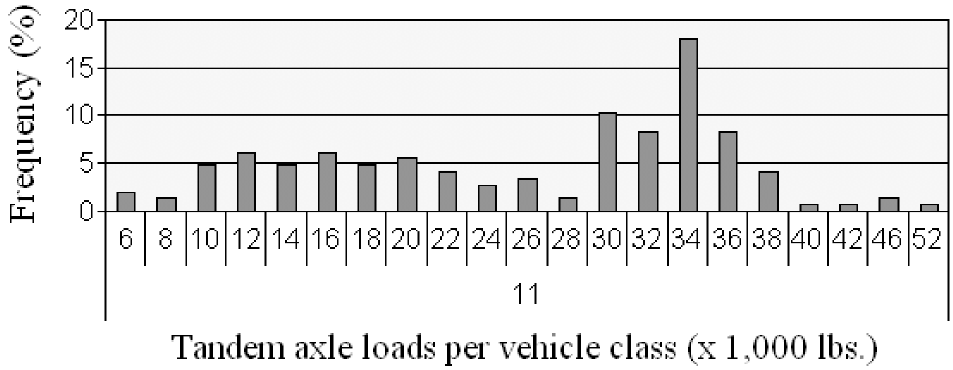

Figure D-13. Tandem axle load spectrum for Class 11 vehicles (Station P4N-2002)

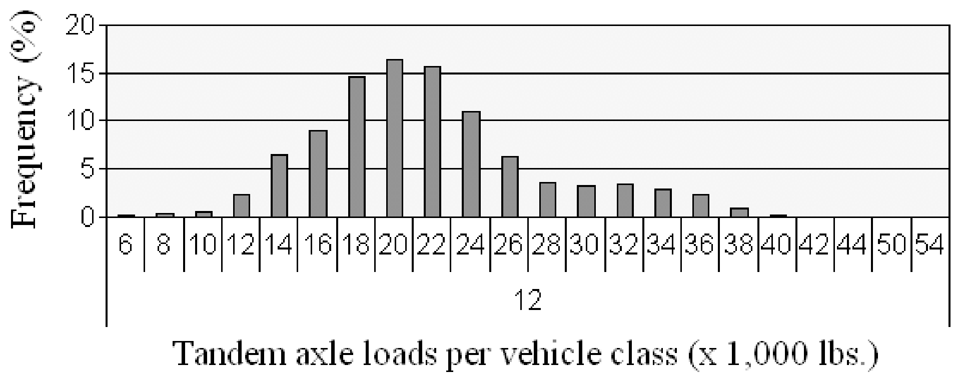

Figure D-14. Tandem axle load spectrum for Class 12 vehicles (Station P4N-2002)

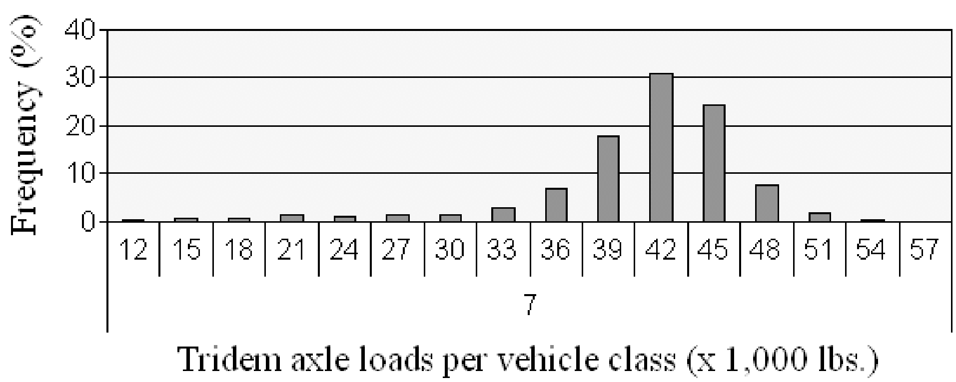

Figure D-15. Tridem axle load spectrum for Class 7 vehicles (Station P4N-2002)

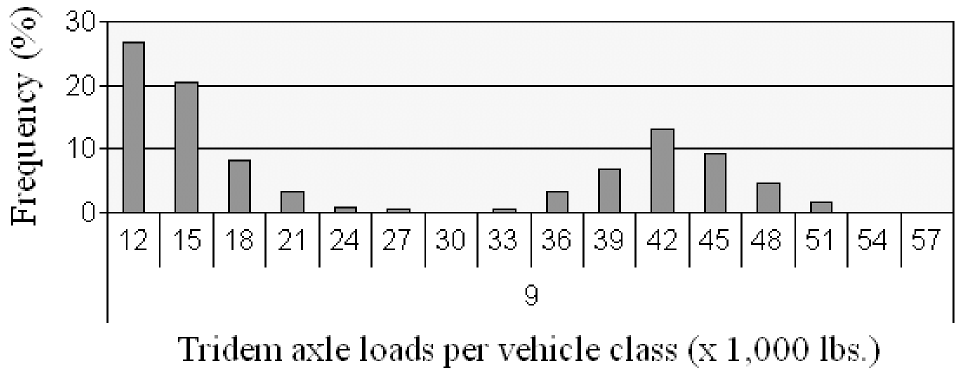

Figure D-16. Tridem axle load spectrum for Class 9 vehicles (Station P4N-2002)

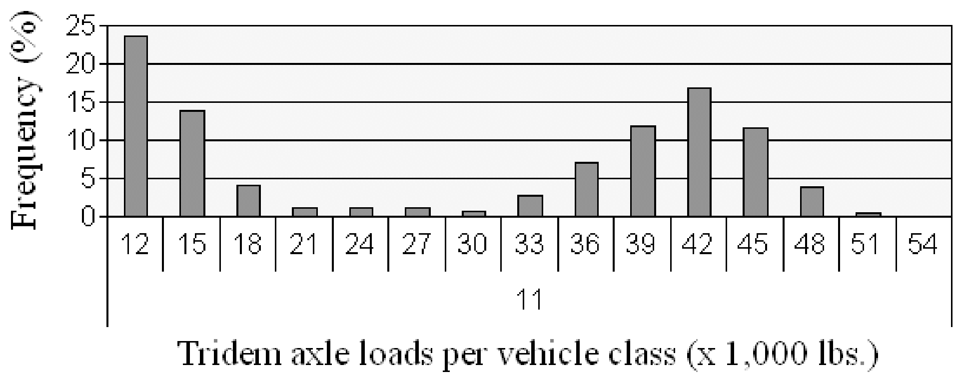

Figure D-17. Tridem axle load spectrum for Class 11 vehicles (Station P4N-2002)

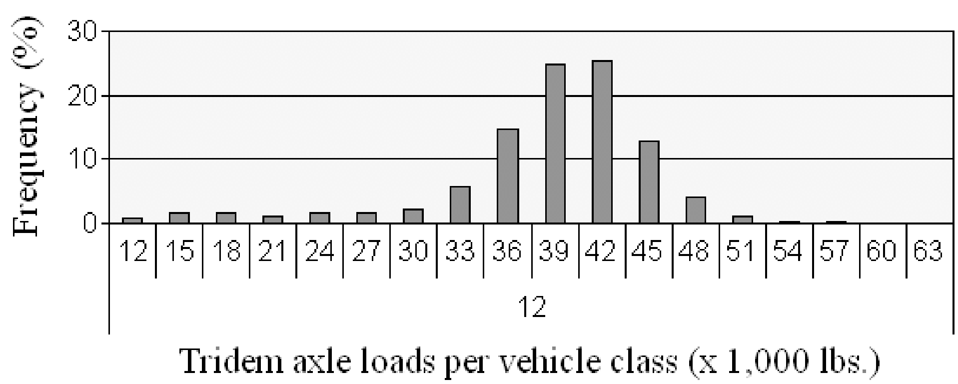

Figure D-18. Tridem axle load spectrum for Class 12 vehicles (Station P4N-2002)

Load spectra for Station P1S and remaining vehicle classes.

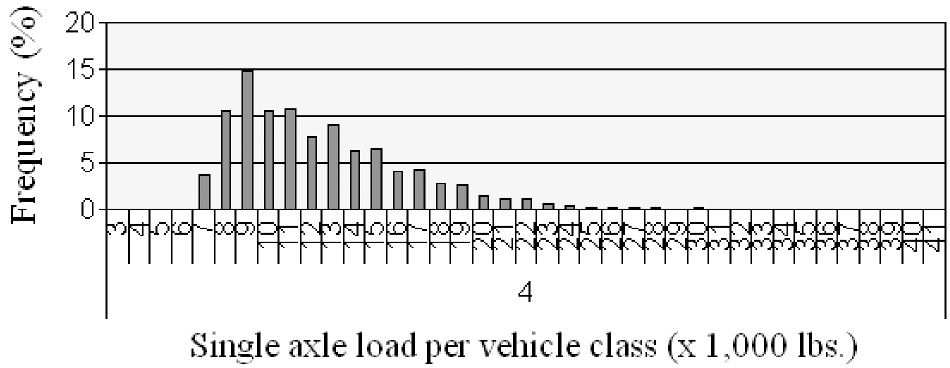

Figure D-19. Single axle load spectrum for Class 4 vehicles (Station P1S-2000)

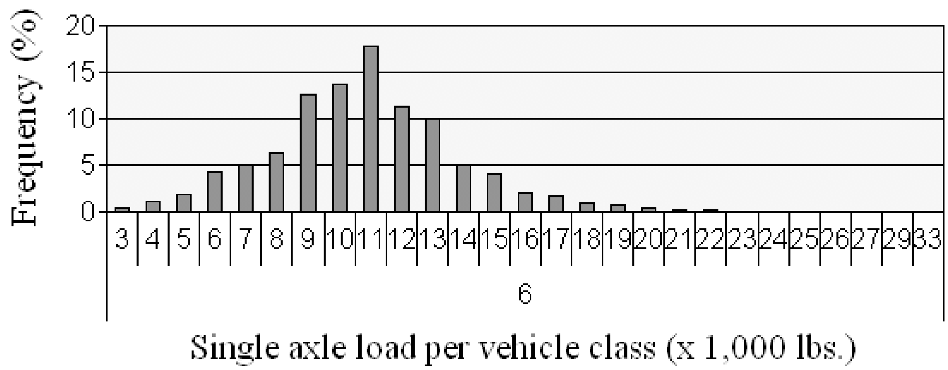

Figure D-20. Single axle load spectrum for Class 6 vehicles (Station P1S-2000)

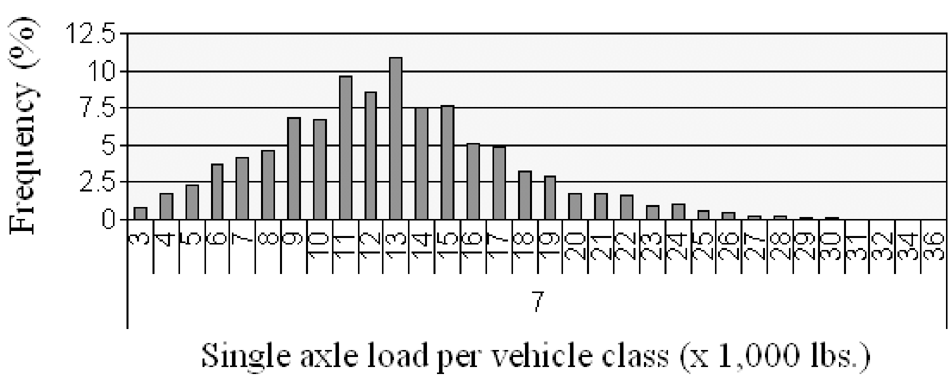

Figure D-21. Single axle load spectrum for Class 7 vehicles (Station P1S-2000)

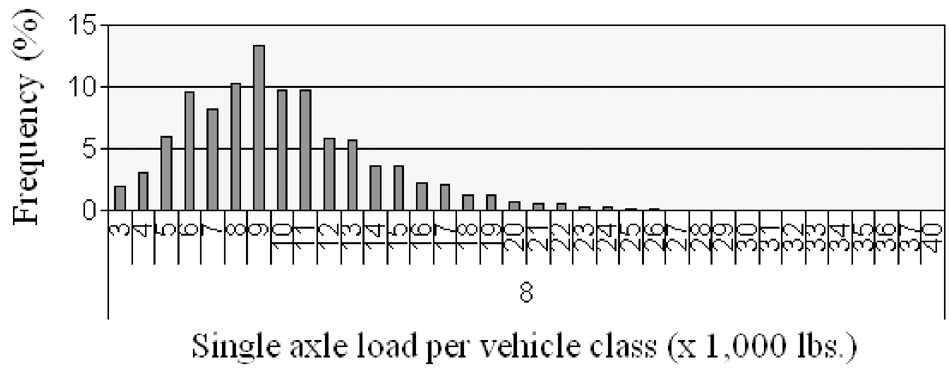

Figure D-22. Single axle load spectrum for Class 8 vehicles (Station P1S-2000)

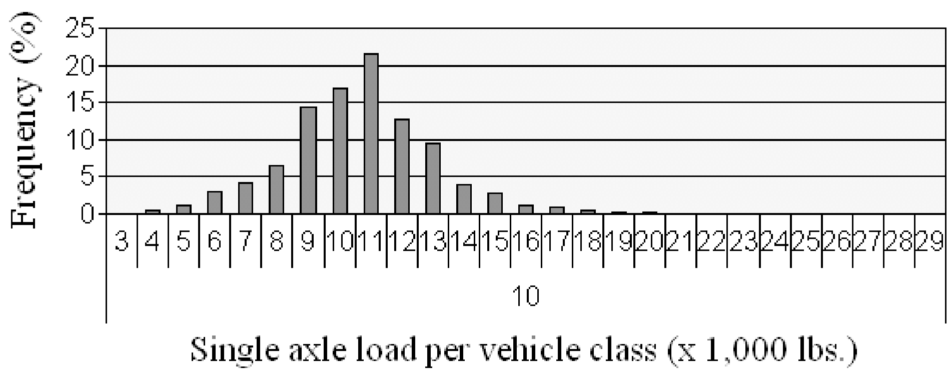

Figure D-23. Single axle load spectrum for Class 10 vehicles (Station P1S-2000)

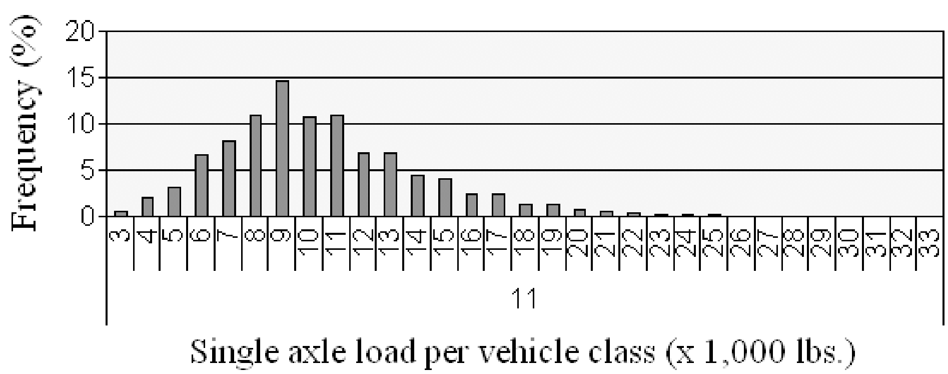

Figure D-24. Single axle load spectrum for Class 11 vehicles (Station P1S-2000)

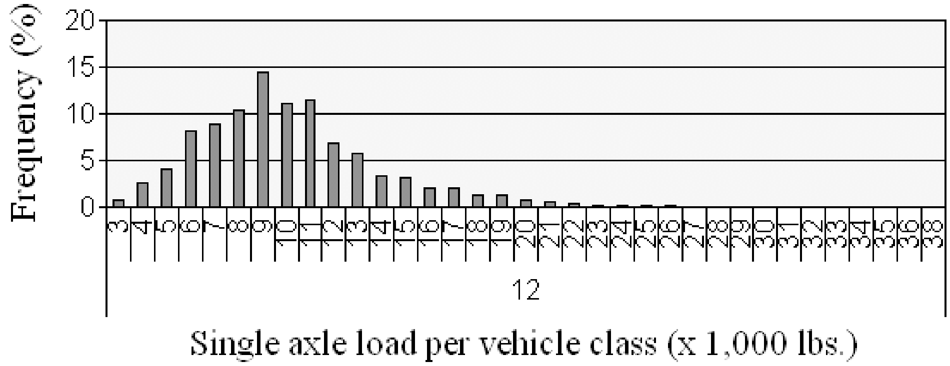

Figure D-25. Single axle load spectrum for Class 12 vehicles (Station P1S-2000)

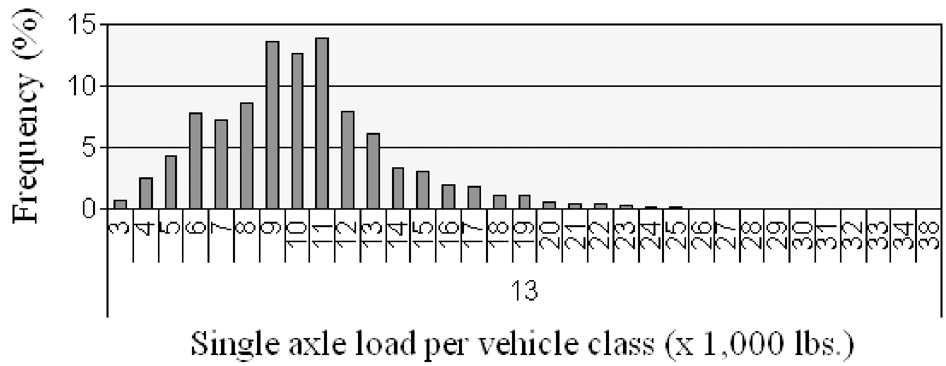

Figure D-26. Single axle load spectrum for Class 13 vehicles (Station P1S-2000)

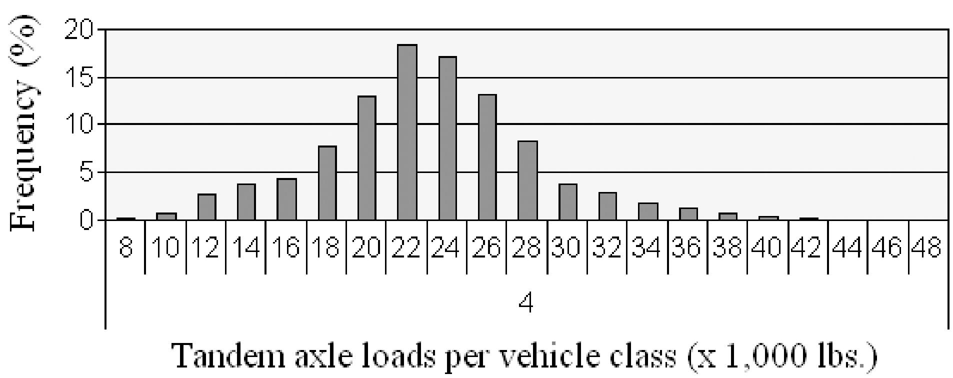

Figure D-27. Tandem axle load spectrum for Class 4 vehicles (Station P1S-2000)

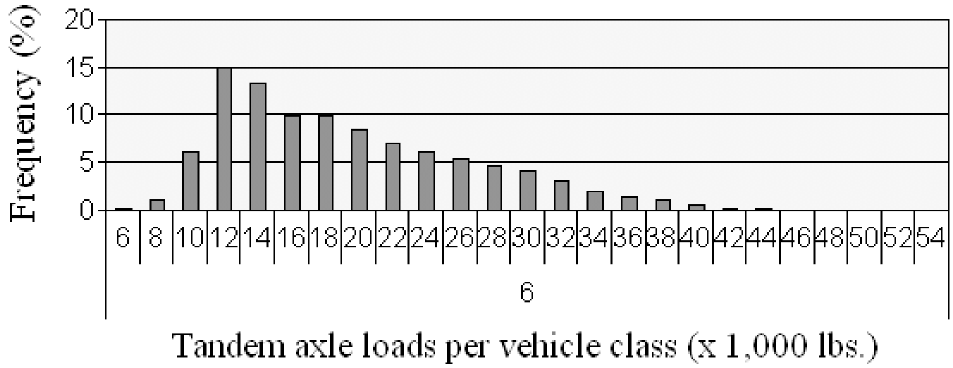

Figure D-28. Tandem axle load spectrum for Class 6 vehicles (Station P1S-2000)

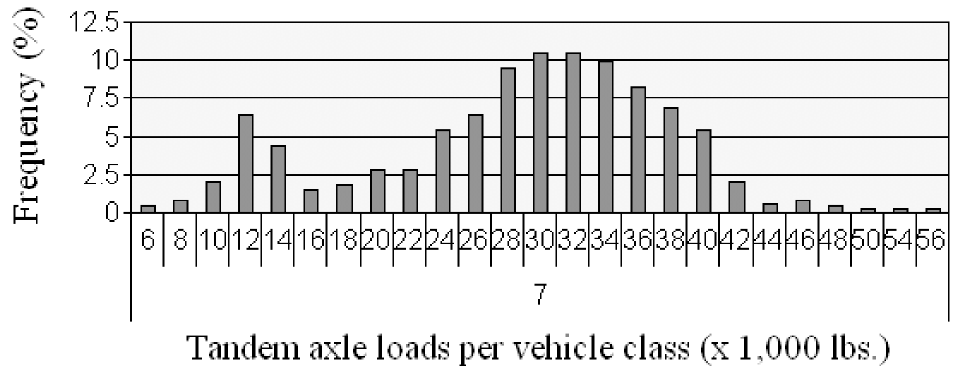

Figure D-29. Tandem axle load spectrum for Class 7 vehicles (Station P1S-2000)

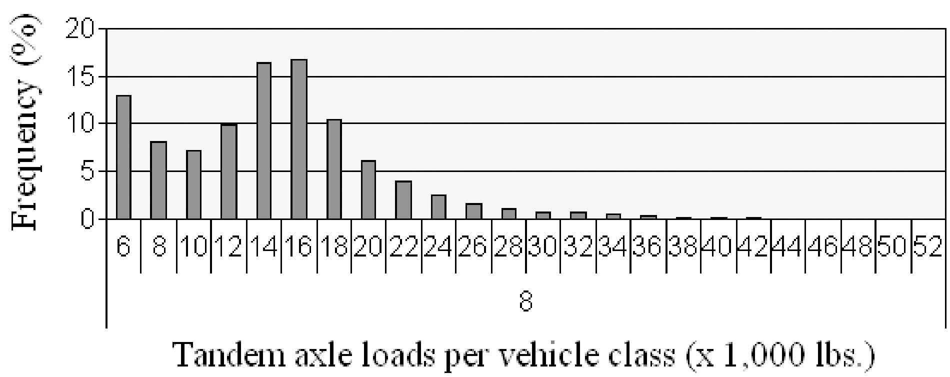

Figure D-30. Tandem axle load spectrum for Class 8 vehicles (Station P1S-2000)

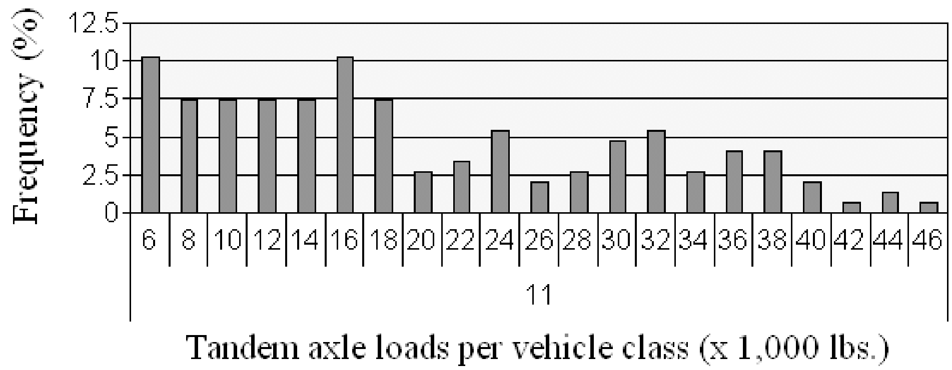

Figure D-31. Tandem axle load spectrum for Class 11 vehicles (Station P1S-2000)

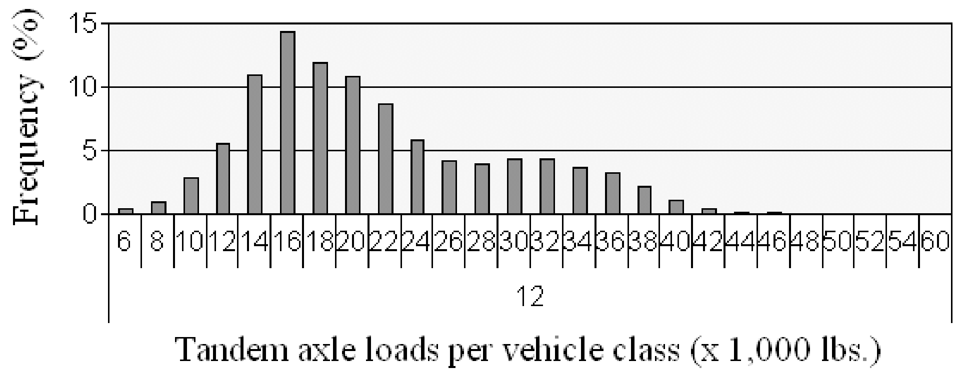

Figure D-32. Tandem axle load spectrum for Class 12 vehicles (Station P1S-2000)

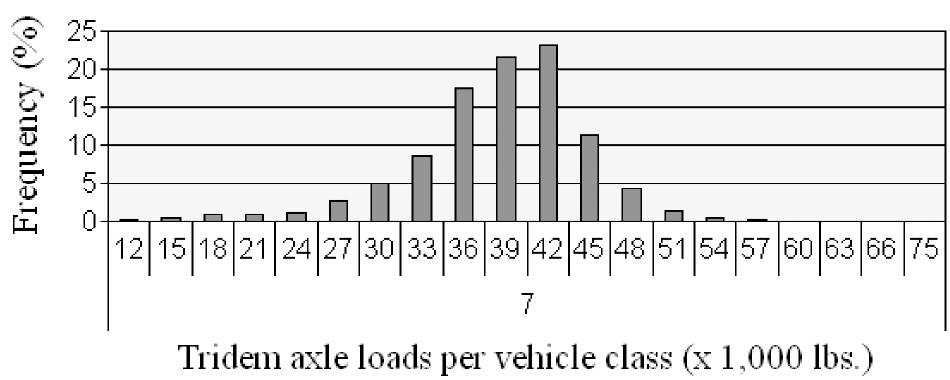

Figure D-33. Tridem axle load spectrum for Class 7 vehicles (Station P1S-2000)

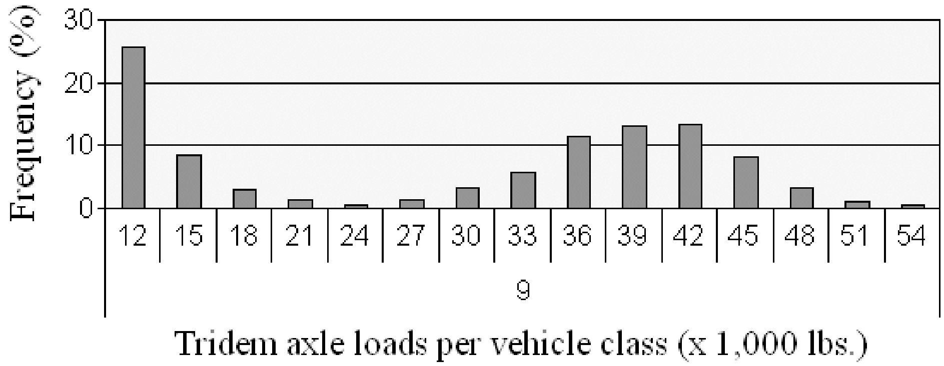

Figure D-34. Tridem axle load spectrum for Class 9 vehicles (Station P1S-2000)

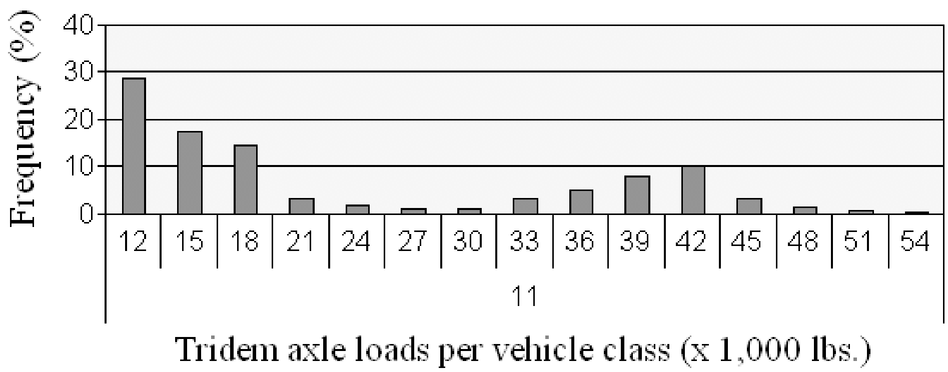

Figure D-35. Tridem axle load spectrum for Class 11 vehicles (Station P1S-2000)

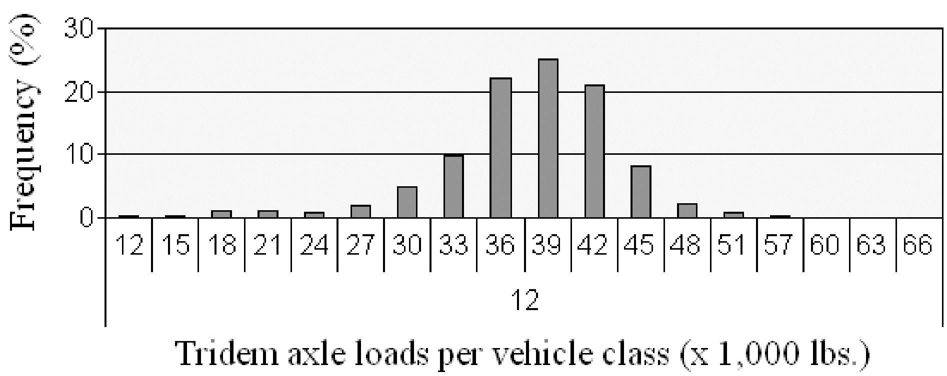

Figure D-36 .Tridem axle load spectrum for Class 12 vehicles (Station P1S-2000)

APPENDIX E TRIDEM AXLE LOAD SPECTRA

Tridem axle load spectra for the remaining stations (Class 10 vehicles).

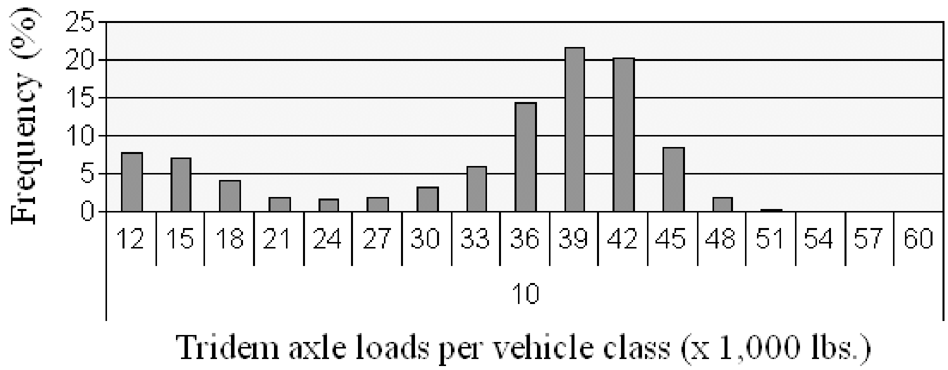

Figure E-1. Tridem axle load spectrum for Class 10 vehicles (Station B03-2002)

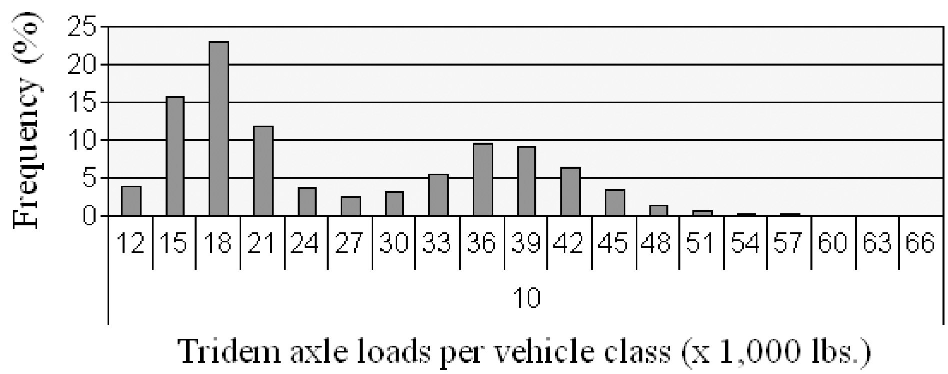

Figure E-2. Tridem axle load spectrum for Class 10 vehicles (Station B04-SB-2002)

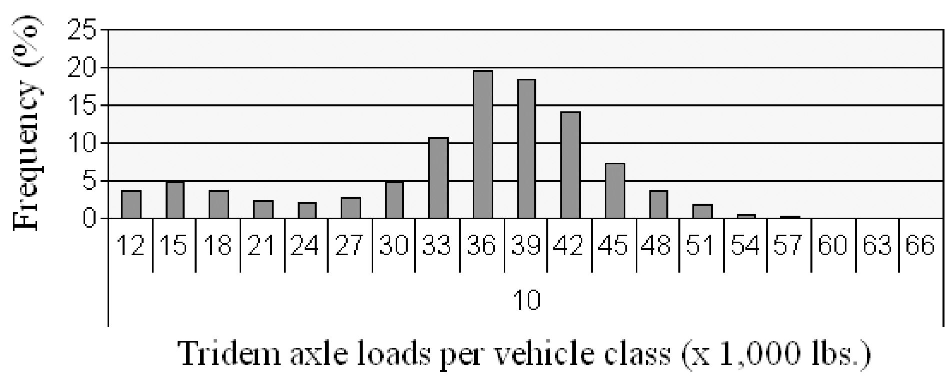

Figure E-3. Tridem axle load spectrum for Class 10 vehicles (Station B03-NB-2002)

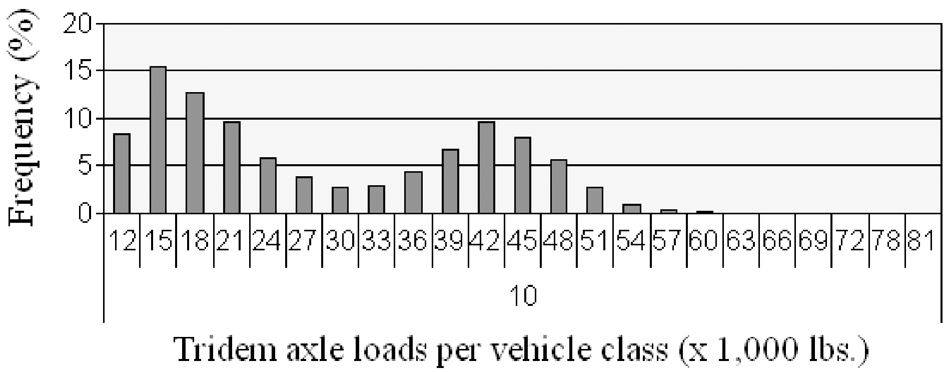

Figure E-4. Tridem axle load spectrum for Class 10 vehicles (Station P1N-2002)

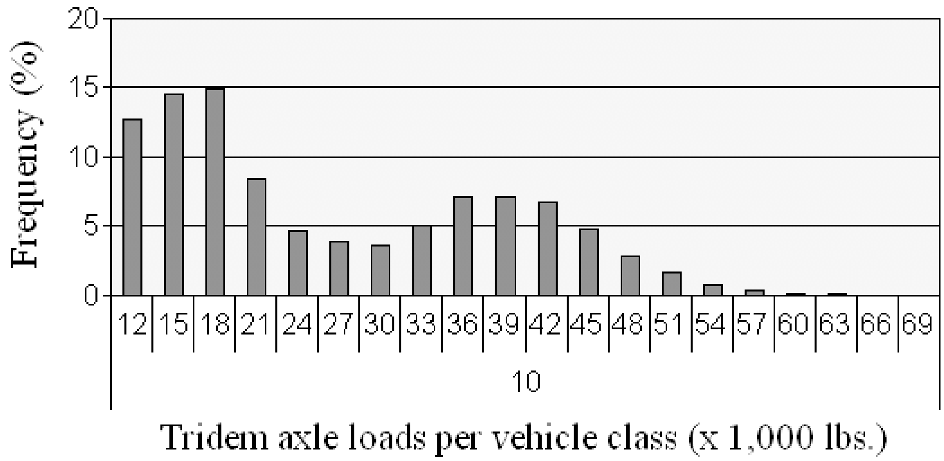

Figure E-5. Tridem axle load spectrum for Class 10 vehicles (Station P3N-2000)

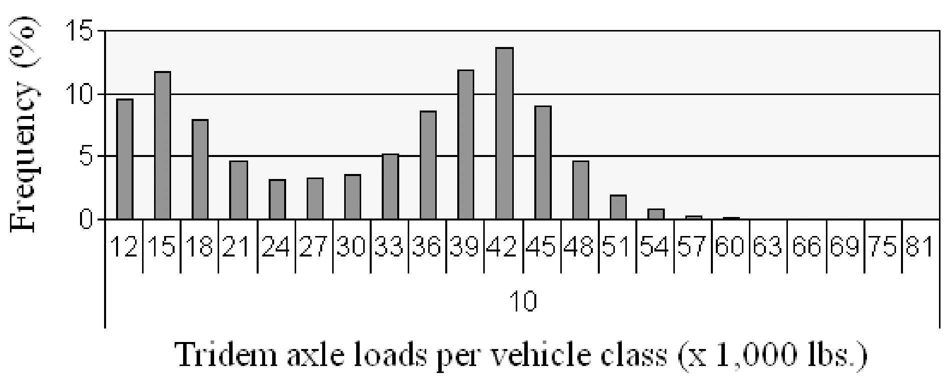

Figure E-6. Tridem axle load spectrum for Class 10 vehicles (Station P3S-2001)

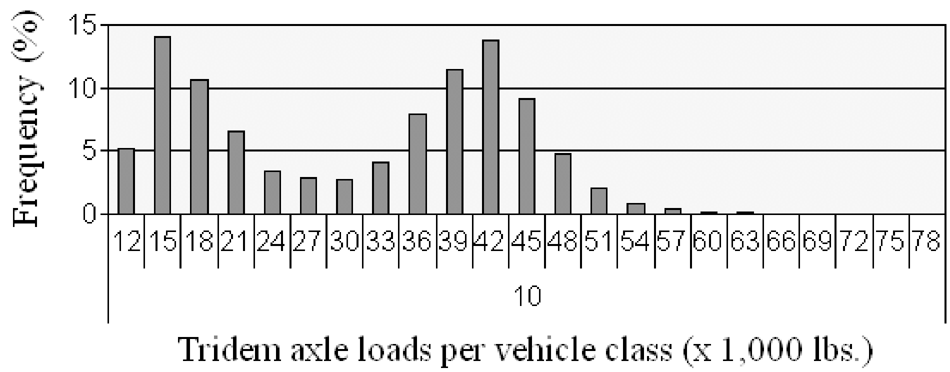

Figure E-7. Tridem axle load spectrum for Class 10 vehicles (Station 6N-2000)

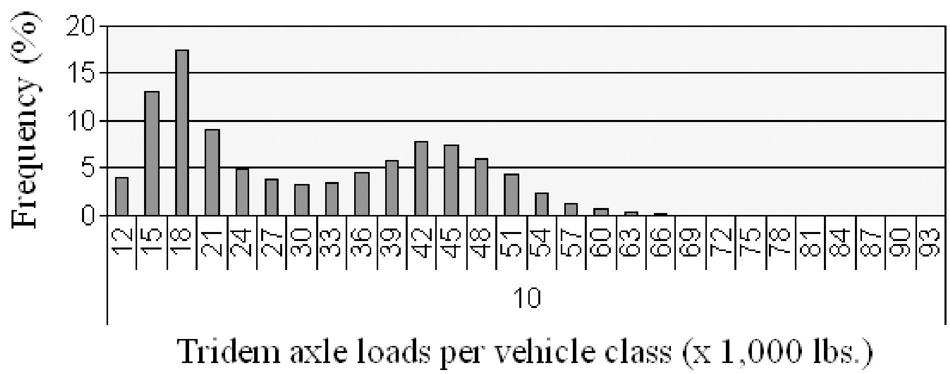

Figure E-8. Tridem axle load spectrum for Class 10 vehicles (Station P6S-2000)

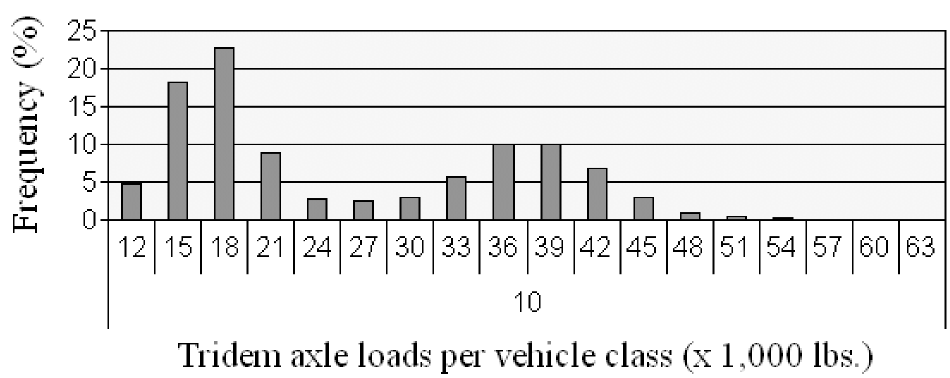

Figure E-9. Tridem axle load spectrum for Class 10 vehicles (Station P04 (SB))

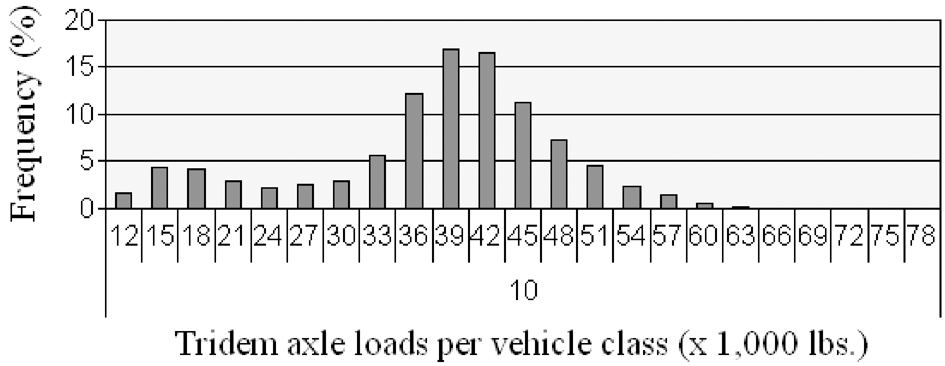

Figure E-10. Tridem axle load spectrum for Class 10 vehicles (Station P04-NB-2001)

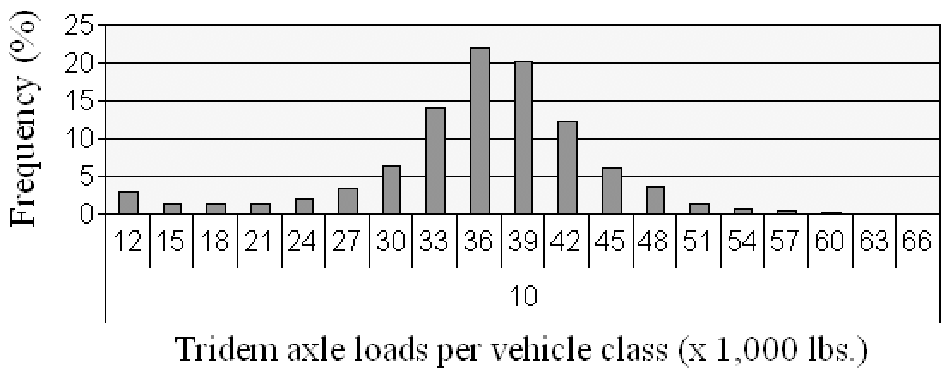

Figure E-11. Tridem axle load spectrum for Class 10 vehicles (Station P18-SB-2002)

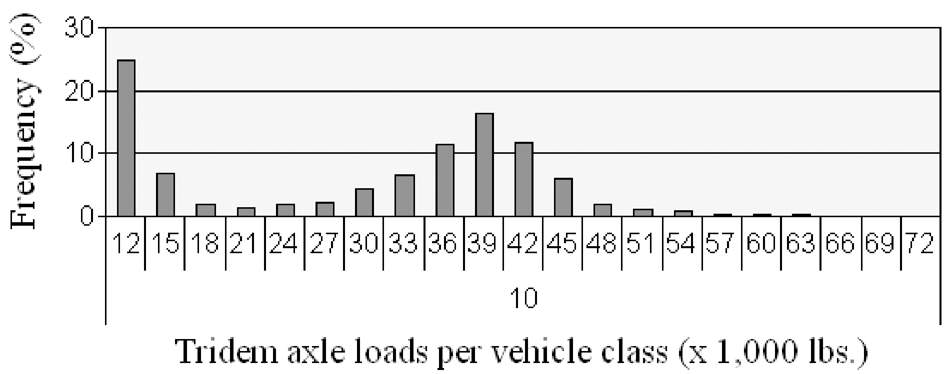

Figure E-12. Tridem axle load spectrum for Class 10 vehicles (Station P18-NB-2002)

APPENDIX F: STATISTICS REPORT

Report prepared by the Statistics Department at the University of Washington

Problem statement

As I understand, you want to decide on whether to aggregate load spectra from different highways in different regions in terms of potential road damages. Load spectra are the distributions of trucks by load size averaging over a period of time, which can be displayed as histograms with the number of trucks on the vertical axis and load size on the horizontal axis. The period can be a day, a month or a year. The load size is represented by kips or 1000 pounds. A typical load spectrum has two modes, one around 30 kips and the other around 70 kips, representing empty load and full load for trucks. As you commented, load spectra with extreme modes are probably not accurate in recording the information, maybe because of mal-calibration of sensors or detectors. So the focus of this analysis will be on distinguishing “valid” load spectra. The practical reason for distinguishing “valid” load spectra is that highway pavement should be designed with added strength for those highways that have extremely heavy truck load.

Since the load spectra are empirically derived and do not have any a priori rationale for using any common distributions, such as the normal distribution, some sort of empirical summaries are preferred. These load spectra are typically bi-modal but can be in other shapes. So one cannot simply use common statistics, such as means or median to describe them. In addition, since every pin in histogram should not be treated equal, appropriate weights should be assigned to the pins depending on their load sizes. So the pavement damage function is used to evaluate the potential damages of a load spectrum.

A key challenge in distinguishing two load spectra in terms of pavement damage is that we do not know the potential variability of the damage index. We can easily calculate two indexes for two load spectra. Without the knowledge of variability, we cannot evaluate how different the two load spectra are given a particular difference between these two indexes. Comes to the rescue the bootstrap method. In a nutshell, the bootstrap method is to generate fake samples based on one or a few original samples. The variation in a large number of these fake samples has proven to approximate reasonably well the true variability in underlying population. The name bootstrap, based on an old saying about pulling oneself up pulling one’s own bootstrap, implies many new samples generated by an original sample. The power of bootstrap is that one particular sample can generate valuable information about whole population for any statistics one is interested in. To certain extent, the bootstrap is similar to a hologram that one tiny part can provide all information of the whole (To have a better understanding of the bootstrap, you are encouraged to read an introductory article by Diaconis and Efron listed in the reference).

The actual procedure of the bootstrap is quite simple. It generates fake samples by sampling with replacement. In the context of your study, many additional samples can be generated by sampling each load spectrum with replacement. For example, say, the first load spectrum has a total of 22200 trucks distributed across load size. A fake sample of 22200 trucks can be obtained by sampling the original spectrum with replacement. This new sample probably has different frequency distribution because the chance of getting exactly the same distribution may be small. Then we can calculate the pavement damage index for this fake sample. If we run this sampling process 1000 times, we will have 1000 indexes for each spectrum. Then a statistic test, such as t test, can be used to evaluate the statistical difference between two distributions of damage indexes derived from two original load spectra.

Results

First, let me discuss the pavement damage index to make sure that they are calculated correctly. From email communications with you, the pavement damage index appears to be something like this:

Pavement Damage Index (PDI) = $\mathbf{\Sigma(N_i*(load_i/80)^{\wedge}4)/1000}$

The weight assigned to the load size in terms of their potential in damaging the pavement is proportional to a load size divided by 80 then raised to the power of 4, as you described in the email. Essentially, 80 kips load size has a weight of 1 and 120 kips load size has a weight about 5 (see Figure F-1).

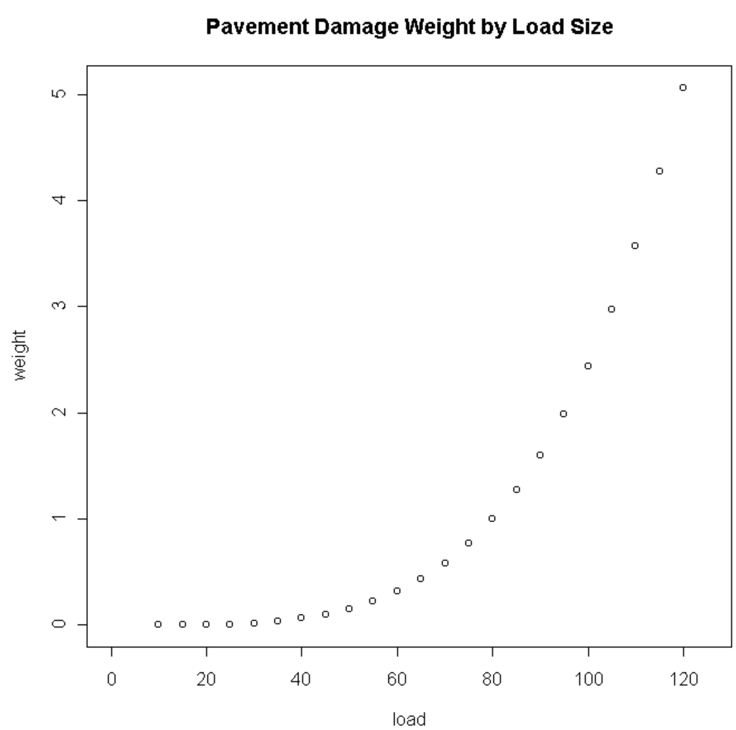

Figure F-1. Pavement Damage Weight by Load Size

Since each load size has different number of vehicles, the potential pavement damage for that load is the multiplication of number of vehicles and specific weight assigned to the load size. Therefore, the total pavement damage index for a load spectrum at a particular location and time is the sum of the effects from all load sizes. Since the PDI is around 10s of thousands, I feel that it is easier to compare PDI by dividing it by 1000.

To illustrate the use of the bootstrap, I simulated two load spectra based on several load spectra from your research methodology report by specifying frequencies based on your chart. On the vertical axes is the number of trucks in thousands. On the horizontal axes is the load size. These two load spectra are quite different, especially at the high end. The lower spectrum has more trucks on the higher load (see Figure F-2). The PDI are 16.3 and 25.6 for the upper and lower spectra correspondingly. So the PDI for the lower spectrum is about 60% larger than the first one, a very large difference.

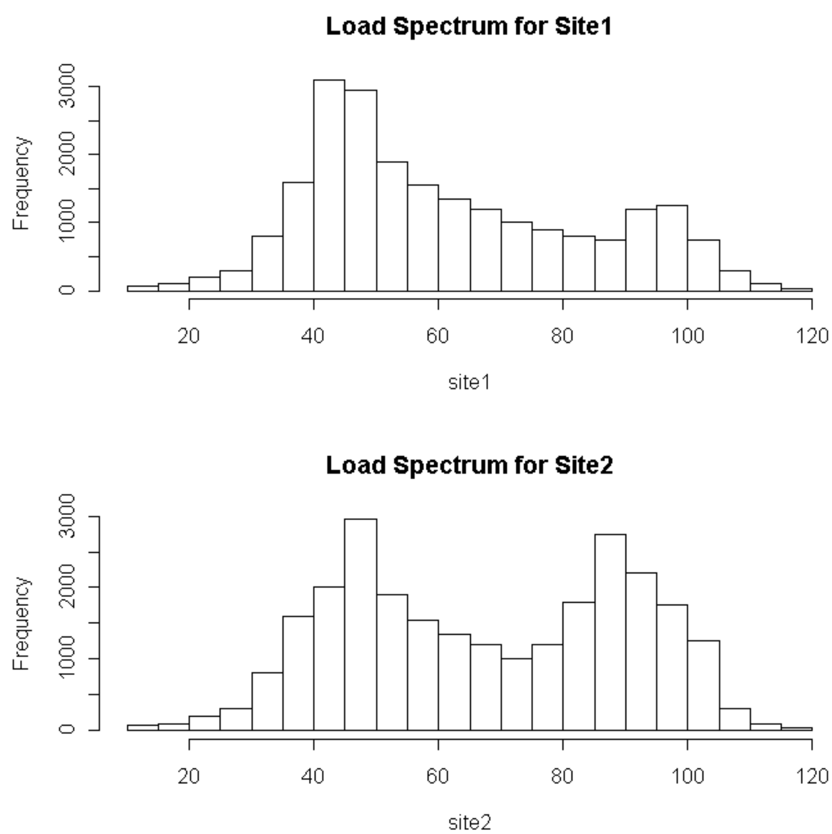

Figure F-2. Two simulated load spectra

What will the bootstrap method tell us about their difference? I generate 1000 samples for each load spectrum and calculate 1000 pavement indexes based on those samples. The distributions of PDI are shown in Figure F-3. As one can see, the distributions are close to normal distributions with nice bell-shape curves, as central limit theory would predict.

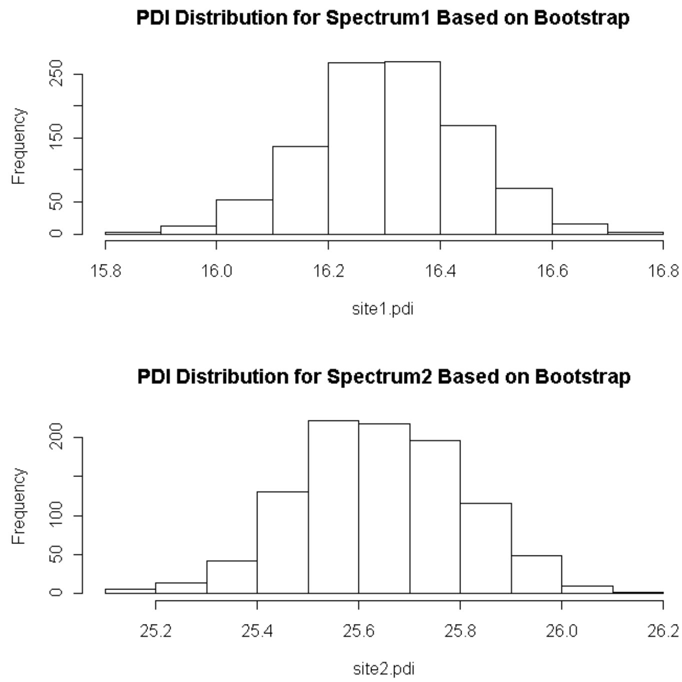

Figure F-3. Derived distributions of PDI

A natural way to test the mean difference between derived PDI distributions is the two-sample t test. The t statistic is 1364, with basically a zero p value. The result is not surprising since two PDI distributions do not overlap at all. The variability of each PDI is fairly narrow, within a range of 1. The explanation for this low variability of PDI is that we have a huge sample size and large degree of freedom. For example, the first spectrum has 22200 cases. Even a small difference between two spectra with similar sample sizes would be identified to distinguish these two.

To test the idea that a small difference between two spectra can be picked up statistically, I replicate the first load spectrum with just one small change. I change the number of trucks at load size 90 kips from 1200 to 1250. It is a relative small change that is barely identifiable visually from the charts of load spectra.

The PDI are 16.30466 and 16.41010 respectively for the two spectra. The difference of PDI is only about 0.1. However, the t test based on bootstrap samples indicates that the difference is statistically significant with a t statistic of 17 and a p value close to zero.

This raises doubt of the usefulness of the bootstrap method in distinguishing load spectra or any statistic method for that purpose. The basic reason is the large sample size for load spectra. Other criteria in addition to statistical significance should be used to distinguish them. For example, it is perceivable to categorize load spectra by PDI, say all spectra with PDI under 10 can be grouped together. But I have no substantive knowledge to judge whether it is a reasonable thing to do.

Summary

The objective of the report is to provide rationales and results for using the bootstrap method to distinguish load spectra statistically in terms of their pavement damage. The bootstrap method is a powerful tool to explore potential variability of summary statistics in wide range of applications. However, in this case, it does not help you to make the decision as whether to aggregate load spectra from different sources, because a small difference in load spectra that cannot be identified visually can be statistically significant. The limitation is not just for the bootstrap method since the cause comes from large sample size. Methods or criteria other than statistics should be explored in order to make reasonable decision.

References

Diaconis, P. and Efron, B. (1983). Computer-Intensive Methods in Statistics. Scientific American, 48, 116-130. (for introduction to the bootstrap method)

Venables, W. N., & Ripley, B. D. (1999). Modern Applied Statistics with S-Plus. New York: Springer-Verlag. (for statistical functions related to bootstrap in S-Plus and R).

APPENDIX G: 2002 DESIGN GUIDE INPUT

2002 Design Guide Sensitivity analysis input

The inputs for the five load spectra were similar to the example below. The two differences were:

1. The load spectrum associated with:
   a. Station P1N,
   b. Station P4N,
   c. Station P6 (NB)
   d. Station P6 (SB), and
   e. Station P18
2. The pavement section properties associated with the thin and thick HMA:
   a. Traffic (i.e. 10,000, and 1,000 daily Class 9 vehicles, respectively),
   b. Thickness of AC (i.e. 8 and 4 inch, respectively), and
   c. Thickness of base (i.e. 12 and 8 inch, respectively)

Project: AC_New.dgp

General Information

Design Life	30 years
Pavement construction month:	November, 1990
Traffic open month:	November, 1990
Type of design	Flexible

Description:

Analysis Parameters

Analysis type	Deterministic

Performance Criteria

	Limit	Reliability
Initial IRI (in/mi)	63	
Terminal IRI (in/mi)	300	50
AC Bottom Up Cracking (Alligator Cracking) ():	100	50
Permanent Deformation (AC Only) (in):	3	50
Permanent Deformation (Total Pavement) (in):	3	50

Default Input Level

Default input level	Level 3, Default and historical agency values.

Traffic

Two-way average annual daily truck traffic:	10000
Number of lanes in design direction:	1
Percent of trucks in design direction (%):	100
Percent of trucks in design lane (%):	100
Operational speed (mph):	60

Traffic -- Monthly Adjustment Factors

Monthly Adjustment Factors (Level 3, Default MAF)

	Vehicle Class									
Month	**Class 4**	**Class 5**	**Class 6**	**Class 7**	**Class 8**	**Class 9**	**Class 10**	**Class 11**	**Class 12**	**Class 13**
January	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
February	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
March	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
April	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
May	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
June	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
July	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
August	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
September	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
October	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
November	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
December	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Vehicle Class Distribution

(Level 3, Default Distribution)

AADTT distribution by vehicle class

Class 4	0.0%
Class 5	0.0%
Class 6	0.0%
Class 7	0.0%
Class 8	0.0%
Class 9	100.0%
Class 10	0.0%
Class 11	0.0%
Class 12	0.0%
Class 13	0.0%

Hourly truck traffic distribution

by period beginning:

Midnight	2.3%	Noon	5.9%
1:00 am	2.3%	1:00 pm	5.9%
2:00 am	2.3%	2:00 pm	5.9%
3:00 am	2.3%	3:00 pm	5.9%
4:00 am	2.3%	4:00 pm	4.6%
5:00 am	2.3%	5:00 pm	4.6%
6:00 am	5.0%	6:00 pm	4.6%
7:00 am	5.0%	7:00 pm	4.6%
8:00 am	5.0%	8:00 pm	3.1%
9:00 am	5.0%	9:00 pm	3.1%
10:00 am	5.9%	10:00 pm	3.1%
11:00 am	5.9%	11:00 pm	3.1%

Traffic Growth Factor

Vehicle Class	Growth Rate	Growth Function
Class 4	4.0%	No Growth
Class 5	4.0%	No Growth
Class 6	4.0%	No Growth
Class 7	4.0%	No Growth
Class 8	4.0%	No Growth
Class 9	4.0%	No Growth
Class 10	4.0%	No Growth
Class 11	4.0%	No Growth
Class 12	4.0%	No Growth
Class 13	4.0%	No Growth

Traffic -- Axle Load Distribution Factors

Level 1: Site Specific -- normalized initial axle load distribution factors are summarized in worksheet: "Initial LDF"

Traffic -- General Traffic Inputs

Mean wheel location (inches from the lane marking):	20
Traffic wander standard deviation (in):	9
Design lane width (ft):	12

Number of Axles per Truck

Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0.00	0.00
Class 5	2.00	0.00	0.00	0.00
Class 6	1.02	0.99	0.00	0.00
Class 7	1.00	0.26	0.83	0.00
Class 8	2.38	0.67	0.00	0.00
Class 9	1.00	2.00	0.00	0.00
Class 10	1.19	1.09	0.89	0.00
Class 11	4.29	0.26	0.06	0.00
Class 12	3.52	1.14	0.06	0.00
Class 13	2.15	2.13	0.35	0.00

Axle Configuration

Average axle width (edge-to-edge) outside dimensions,ft):	8.5
Dual tire spacing (in):	12

Axle Configuration

Single Tire (psi):	120
Dual Tire (psi):	120

Average Axle Spacing

Tandem axle(psi):	51.6
Tridem axle(psi):	49.2
Quad axle(psi):	49.2

Climate

icm file:	C:\DG2002\Projects\seatlle.icm
Latitude (degrees.minutes)	47.28
Longitude (degrees.minutes)	-122.19
Elevation (ft)	447
Depth of water table (ft)	10

Structure--Design Features

Structure--Layers

Layer 1 -- Asphalt concrete

Material type:	Asphalt concrete
Layer thickness (in):	8

General Properties

General

Reference temperature (F°):	70
Design frequency (Hz):	n/a

Volumetric Properties

Effective binder content (%):	9
Air voids (%):	4
Total unit weight (pcf):	145

Poisson's ratio: 0.35 (user entered)

Thermal Properties

Thermal conductivity asphalt (BTU/hr-ft-F°):	0.67
Heat capacity asphalt (BTU/lb-F°):	0.23

Asphalt Mix

Cumulative % Retained 3/4 inch sieve:	2
Cumulative % Retained 3/8 inch sieve:	38
Cumulative % Retained #4 sieve:	65
% Passing #200 sieve:	4

Asphalt Binder

Option:	Superpave binder grading
A	10.3120 (correlated)
VTS:	-3.4400 (correlated)

High temp. °F	Low temperature, °F						
	14	3.2	-7.6	-18.4	-29.2	-40	-50.8
114.8							
125.6							
136.4							
147.2							
158							
168.8							
179.6							

Layer 2 -- Crushed gravel

Unbound Material:	Crushed gravel
Thickness(in):	12

Strength Properties

Input Level:	Level 2
Analysis Type:	ICM inputs (Using ICM)
Poisson's ratio:	0.4
Coefficient of lateral pressure,Ko:	0.5
Modulus (input) (psi):	40000

ICM Inputs

Gradation and Plasticity Index

Plasticity Index, PI:	1
Passing #200 sieve (%):	10
Passing #4 sieve (%):	30
D60 (mm):	2

Thermal Properties

Dry thermal conductivity (BTU/hr-ft-F°):	0.23
Dry heat capacity (BTU/lb-F°):	0.17

Calculated/Derived Parameters

Maximum dry unit weight (pcf):	122.3 (derived)
Specific gravity of solids, Gs:	2.67 (derived)
Saturated hydraulic conductivity (ft/hr):	37 (derived)
Optimum gravimetric water content (%):	11.2 (derived)
Calculated degree of saturation (%):	82.8 (calculated)

Soil water characteristic curve parameters: Default values

Parameters	Value
a	11.4
b	1.72
c	0.518
Hr.	371

Layer 3 -- CL

Unbound Material:	CL
Thickness(in):	Semi-infinite

Strength Properties

Input Level:	Level 3
Analysis Type:	ICM inputs (Using ICM)
Poisson's ratio:	0.45
Coefficient of lateral pressure,Ko:	0.5
Modulus (input) (psi):	14000

ICM Inputs

Gradation and Plasticity Index

Plasticity Index, PI:	15
Passing #200 sieve (%):	75
Passing #4 sieve (%):	95
D60 (mm):	0.1

Thermal Properties

Dry thermal conductivity (BTU/hr-ft-F°):	0.23
Dry heat capacity (BTU/lb-F°):	0.17

Calculated/Derived Parameters

Maximum dry unit weight (pcf):	107.9 (derived)
Specific gravity of solids, Gs:	2.73 (derived)
Saturated hydraulic conductivity (ft/hr):	3.29e-006 (derived)
Optimum gravimetric water content (%):	18.6 (derived)
Calculated degree of saturation (%):	87.6 (calculated)

Soil water characteristic curve parameters: Default values

Parameters	Value
a	68.1
b	1.15
c	0.658
Hr.	2720

Distress Model Calibration Settings - Flexible

AC Fatigue	Level 3 (Nationally calibrated values)
k1	1
k2	3.9492
k3	1.281
AC Rutting	Level 3 (Nationally calibrated values)
k1	-2.051
k2	1.5606
k3	0.4791
Standard Deviation Total Rutting (RUT):	RUT*1
Thermal Fracture	Level 3 (Nationally calibrated values)
k1	353.47
Std. Dev. (THERMAL):	THERMAL*1
CTB Fatigue	Level 3 (Nationally calibrated values)
k1	1
k2	1
Subgrade Rutting	Level 3 (Nationally calibrated values)
Granular:	
k1	6.3
Fine-grain:	
k1	2.9
AC Cracking	
AC Top Down Cracking	
C1 (top)	4.2
C2 (top)	2.1
C3 (top)	0
C4 (top)	1000
Standard Deviation (TOP)	TOP*1
AC Bottom Up Cracking	
C1 (bottom)	1
C2 (bottom)	1
C3 (bottom)	0
C4 (bottom)	6000
Standard Deviation (TOP)	BOTTOM*1
CTB Cracking	
C1 (CTB)	1
C2 (CTB)	1
C3 (CTB)	0
C4 (CTB)	1000
Standard Deviation (CTB)	CTB*1

IRI

IRI Flexible Pavements with GB

C1 (GB)	0.0463
C2 (GB)	0.00119
C3 (GB)	0.1834
C4 (GB)	0.00384
C5 (GB)	0.00736
C6 (GB)	0.00115
Std. Dev (GB)	0.387

IRI Flexible Pavements with ATB

C1 (ATB)	0.009995
C2 (ATB)	0.000518
C3 (ATB)	0.00235
C4 (ATB)	18.36
C5 (ATB)	0.9694
Std. Dev (ATB)	0.292

IRI Flexible Pavements with CTB

C1 (CTB)	0.00732
C2 (CTB)	0.07647
C3 (CTB)	0.000145
C4 (CTB)	0.00842
C5 (CTB)	0.000212
Std. Dev (CTB)	0.229

APPENDIX H: DEVELOPED LOAD SPECTRA

Table H-1. Developed single axle load spectra

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
4	4	5.57724484104852E-03
4	5	7.43632645473136E-03
4	6	7.99405093883621E-02
4	7	3.72188139059305
4	8	9.31213980293735
4	9	12.2885294664436
4	10	10.838445807771
4	11	15.4303773935676
4	12	11.2548800892359
4	13	9.27309908905001
4	14	4.31678750697156
4	15	3.37795129206172
4	16	2.23833426287414
4	17	2.93548986800521
4	18	2.57482803495073
4	19	3.74233128834356
4	20	2.82022680795687
4	21	2.44097415876557
4	22	1.90369957241123
4	23	0.747350808700502
4	24	0.485220301171221
4	25	0.12455846811675
4	26	5.76315300241681E-02
4	27	9.2954080684142E-03
4	28	7.43632645473136E-03
4	29	3.71816322736568E-03
4	30	1.85908161368284E-03
5	3	25.9771131062833
5	4	33.8863947744797
5	5	12.6789867981712
5	6	6.26669294751332
5	7	4.54633583592158

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
5	8	4.05942407350617
5	9	3.71526671926416
5	10	2.18691374959115
5	11	1.97299696714017
5	12	1.10143243145989
5	13	0.990687664848311
5	14	0.570749095432235
5	15	0.54556030031059
5	16	0.361827106043753
5	17	0.357423094956387
5	18	0.228901161638485
5	19	0.21096287257531
5	20	0.122345576305131
5	21	7.40625767009553E-02
5	22	6.14950328662754E-02
5	23	2.92705614953014E-02
5	24	2.47054280510801E-02
5	25	1.09026128138462E-02
5	26	8.4320700087382E-03
5	27	4.24288873051158E-03
5	28	3.00761732795758E-03
5	29	1.6112235685487E-03
5	30	0.001235271402554
5	31	4.29659618279654E-04
5	32	3.75952165994697E-04
5	33	5.37074522849567E-05
5	34	5.37074522849567E-05
5	35	1.07414904569913E-04
6	3	0.322676315321193
6	4	1.5066136781541
6	5	2.19348715819444
6	6	2.99780532653182
6	7	2.0629930600866
6	8	3.73569013583249
6	9	11.5416098226467
6	10	15.8894359096032

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
6	11	22.0677383000178
6	12	13.4812266445222
6	13	10.8606678925203
6	14	5.16875259505309
6	15	3.49724182928999
6	16	1.52678094786168
6	17	1.12462186369298
6	18	0.635862150779999
6	19	0.512485912568954
6	20	0.377246574529925
6	21	0.268106056112462
6	22	0.177946497419776
6	23	3.91482294323507E-02
6	24	1.06767898451865E-02
6	26	1.18630998279851E-03
7	3	1.32541526809536
7	4	1.14467682244599
7	5	1.45451415784491
7	6	2.50451846114123
7	7	2.15164816249247
7	8	2.65083053619072
7	9	5.77502366812979
7	10	8.86479042946897
7	11	19.0894224976332
7	12	17.0496600395903
7	13	14.3816163180997
7	14	6.10207418882864
7	15	4.44960840003443
7	16	2.84017557449006
7	17	2.59058438764093
7	18	1.92787675359325
7	19	2.1430415698425
7	20	1.66967897409416
7	21	1.11885704449608
7	22	0.542215336948102
7	23	0.180738445649367

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
7	24	3.44263705998795E-02
7	26	8.60659264996988E-03
8	3	3.71481335197857
8	4	6.13851556912435
8	5	6.93378451947608
8	6	8.79759604607223
8	7	7.14941448990702
8	8	9.55336841768166
8	9	14.8154869287674
8	10	9.95046915530695
8	11	9.30304550646356
8	12	5.16657948953341
8	13	4.53249927945431
8	14	2.77063162501735
8	15	2.85549589555824
8	16	1.96201923590132
8	17	2.08744756028566
8	18	1.41440450901483
8	19	1.27990264627078
8	20	0.676779214124831
8	21	0.393898312321865
8	22	0.238046947554948
8	23	9.98089219568954E-02
8	24	6.72509313720258E-02
8	25	3.36254656860129E-02
8	26	2.50856648768667E-02
8	27	9.07353835971776E-03
8	28	1.38771763148625E-02
8	29	5.87111305628796E-03
8	30	3.73616285400143E-03
8	31	1.6012126517149E-03
8	32	2.66868775285816E-03
8	33	2.66868775285816E-03
8	37	5.33737550571633E-04
9	3	0.272713458660766
9	4	1.40029807279135

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
9	5	1.83603581301316
9	6	2.111063813943
9	7	1.5348434212155
9	8	2.38116083351699
9	9	9.06364689343143
9	10	18.3081299806685
9	11	32.2823298786274
9	12	15.6337267048868
9	13	6.42225100305218
9	14	1.38761840644771
9	15	1.19168737175675
9	16	1.22690866715574
9	17	1.74244779952441
9	18	1.28899877933053
9	19	1.11430115415153
9	20	0.473474842435019
9	21	0.206497423310661
9	22	0.089763987131145
9	23	1.82144413349072E-02
9	24	7.64805271520966E-03
9	25	2.61643908678225E-03
9	26	1.30821954339113E-03
9	27	3.01896817705645E-04
9	28	4.02529090274193E-04
9	29	2.01264545137096E-04
9	30	6.03793635411289E-04
9	32	4.02529090274193E-04
9	33	2.01264545137096E-04
9	34	2.01264545137096E-04
10	3	7.49907689028127E-02
10	4	0.427104785324649
10	5	0.770463534311132
10	6	1.71070312410782
10	7	2.24705842047362
10	8	3.77618491124823
10	9	11.5957807224238

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
10	10	21.5577524086502
10	11	32.2475532834156
10	12	15.0876097739238
10	13	7.029718422986
10	14	1.84050948043198
10	15	0.950898176239727
10	16	0.336126136757277
10	17	0.193757874982394
10	18	8.03200621243324E-02
10	19	0.044157000978306
10	20	1.44652244584106E-02
10	21	6.85194842766817E-03
10	22	3.04531041229696E-03
10	23	1.14199140461136E-03
10	24	1.52265520614848E-03
10	25	7.61327603074241E-04
10	26	1.14199140461136E-03
10	28	3.8066380153712E-04
11	3	0.348666018826297
11	4	1.4367876015031
11	5	1.58526260473535
11	6	4.81918163581084
11	7	3.64180822534835
11	8	4.09140388120331
11	9	10.0203944597136
11	10	11.9751763140663
11	11	12.5248674777183
11	12	7.58014939254539
11	13	9.13454921570999
11	14	6.94829649957668
11	15	7.71235887576062
11	16	5.22373431315714
11	17	5.27503326090311
11	18	3.0887805447698
11	19	2.57579106731006
11	20	1.15193246889741

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
11	21	0.56095190827915
11	22	0.25148996334002
11	23	4.00382031188092E-02
11	24	9.59248616388137E-03
11	25	1.66825846328372E-03
11	26	2.08532307910465E-03
12	3	0.198173358607617
12	4	0.812577049006482
12	5	2.01089622078766
12	6	6.47476769310304
12	7	5.55680748684367
12	8	7.16207797028062
12	9	16.9388512573072
12	10	14.3506674266626
12	11	13.2358594361007
12	12	7.58758732220735
12	13	7.81823725128912
12	14	5.190948978645
12	15	4.85756704092048
12	16	2.71543896393112
12	17	2.23624385264916
12	18	1.17379604713742
12	19	0.907355611818821
12	20	0.418881480401384
12	21	0.195522209997481
12	22	0.110022667320617
12	23	2.38603374912181E-02
12	24	1.39185302032105E-02
12	25	4.63951006773685E-03
12	26	1.32557430506767E-03
12	27	6.62787152533835E-04
12	28	1.98836145760151E-03
12	30	6.62787152533835E-04
12	34	6.62787152533835E-04
13	3	0.962712668207955
13	4	5.20441836109629

Single axle load spectrum per vehicle class		
Veh Class	**singles**	**frequency**
13	5	4.95425534017033
13	6	4.88746616080779
13	7	3.27148418203015
13	8	5.51228090975557
13	9	14.0403501491888
13	10	16.2930029442567
13	11	17.6173256664098
13	12	7.80445392929832
13	13	5.27239314719308
13	14	2.91935898195902
13	15	3.10154721678819
13	16	2.19930049202679
13	17	2.39492560317743
13	18	1.47489477740234
13	19	1.17967870057502
13	20	0.492421996956943
13	21	0.241863773786235
13	22	0.122907898116861
13	23	3.51729997826388E-02
13	24	0.011065662852965
13	25	3.55682020273875E-03
13	26	1.18560673424625E-03
13	27	3.9520224474875E-04
13	28	3.9520224474875E-04
13	34	3.9520224474875E-04
13	35	7.904044894975E-04

Table G-2. Developed tandem axle load spectra

Tandem axle load spectrum		
Veh Class	**tandem bins**	**frequency**
4	6	4.02252614641995E-02
4	8	4.02252614641995E-02
4	10	2.21238938053097
4	12	5.95333869670153
4	14	6.47626709573612
4	16	6.51649235720032
4	18	6.73773129525342
4	20	11.5446500402253
4	22	13.515687851971
4	24	14.6621078037007
4	26	10.6999195494771
4	28	7.30088495575221
4	30	4.66613032984714
4	32	3.21802091713596
4	34	2.57441673370877
4	36	1.46822204344328
4	38	0.80450522928399
4	40	0.764279967819791
4	42	0.281576830249397
4	44	0.181013676588898
4	46	0.140788415124698
4	48	0.100563153660499
4	50	6.03378921962993E-02
4	52	2.01126307320998E-02
4	56	2.01126307320998E-02
5	18	25
5	20	75
6	6	0.738658973338639
6	8	2.52686032630322
6	10	12.4104655789893
6	12	9.75925189017111
6	14	7.3741543971349
6	16	7.3741543971349
6	18	7.533326701154
6	20	7.19011142061281

Tandem axle load spectrum		
Veh Class	**tandem bins**	**frequency**
6	22	6.51362912853164
6	24	5.71776760843613
6	26	5.56605650616793
6	28	5.50636689216076
6	30	5.13828093911659
6	32	4.43444090728213
6	34	3.40479506565858
6	36	3.54655789892559
6	38	2.64126541981695
6	40	1.32311977715877
6	42	0.569538400318345
6	44	0.35316354954238
6	46	0.169120573020294
6	48	0.154198169518504
6	50	2.98448070035814E-02
6	52	4.9741345005969E-03
6	54	7.46120175089534E-03
6	56	7.46120175089534E-03
6	60	2.48706725029845E-03
6	62	2.48706725029845E-03
7	6	0.992555831265509
7	8	0.496277915632754
7	10	3.84615384615385
7	12	4.46650124069479
7	14	2.23325062034739
7	16	2.10918114143921
7	18	3.97022332506203
7	20	7.5682382133995
7	22	4.83870967741936
7	24	2.85359801488834
7	26	3.2258064516129
7	28	5.21091811414392
7	30	7.5682382133995
7	32	11.9106699751861
7	34	13.5235732009926
7	36	12.4069478908189

Tandem axle load spectrum		
Veh Class	tandem bins	frequency
7	38	7.44416873449131
7	40	3.59801488833747
7	42	0.86848635235732
7	44	0.496277915632754
7	46	0.372208436724566
8	6	8.06370704790569
8	8	4.78638909790151
8	10	6.13243039879609
8	12	11.1654543934454
8	14	14.2044979516763
8	16	11.1863556558816
8	18	10.1412925340691
8	20	8.37304573196221
8	22	6.61315943482986
8	24	4.97032020734052
8	26	3.69116294624195
8	28	2.21135356575537
8	30	1.32095978597107
8	32	1.25825599866232
8	34	1.37530306830533
8	36	1.94381740657136
8	38	1.44218710810133
8	40	0.693921912883538
8	42	0.250815149235014
8	44	0.133768079592007
8	46	3.76222723852521E-02
8	48	4.18025248725023E-03
9	6	0.14696240023514
9	8	0.346039928553664
9	10	1.45153632232246
9	12	4.59302719934884
9	14	6.85952655497524
9	16	7.09263153134821
9	18	6.72884306676615
9	20	6.68351081869362
9	22	6.94781704311651

Tandem axle load spectrum		
Veh Class	**tandem bins**	**frequency**
9	24	6.60923828257478
9	26	6.069999321712
9	28	6.04840715367745
9	30	7.16961721947139
9	32	10.0064437360103
9	34	10.6602003210563
9	36	8.94921883831875
9	38	3.14917814103869
9	40	0.429695448687513
9	42	4.35234800696376E-02
9	44	8.93079201428927E-03
9	46	3.16534400506455E-03
9	48	1.13048000180877E-03
9	50	6.78288001085261E-04
9	52	6.78288001085261E-04
10	6	1.80572754204743
10	8	9.05058231578287
10	10	5.71108359327241
10	12	3.89595122027682
10	14	12.220010345314
10	16	9.19322225183002
10	18	4.81527344545982
10	20	3.50173205636629
10	22	3.20312867376209
10	24	3.562079721617
10	26	4.50883270373215
10	28	5.71735348057119
10	30	6.82633979654216
10	32	8.79351693653307
10	34	8.2652789316112
10	36	6.21032336943743
10	38	2.08238631910591
10	40	0.442810790476041
10	42	0.139504992397762
10	44	2.97819646691851E-02
10	46	1.17560386852046E-02

Tandem axle load spectrum		
Veh Class	**tandem bins**	**frequency**
10	48	6.2698872987758E-03
10	50	4.70241547408185E-03
10	52	7.83735912346975E-04
10	54	7.83735912346975E-04
10	60	7.83735912346975E-04
11	6	2.06896551724138
11	8	1.37931034482759
11	10	4.82758620689655
11	12	6.20689655172414
11	14	4.82758620689655
11	16	6.20689655172414
11	18	4.82758620689655
11	20	5.51724137931035
11	22	4.13793103448276
11	24	2.75862068965517
11	26	3.44827586206897
11	28	1.37931034482759
11	30	10.3448275862069
11	32	8.27586206896552
11	34	17.9310344827586
11	36	8.27586206896552
11	38	4.13793103448276
11	40	0.689655172413793
11	42	0.689655172413793
11	46	1.37931034482759
11	52	0.689655172413793
12	6	0.250149737518937
12	8	0.366416516929148
12	10	0.627135961667195
12	12	2.29362646654688
12	14	6.52150935419089
12	16	9.07937850121552
12	18	14.6355212627277
12	20	16.3971391325794
12	22	15.7453405207342
12	24	10.9960187436141

Tandem axle load spectrum		
Veh Class	tandem bins	frequency
12	26	6.28545255963077
12	28	3.60779339745622
12	30	3.23080717330797
12	32	3.50914279674453
12	34	2.83268153472149
12	36	2.26544058062925
12	38	0.986506007116936
12	40	0.243103266039531
12	42	8.80808934925836E-02
12	44	2.46626501779234E-02
12	50	7.04647147940669E-03
12	54	7.04647147940669E-03
13	6	2.93698614904545
13	8	5.32424299286255
13	10	6.56061269450757
13	12	5.12895356837562
13	14	6.09636594875216
13	16	4.31513180298702
13	18	4.2762129141213
13	20	4.66470682262021
13	22	5.20609636594875
13	24	5.90455142505681
13	26	7.29520672184809
13	28	9.08617058982966
13	30	10.4344320969636
13	32	10.5199146564366
13	34	7.03667410295436
13	36	3.86408968023963
13	38	1.02648569383344
13	40	0.198069345120197
13	42	7.64478174148128E-02
13	44	2.50192856993933E-02
13	46	1.32046230080131E-02
13	48	4.86486110821536E-03
13	50	2.08494047494944E-03
13	52	1.38996031663296E-03

Tandem axle load spectrum		
Veh Class	**tandem bins**	**frequency**
13	56	6.9498015831648E-04
13	60	1.38996031663296E-03

Table G-3. Developed tridem axle load spectra

Tridem axle load spectrum		
Veh Class	**Tridem bin**	**frequency**
7	12	0.52795776337893
7	15	0.551955843532517
7	18	0.791936645068395
7	21	1.3678905687545
7	24	1.22390208783297
7	27	1.39188864890809
7	30	1.43988480921526
7	33	2.99976001919846
7	36	7.07943364530838
7	39	17.7345812335013
7	42	30.9815214782817
7	45	24.3100551955844
7	48	7.53539716822654
7	51	1.79985601151908
7	54	0.215982721382289
7	57	4.79961603071754E-02
9	12	26.7889908256881
9	15	20.5504587155963
9	18	8.25688073394496
9	21	3.30275229357798
9	24	0.73394495412844
9	27	0.642201834862385
9	30	9.17431192660551E-02
9	33	0.458715596330275
9	36	3.30275229357798
9	39	6.88073394495413
9	42	13.1192660550459
9	45	9.35779816513761
9	48	4.67889908256881
9	51	1.65137614678899
9	54	9.17431192660551E-02
9	57	9.17431192660551E-02
10	12	4.16748870287384
10	15	8.85450428868033

Tridem axle load spectrum		
Veh Class	**Tridem bin**	**frequency**
10	18	8.74270736450495
10	21	3.74190881504655
10	24	2.83813872213297
10	27	3.06736939019005
10	30	3.43846002085623
10	33	4.80726773954135
10	36	9.97247353043413
10	39	16.487697640991
10	42	19.5494302114747
10	45	10.3849008389467
10	48	2.86726229061563
10	51	0.612534408086957
10	54	0.2207754384976
10	57	0.124949503490131
10	60	6.57628965737531E-02
10	63	3.00630384337157E-02
10	66	1.69104591189651E-02
10	69	6.57628965737531E-03
10	72	2.81840985316085E-03
11	12	23.6278707668353
11	15	13.8575321136629
11	18	4.20397041650448
11	21	1.2066952121448
11	24	1.05099260412612
11	27	1.08991825613079
11	30	0.622810432074737
11	33	2.64694433631763
11	36	7.00661736084079
11	39	11.7555469054107
11	42	16.8158816660179
11	45	11.6387699493967
11	48	3.89256520046711
11	51	0.544959128065395
11	54	3.89256520046711E-02
12	12	0.853578463558766
12	15	1.70715692711753

Tridem axle load spectrum		
Veh Class	**Tridem bin**	**frequency**
12	18	1.57583716349311
12	21	1.0505581089954
12	24	1.64149704530532
12	27	1.51017728168089
12	30	2.16677609980302
12	33	5.77806959947472
12	36	14.8391332895601
12	39	24.8850952068286
12	42	25.2790544977019
12	45	12.8693368351937
12	48	4.00525279054498
12	51	1.18187787261983
12	54	0.196979645436638
12	57	0.262639527248851
12	60	0.131319763624425
12	63	6.56598818122127E-02
13	12	4.7897416556666
13	15	6.48689421082406
13	18	2.05544031680181
13	21	1.17857816330379
13	24	1.39543654535169
13	27	2.5174429568169
13	30	4.81488465648375
13	33	9.62034068766107
13	36	16.8018102960588
13	39	19.8629706455465
13	42	17.7603872022126
13	45	8.5517631529323
13	48	2.66830096171978
13	51	0.719718398390848
13	54	0.30171600980577
13	57	0.213715506945754
13	60	0.141429379596455
13	63	6.60003771450123E-02
13	66	3.77145012257213E-02
13	69	9.42862530643032E-03

Tridem axle load spectrum		
Veh Class	**Tridem bin**	**frequency**
13	72	3.14287510214344E-03
13	78	3.14287510214344E-03