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Utah Commercial Motor Vehicle Weigh-in-Motion Data Analysis and Calibration Methodology

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UTAH COMMERCIAL MOTOR VEHICLE WEIGH-IN-MOTION DATA ANALYSIS AND CALIBRATION METHODOLOGY

by

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GRADUATE COMMITTEE APPROVAL

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ABSTRACT

UTAH COMMERCIAL MOTOR VEHICLE WEIGH-IN-MOTION DATA
ANALYSIS AND CALIBRATION METHODOLOGY

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In preparation for changes in pavement design methodologies and to begin to assess the effectiveness of the weigh-in-motion (WIM) system in Utah, the Utah Department of Transportation (UDOT) contracted with a Brigham Young University (BYU) research team to conduct an evaluation of their commercial motor vehicle (CMV) data collection system statewide. The objective of this research was to evaluate the CMV data collection program in the state of Utah and to make limited recommendations for potential improvements and changes that will aid in more detailed and accurate CMV data collection across the state.

To accomplish the research objectives, several tasks were conducted, including: 1) a review of literature to establish the state-of-the-practice for CMV monitoring, 2) collection of WIM data for the state of Utah, 3) analysis of the collected WIM data, 4) development of a calibration methodology for use in the state, and 5) presentation of recommendations and conclusions based on the research.

The analysis of collected WIM data indicated that the CMV data collection system in the state of Utah currently produces data consistent with expectations with a few exceptions. Recommendations for improvements to the CMV data collection system

come in the form of a proposed calibration methodology that is in line with current standards and the practices in other states. The proposed calibration methodology includes calibration, verification, and a quality assurance programs.

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1 Introduction

Weigh-in-motion (WIM) devices have increased commercial motor vehicle (CMV) data collection potential over the last few decades. Weight data collection is among the most important and expensive of all traffic data collection activities. WIM technology requires the most sophisticated data collection sensors; the most controlled environment; and the most costly equipment, set up, and calibration. The data are used for a number of state highway agency's most significant tasks. Permanent WIM scales have been used in Utah over the last decade with four new sites added in conjunction with the reconstruction of I-15, completed in 2001.

From the beginning of the use of WIM technologies, several limitations have been noted, including the difficulty of obtaining accurate data due to the complex dynamics of a moving vehicle and the changes that occur in the pavement surrounding the WIM site over time. In order to overcome these limitations, calibration procedures and other monitoring activities are required. These activities ensure that the most accurate data are produced. Several of these procedures and activities are outlined in technical documents and are referred to as standards. The way in which the standards are applied varies from organization to organization.

In preparation for changes in pavement design methodologies and to begin to assess the effectiveness of the WIM system in Utah, the Utah Department of Transportation (UDOT) contracted with a Brigham Young University (BYU) research team to conduct an evaluation of their CMV data collection system statewide. This evaluation was established to compare Utah's current CMV data collection system against the standards and the current practices of the industry and those in other states.

1.1 Background

UDOT currently collects traffic data at a number of sites across the state. The primary data collected include traffic volume data, vehicle classification data, and truck weight monitoring data. One of the primary sources available to aid in the collection of this data is the Traffic Monitoring Guide (TMG), published by the United States Department of Transportation (USDOT), Federal Highway Administration (FHWA), and Office of Highway Policy Information (*1*). The TMG was developed to provide information and guidance to state and local highway agencies and metropolitan planning organizations with the objective of relating the intensity of monitoring efforts to meet user-defined needs, to provide an emphasis on the relationship between results obtained using various data collection methods, and to encourage the need to incorporate non-traditional data sources with more traditional sources to improve traffic estimates available to users. The TMG has set specific guidelines for state and local agencies to follow in terms of data collection methodologies. Two of the most critical items contained within these guidelines are the requirements for truck weight monitoring and the relationship between accurate truck weight monitoring and infrastructure needs (*1*).

In addition to the TMG guidelines, the American Association of State Highway and Transportation Officials (AASHTO) has recently invested in a complete restructuring of the AASHTO "Guide for Design of Pavement Structures" (*2*). This new mechanistic-empirical pavement design guide (*3*) has been developed to utilize existing mechanistic-based models and databases that reflect current state-of-the-art pavement design procedures. An essential element of these procedures are the traffic design inputs, including truck-traffic volumes (base year and future growth), truck operating speed, truck lane distribution factors, vehicle class distribution, axle load distribution, axle configurations, tire inflation, and lateral load distribution factors. The new design guide is currently being evaluated by UDOT employees and is expected to be adopted for design purposes in the very near future.

1.2 Problem Statement

Currently, UDOT collects weight data across the state at permanent weigh stations, temporary weigh sites, and a number of automated WIM sites. With the increase in data collection locations, particularly the WIM sites installed as part of the I-15 reconstruction project in the Salt Lake Valley, combined with new pavement design guidelines and the increasing number of CMVs traveling in the state, the need existed to explore current data collection methodologies utilized throughout the state. In particular, the need existed to evaluate the current weight data collected, to monitor WIM data collection sites, to identify potential anomalies among the data collected, and to develop a program for effective data collection, including the requirements outlined in the TMG and the forthcoming new AASHTO Pavement Design Guide (i.e., "Guide for Mechanistic-Empirical Design of New and Rehabilitated Structures") (*3*). Specifically, this research addressed the need to evaluate the current CMV data statewide and to develop a more accurate and succinct methodology for the collection and interpretation of CMV data that can be used throughout UDOT for design and analysis purposes.

1.3 Research Objectives

The objective of this research was to evaluate the CMV data collection program in the state of Utah and to make limited recommendations for potential improvements and changes that will aid in more detailed and accurate CMV data collection across the state. To accomplish these objectives, the research team conducted several tasks, including: 1) a review of literature to establish the state-of-the-practice for CMV monitoring, 2) collection of WIM data for the state of Utah, 3) analysis of the WIM data collected, 4) development of a calibration methodology for use in the state, and 5) presentation of recommendations and conclusions based on the research.

1.4 Organization of the Document

This document is organized into seven chapters. Chapter 1 provides an introduction to the document and research and includes the background, problem statement, research objectives, and organization of the document.

Chapter 2 consists of a detailed literature review and explores WIM history, basic concepts of WIM, WIM technologies, weight data collection standards and their calibration methods, quality assurance methods, the TMG concerning weight data collection, and the new AASHTO Pavement Design Guide.

Chapter 3 outlines the current status of Utah WIM data and includes descriptions of Utah's CMV size and weight regulations, Utah's WIM data set that was made available for analysis, and a preliminary analysis consisting of histograms of gross vehicle weight (GVW), truck class, and total vehicle length.

Chapter 4 outlines the analysis of the WIM data, which includes an analysis of the lane numbering convention and distribution as well as box plots and error bar charts of GVW, daily average graphs of steering-axle weights and drive tandem spacing, and an analysis of vehicles over and under the current weight limit established by the state.

Chapter 5 provides recommendations for calibration improvement and includes the results of a survey of current practices in other states, a description of current calibration practices in Utah, and a recommended procedure based on data collection standards and the practices of other states.

Finally, Chapter 6 provides the conclusions and recommendations for future research.

In addition to the six chapters, five appendices are included in this document. Appendix A contains quarterly histograms for each WIM site produced as part of the preliminary analysis discussed in Chapter 3. Appendix B contains graphs illustrating the percentage of trucks in each lane. Appendix C contains the daily average steering-axle weight graphs for each WIM site. Appendix D contains daily temperature and precipitation graphs for two locations in Utah. Finally, Appendix E contains the daily average drive tandem spacing graphs for each WIM site.

2 Literature Review

The primary areas of focus for the literature review included: 1) WIM history, 2) basic concepts of WIM, 3) WIM technologies, 4) weight data collection standards and their calibration, 5) quality assurance methods, 6) TMG weight data collection, and 7) a discussion of the new AASHTO Pavement Design Guide. The purpose of this chapter is to review existing publications that may contribute to this study.

2.1 WIM History

WIM, as defined by the American Society for Testing and Materials (ASTM), is "the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle" (*4*). Interest in the number of heavy vehicles operating on roadways in North America grew in parallel with road construction growth. Heavy vehicles are a major component to road damage and important in bridge design. In addition, there are limitations associated with static scales and their ability to enforce weight limits and to collect unbiased data (*5*).

As a consequence of the limitations mentioned above, research was undertaken in the U.S. to develop an in-motion scale system. In the 1950s, the U.S. Bureau of Public Roads, the Virginia State Department of Highways, and the Williams Construction Company installed a load cell WIM system on the Henry G. Shirley Memorial Highway. This system featured a large concrete platform 12 feet wide, 3 feet long, and 1 foot deep. The platform was supported by columns with strain gauges bonded to the underside. Many of the limitations to the success of these early systems are still faced by today's systems. Some of the complexities of high-speed weighing include (*5*):

- The speed of the vehicle;
- The time period during which tires are on the scale sensor;
- The response of the sensor itself to the forces applied and the environment in which it operates;
- The dynamic nature of tire forces applied to the roadway (and sensor); and
- The complexity of the relationship between the scale sensor signal, the dynamic measurement, and the static weight of the forces being applied.

In the 1950s, accounting for these complex interactions was especially difficult because high-speed data collection and processing equipment was not available (*5*).

The aforementioned Bureau of Public Roads system was installed in several states from Iowa to Oregon in the 1950s and 1960s. No significant improvements were made to WIM technologies until the late 1960s. These improvements stemmed from a decrease in the cost of computing power. This second generation of systems used strain gauge load cells with six triangular steel plates as their weighing surface. These scales produced better results than the original Bureau of Public Roads scales (*5*).

The 1970s and 1980s brought an increased willingness in the U.S. and Canada to test WIM technologies and to consider and refine technologies found elsewhere in the world. By the mid 1980s, U.S. testing and adoption of WIM systems developed around the world was moving forward rapidly. Much of the late 1980s and early 1990s were devoted to testing and refining systems that these technologies used. Most recently, North American efforts have involved testing new sensor systems and improving training for agency staff in the techniques of effective WIM design, installation, calibration, operation, and maintenance.

The first international WIM conference was held in 1974 as a starting point in the process to formalize WIM technology and meet needs on a more standardized level throughout the world (*5*). The fourth international WIM conference was held in February 2005 in Taiwan.

2.2 Basic Concepts of WIM

In addition to weight data, WIM sites collect a variety of ancillary traffic data. This ancillary data include traffic volume, speed, directional distribution, lane distribution, date and time of passage, axle spacing, and vehicle classification. Of all data collection methodologies, WIM data collection requires the most sophisticated technology for data collection sensors, as well as the most controlled operating environment (smooth, level pavement) and the highest equipment set-up and calibration costs (*6*).

The primary reason for this sophistication in technology and high-cost equipment comes from the desire to determine the static weight from a dynamic measurement. With the standard static scale, trucks are stopped and weighed without any interaction between the truck and the roadway. A variety of forces are at work when a truck is in motion. These forces include gravity and a number of dynamics forces such as those due to (*7*):

- Roadway roughness,
- Vehicle speed,
- Vehicle acceleration and deceleration,
- Out-of-balance tires and wheels,
- Tire inflation pressure,
- Suspension,
- Aerodynamics and wind, and
- Other dynamic factors.

A moving vehicle's dynamic weight varies due to the dynamic forces acting on the vehicle. Because of these forces, calibration can be problematic and requires a sophisticated process.

The difference between the dynamic weight of a moving vehicle and the static weight is illustrated in Figure 2.1 (*1*, *8*). In this figure, W_s represents the static weight of a vehicle, while W_d represents the dynamic weight at the WIM location. The fluctuating line represents the variation in the dynamic weight of the vehicle due to the factors outlined (*1*, *8*).

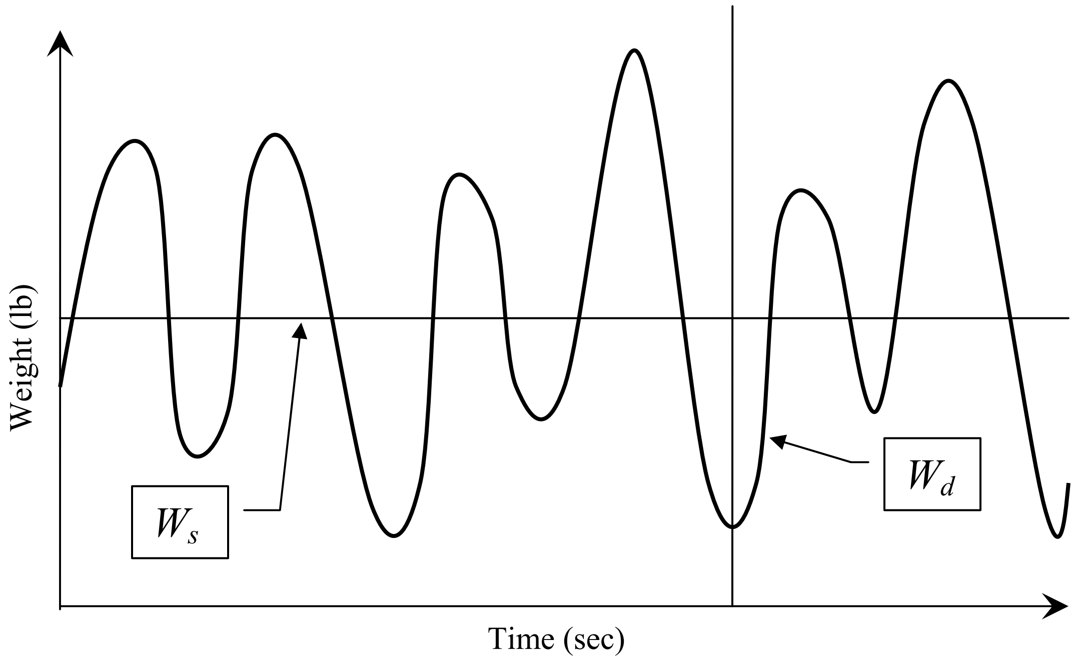

Figure 2.1 Static versus dynamic vehicle weight (adapted from *1, 8*).

It is important to understand vehicle classification when discussing WIM calibration and data. Figure 2.2 displays the FHWA vehicle classification scheme. It includes 13 classes of vehicles from motorcycles as Class 1 and seven or more axle vehicles with multiple trailers as Class 13.

2.3 WIM Technologies

Several technologies are discussed in this section. Each of these technologies works differently to produce weight measurements. All of the systems use factors that change the reading of the sensor (e.g., strain in metal plate or electric charge) into a

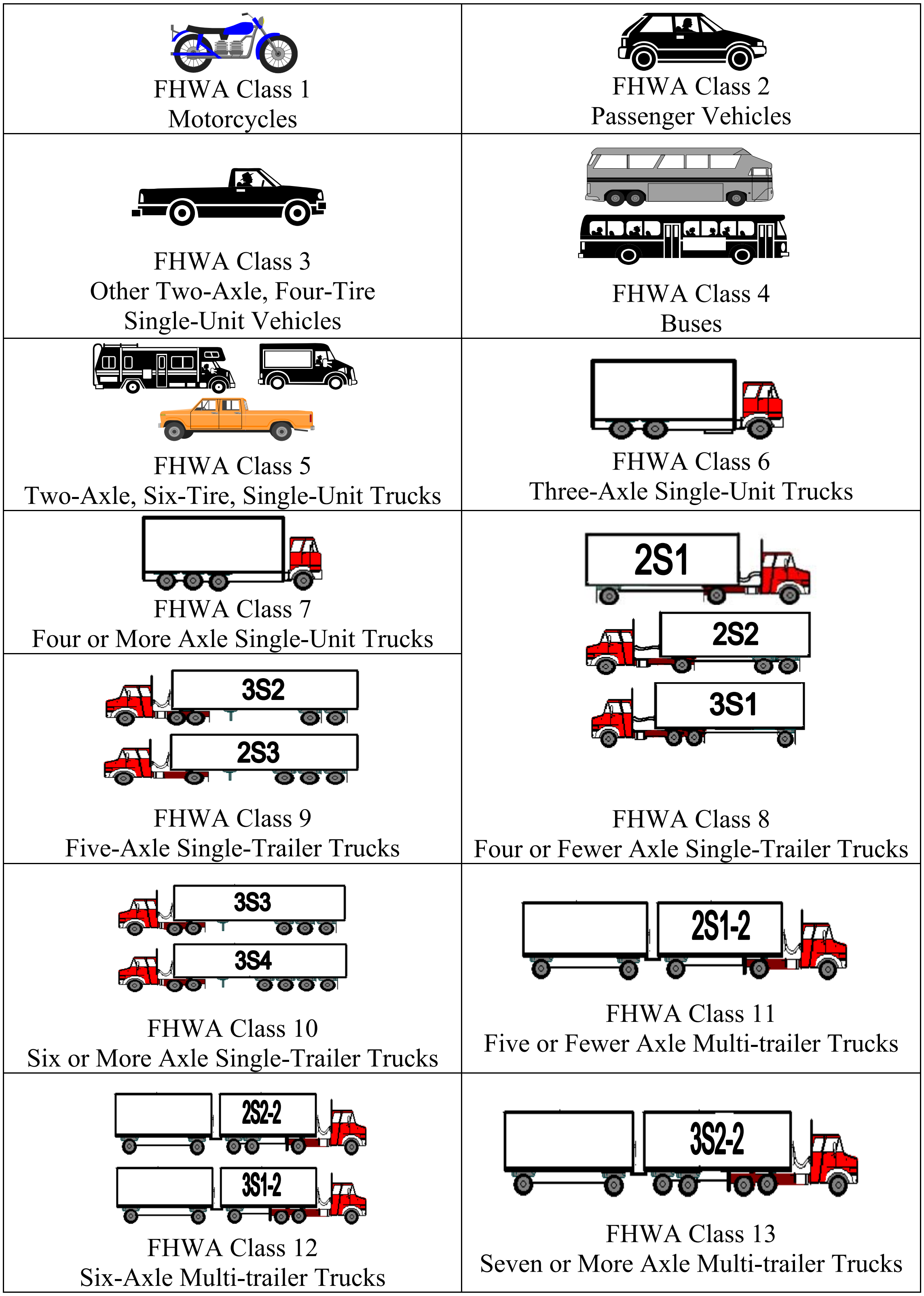

Figure 2.2 FHWA vehicle classification scheme (*6*).

weight. A factor for weight is a number that is multiplied by the sensor reading to produce the corresponding weight in pounds or other meaningful units. These factors may be adjusted to calibrate the WIM systems and vary depending on the manufacturer and the technology used.

The three commonly used WIM sensor technologies are 1) piezoelectric, 2) bending plate, and 3) single load cell sensors. In addition, three promising sensor technologies are currently being tested but have not been widely used: 1) quartz, 2) fiber optic, and 3) seismic. The following subsections provide a brief summary of each of these six technologies.

2.3.1 Piezoelectric

The piezoelectric WIM sensor is the most commonly used for data collection purposes. It consists of a copper strand encircled by a piezoelectric material all encased in a copper sheath. When pressure is applied to the piezoelectric material, an electrical charge is produced and in turn measured and analyzed to determine the dynamic load of the axle or wheel. The dynamic load is then used to estimate the static load of the axle or wheel (*8*, *9*, *10*, *11*).

Inductive loops and two piezoelectric sensors (for classification) are usually installed in the lane with the WIM piezoelectric sensors. The loops and sensors gather additional information about vehicles as they pass over the system. Installation of the WIM piezoelectric sensor is relatively simple and quick. A small cut is made in the pavement about 1 to 2 inches wide by 1 to 2 inches deep. The sensor is placed in the cut and secured with a fast-curing grout. Installation of the entire system can generally be completed in one day (*8*, *9*, *10*, *11*).

Piezoelectric WIM systems are expected to accurately estimate the vehicle weight within 10 to 15 percent of the actual vehicle weight for 95 percent of the vehicles measured. The estimated average cost per lane per year over a 12-year period for a fully installed piezoelectric WIM system is approximately $4,200 (year 2001 dollars) (*8*, *10*, *11*).

2.3.2 Bending Plate

Bending plate sensors consist of two steel plates placed adjacent to each other in the lane, each covering one half the width of the lane. The plates have strain sensors placed strategically on the undersides of the plates. By measuring and analyzing the strain as a vehicle passes over, the system determines the dynamic load of the wheel or axle, and then static load of the wheel or axle is subsequently computed. Like the piezoelectric sensor, the bending plate is usually installed in a lane with two inductive loops and an axle sensor to provide additional information such as speed and axle spacing (*8*, *9*, *10*, *11*).

Two basic methods for installing a bending plate scale exist depending on the pavement type. In concrete roads, a cut and excavation is made. The frame of the scale is anchored to the existing concrete roadway using epoxy and anchoring bars. This is called the quick installation. Asphalt roads necessitate a concrete foundation for the scale. A cut and excavation is made in the road 2 feet 6 inches deep by 4 feet 10 inches wide by 13 feet 10 inches long. The foundation is poured and once cured provides a solid foundation for the scale. This installation is referred to as a vault installation. Installing a complete lane of scales, loops, and axle sensor can generally be accomplished in a day using the shallow quick method and in three days using the concrete vault installation (*8*, *11*).

Bending plate WIM systems are expected to accurately estimate the vehicle weight within 5 to 10 percent of the actual vehicle weight for 95 percent of the vehicles measured. The estimated average cost per lane per year over a 12-year period for a fully installed bending plate WIM system is approximately $5,000 (year 2001 dollars) (*8*, *11*).

2.3.3 Load Cells

The load cell systems consist of weighing platforms with hydraulic cylinders placed beneath them. The dynamic force of the wheel or axle on the scale is measured by analyzing the change in hydraulic pressure. Through the calibration process, the static weight of the wheel or axle is subsequently determined. This system has two platforms, each 6 feet long, placed adjacent to each other in order to cross a 12-foot lane. Single load cell systems have only one hydraulic cylinder under the center of each platform.

Multiple load cell systems have up to four hydraulic cylinders in an effort to improve accuracy (*8*, *9*, *10*, *11*).

Similar to the bending plate, the single load cell scale requires a concrete vault. Vault installation requires the road to be cut and excavated. The vault is poured with the final dimensions at 3 feet 2 inches deep by 4 feet 10 inches wide by 13 feet 9 inches long. Like the other scales, the single load cell scale is usually installed with inductive loops and an axle sensor to obtain additional information about the vehicle such as speed and axle spacing. This complete installation, including scales, inductive loops, and axle sensor, can generally be done in three days (*8*, *11*).

Single load cell WIM systems are expected to accurately estimate the vehicle weight within 3 to 6 percent of the actual vehicle weight for 95 percent of the vehicles measured. The estimated average cost per lane per year over a 12-year period for a fully installed single load cell WIM system is approximately $7,300 (year 2001 dollars) (*8*, *10*, *11*).

2.3.4 Quartz

The quartz (Kistler) sensor works on the same principle as the piezoelectric sensor. Quartz disks are fitted in the middle of a light metal profile. When force is applied to the sensor, an electric charge is produced. This charge is analyzed and measured to determine the dynamic force of the wheel or axle on the scale. This force is subsequently used to determine the static weight, where the charge is proportional to the force acting on the scale (*11*). This sensor has been observed to be less temperature-sensitive then piezoelectric sensors (*12*).

Like the other sensors, installation of other recording devices is common to collect additional information about the vehicles. The quartz sensors are easy to install. Each sensor is about 3 feet 3 inches long. Typically, four of these sensors are used to cover a 12-foot lane. Again, similar to the piezoelectric, a simple saw cut is made in the roadway about 2 inches deep and 3 inches wide depending on the particular sensor. The sensor is placed in the saw cut and secured with a fast-curing grout. Complete installation consisting of eight sensors (double coverage of a 12-foot lane) and two loops can generally be accomplished in less than a day (*11*).

Quartz WIM systems are expected to accurately estimate the vehicle weight within 10 percent of the actual vehicle weight for 95 percent of the vehicles measured. The estimated average cost per lane per year over a 12-year period for a fully installed quartz WIM system is approximately $7,500 (year 2001 dollars) (*11*).

2.3.5 Fiber Optic

Several types of fiber-optic sensors are also in development although not yet in use commercially (*13*, *14*). A typical sensor is constructed of two metal plates welded around an optical fiber. An applied force causes a change in the properties of the fiber that can be detected in the light passing through it. This change is proportional to the force applied. Fiber-optic sensors have lower power requirements and are less sensitive to harsh environments than traditional sensors. As a result, highly accurate fiber-optic sensors may be produced for about the same cost as a traditional piezoelectric sensor (*13*, *14*).

2.3.6 Seismic

Seismic WIM (SWIM) data collection is a relatively new concept. The system consists of geophones installed on the side of the roadway in connection with a speed-monitoring system. The weight can be derived by measuring the speed and seismic signal of a passing vehicle. The SWIM concept was initially developed by VorTek LLC, a company that primarily works on detection and warning systems for tornados. The system is still in development, and tests are being performed by the Florida Department of Transportation, the National Center for Asphalt Technology, and Kentucky Department of Transportation. SWIM systems have several limitations. For instance, SWIM systems cannot collect data for individual lanes; they are dependent on truck, pavement, and soil properties; and they are sensitive to temperature, moisture, and wind (*15*, *16*, *17*).

2.3.7 Summary Table for WIM Technologies

Table 2.1 provides a summary of the WIM technologies in use and technologies still undergoing research. The table includes information on the performance and estimated average cost, which is averaged over a 12-year period. This information is provided as far as it is available.

Table 2.1 Summary Table for WIM Technologies

WIM System	Performance (Percent Error on GVW at Highway Speeds)	Estimated Average Cost per Lane (12-Year Life Span)
Piezoelectric	±10 to15%	$4,200 (year 2001 dollars)
Bending Plate	±5 to10%	$5,000 (year 2001 dollars)
Load Cell	±3 to 6%	$7,300 (year 2001 dollars)
Quartz	±10%	$7,500 (year 2001 dollars)
Fiber Optic	Highly accurate	$4,200 (year 2001dollars)
Seismic	Unknown	Unknown

2.4 Weight Data Collection Standards and Their Calibration Methods

A number of weight data collection standards exist across the United States, several of which are discussed in this section. Each one provides insight in current practices in weight data collection. Each program is different, with variations ranging from the goals of the system to the calibration of the scale. The general aspects of each standard are discussed with particular attention paid to calibration methods. The standards are summarized in Table 2.2 and discussed in the paragraphs that follow. The calibration methods for each standard are explored in the following sections beginning with an overview of the standards, followed by discussion of test trucks and auto-calibration methodologies.

2.4.1 Overview of Standards

The standards that outline a test truck procedure include: 1) ASTM Designation: E 1318-02, 2) “States’ Successful Practices WIM Handbook,” 3) TMG, 4) Long Term Pavement Performance (LTPP) program, and 5) the International Road Dynamics (IRD)

Software Users Manual. An overview of these standards will be provided in the following sections.

Table 2.2 Summary of Standards for Calibration of WIM Scales

Standard	Calibration Procedure	Calibration Frequency
ASTM Designation: E 1318-02	Test trucks	At least annually
States' Successful Practices Weigh-in-Motion Handbook	Test trucks and Automatic Calibration	Not Specified
TMG	Test trucks	Not Specified
LTPP	Test trucks if away from static scale and traffic stream trucks if near static scale	Bi-annually
IRD Software User's Manual	Test trucks and auto-calibration	Not Specified

2.4.1.1 ASTM Designation: E 1318-02. The ASTM Designation: E 1318-02 is the "Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods." The standard specifies four types of WIM systems based on performance. Type I is designed for installation at a data collection site in one or more lanes of the highway. It produces all of the data listed in Table 2.3. Type II is the same as Type I except that it does not produce item 1 in Table 2.3, the wheel load data. Type III is designed for installation in one or more lanes off the main highway lanes at weight-enforcement stations or in one or more main highway lanes. The document provides several options for Type III systems with regards to the data items in Table 2.3. Type IV has not yet been approved for use in the United States. With this type, vehicles are weighed at speeds from 2 to 10 mph (*4*).

Table 2.3 Data Items Produced by WIM System

1	Wheel Load
2	Axle Load
3	Axle-Group Load
4	Gross-Vehicle
5	Speed
6	Center-to-Center Spacing Between Axles
7	Vehicle Class (via axle arrangement)
8	Site Identification Code
9	Lane and Direction of Travel
10	Date and Time of Passage
11	Sequential Vehicle Record Number
12	Wheelbase (front-most to rear-most axle)
13	Equivalent Single-Axle Loads (ESALs)
14	Violation Code

Three testing procedures are outlined in ASTM Designation: E 1318-02: 1) type approval, 2) calibration, and 3) on-site acceptance. The type approval test is done to evaluate the performance capabilities of a new type or model WIM system. The details of this test are not discussed here, but the calibration procedure and the on-site acceptance test will be discussed in Section 2.4.2 of this report (*4*).

2.4.1.2 States' Successful Practices Weigh-in-Motion Handbook. The "States' Successful Practices Weigh-in-Motion Handbook" is intended to provide practical advice for users of WIM technology. It describes a calibration procedure used by the California

Department of Transportation (Caltrans) and an auto-calibration system used by the Minnesota Department of Transportation (Mn/DOT) (*10*).

2.4.1.3 TMG. The TMG was published in 2001 in an attempt to offer suggestions to improve and enhance current programs with an eye to the future of traffic monitoring. The guide provides examples of statewide monitoring systems and the logic and science behind them. The information is provided to help highway agencies optimize their systems, including weight data collection. The calibration of WIM sites is strongly encouraged by the TMG, because a slight error in vehicle weight measurement can lead to a large error in estimated pavement damage. The TMG indicates that, at the time of the document, an inexpensive calibration procedure had not been developed. A number of attempts have been made to develop alternative methods of calibration, but none have been widely adopted. The most common approach is to use test trucks of known weight, while a number of variations exist to the use of test trucks. The drawback to using test trucks as outlined in the TMG is the fact that use of one or two vehicles to calibrate a scale can create bias in the calibration. The TMG recommends that the most predominate type of trucks should be used as test trucks; however, even the use of two types of trucks is not representative of all the trucks operating on the roadway. The TMG does indicate that biases can be monitored and checked using quality assurance methods (*1*).

2.4.1.4 LTPP. The LTPP program was first established in 1987 by the Strategic Highway Research Program (SHRP), but later management was passed to the FHWA. The LTPP program is a long-term (20-year) study of in-service pavements. The program includes more than 2,400 test sites throughout North America in all 50 states, the District of Columbia, Puerto Rico, and the 10 Canadian Provinces. However, only a portion of these locations have WIM scales. The test sites are divided into two groups of Specific Pavement Studies (SPS) and General Pavement Studies (GPS). SPS sites generally contain WIM sensors (*18*).

The objectives of the LTPP program include (*18*):

- Evaluate existing design methods.
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements.

- Develop improved design equations for new and reconstructed pavements.
- Determine the effects of loading, environment, material properties and variability, construction quality, and maintenance levels on pavement distress and performance.
- Determine the effects of specific design features on pavement performance.
- Establish a national long-term database to support SHRP's objectives and meet the future needs of the highway industry.

The ultimate goal of the LTPP program is to provide answers pertaining to how and why pavements perform as they do. Primarily, the program accomplishes these goals by collecting, storing, and processing data. Providing access to good quality data is vital to the program (*18*).

The LTPP program has a number of core functions (*18*):

- Data collection and management: data is collected, processed, and stored. It is made readily available, and quality is monitored.
- Data analysis: an effort is made to understand pavement performance based on collected data.
- Product development: a number of usable tools have been developed, including software, video, and contributions to procedures, including the new 2002 Pavement Design Guide.
- Communication: ensure access to LTPP program information through meetings, contests, publications, reports, video, and a website.

The LTPP program includes partnerships with a number of organizations (*18*):

- AASHTO,
- State highway agencies,
- FHWA,
- Transportation Research Board (TRB),
- Canadian Strategic Highway Research Program, and
- Provincial Highway Agencies.

The LTPP program provides three methods for ensuring that WIM scales are producing quality data, two of which are similar. These methods are used both to check the calibration and to adjust the calibration factors if the site requirements are not met. Site validation is recommended to be done on a bi-annual basis and that the data be monitored on at least a monthly basis to ensure that the scales remain calibrated. Two methods are outlined in the "Guide to LTPP Traffic Data Collection and Processing" (*19*), and the other is given in the "Data Collection Guide for SPS WIM Sites" (*20*). These methods are discussed in Section 2.4.2 of this report.

2.4.1.5 IRD User Manual. The IRD Software User Manual provides information about on-site calibration and the system's auto-calibration capability. The purpose of this manual is to provide information and guidance so that the user can take advantage of all the capabilities of the IRD WIM system software (*21*).

2.4.2 Test Truck Methodology

All of the standards recommend or at least refer to the use of test trucks for the calibration of WIM sensors. Each of these standards is discussed and their calibration methods explored and compared in this section of the report. Because of the similarities in the methodologies, a general discussion of the use of test trucks is provided, pointing out major differences in the procedures. The description of the test truck methodology includes an overview of the standards that recommend the use of test trucks, including 1) pre-calibration procedures, 2) choosing test trucks, 3) execution of test runs, 4) verification procedures, and 5) performance requirements.

2.4.2.1 Pre-Calibration Procedures. The ASTM Designation: E 1318-02 states that site conditions should be recorded as part of the pre-calibration procedure. Each lane where a sensor is installed should be described quantitatively and made a matter of record. An estimate of location and magnitude of each observed pavement surface deviation greater than 0.125 inches measured beneath the straight edge with the circular plate should be noted (*4*).

In the "States' Successful Practices Weigh-in-Motion Handbook," the first step in the California calibration method includes a component operation check. The roadway sensors should send signals to the on-site controller, and the on-site controller should convert these signals to usable data. An inconsistency here may indicate a problem with a system component or reflect an irregular traffic condition (*10*).

The IRD Software User's Manual Version 7.5.0 also includes a discussion about pre-calibration. The pre-calibration should begin with checking the "sensitivity levels" or "threshold levels" of the piezoelectric sensors. Adjusting the threshold values is an iterative process. The threshold must be set low enough to ensure that vehicle axles are properly registered by the system, but high enough so that background noise does not create "ghost axles." The loop sensors also need their sensitivity levels checked. The size of the change in inductance necessary to turn on the loop may need adjustment. It must be sensitive enough to trigger when a vehicle passes over it, but not so sensitive that a vehicle in the adjacent lane causes it to trigger (*21*).

2.4.2.2 Choosing Test Trucks. The ASTM Designation: E 1318-02 states that test vehicles should consist of one Class 5 and one Class 9 vehicle with suspensions representative of the suspensions at the site. Both should be loaded to 90 percent of their respective registered GVW. The loads should be non-shifting, and loading should be symmetric from side to side. The vehicles should be in mechanically good condition, and the tires should be properly inflated and dynamically balanced (*4*).

Based on the "States' Successful Practices Weigh-in-Motion Handbook," one Class 9 with air suspension for both tandem axle groups is used because it is the most predominant truck on California's highways and is subsequently recommended as a test truck (*10*).

The LTPP program uses a minimum of two test trucks. Truck #1 must be a Class 9 loaded between 76,000 pounds to 80,000 pounds GVW. Air suspension is required for both the tractor and trailer. All the loads must be legal in every respect, including GVW and individual wheel and axle weights. According to the "Guide to LTPP Traffic Data Collection and Processing," Truck #2 must be different from Truck #1 either by configuration or at least suspension. The "Data Collection Guide to SPS WIM Sites" has a more complicated requirement for Truck #2 indicating that it should be one of the following options in descending order of preference (*19*):

- Predominant truck (including dump trucks) for the particular site, if it supplies a majority of the axle loads for the site, loaded within 4,000 pounds GVW of the maximum legal weight for the truck and location. If this turns out to be the same type truck as Truck #1, then one of the following options should be used for Truck #2.
- Class 9 truck (3S2) similar to Truck #1 but loaded between 60,000 and 64,000 pounds GVW.
- Class 9 truck (3S2) similar to Truck #1 but with steel suspension loaded to between 60,000 and 64,000 pounds GVW.
- Class 9 truck (3S2) similar to Truck #1 but with steel suspension loaded to between 76,000 and 80,000 pounds GVW.
- Class 9 truck (3S2) similar to Truck #1 but with a split tandem trailer (no load equalization between axles) loaded between 76,000 and 80,000 pounds GVW.
- Class 10 truck (3S3) with any suspension type loaded above 88,000 pounds GVW.

According to the LTPP program, if more than two test trucks are used, the third test truck may be loaded and configured as desired. The agency should also make sure that the tires have a conventional highway tread pattern, as an off-road tread can cause unusual sensor readings from some WIM systems. Loads should not be able to shift throughout the test. Steel plates, concrete blocks, and other similar materials are good for loading and should be securely attached so that load shifting is minimized (*19*, *20*).

2.4.2.3 Execution of Truck Runs. The ASTM Designation: E 1318-02 states that a calibration procedure for Type I, Type II, and Type III systems should be done immediately after installation, reinstallation, when site-conditions or system components change, or at least annually. The calibration procedure requires that two loaded, pre-weighed and measured test vehicles make multiple runs over the WIM-system sensors in each lane at specified speeds. The calibration procedure contains five parts (*4*):

1. Adjust all WIM-system settings to vendor's recommendations or to a best estimate of the proper settings based on previous experience.

2. Use a radar speed meter to measure the speed of each test truck every time it passes over the sensors. The radar speed meter should have been calibrated within the last 30 days.
3. Run each vehicle through a series of three or more runs over the WIM-system sensors at minimum, maximum, and intermediate speeds. All speeds must be between 10 and 80 mph. The maximum must be below the legal limit, and the minimum should differ from the maximum by more than 20 mph. The maximum should be above the average speed and the minimum below the average speed. The intermediate speed should be representative of the prevailing speed of the truck traffic. At each speed, one or more runs will be made with the wheels at the left edge of the lane and one or more with the wheels at the right edge of the lane. Other runs will be made with the truck centered in the lane. An example of a possible test truck plan is provided in Table 2.4.

Table 2.4 Example of Test Truck Run Plan (*4*)

Run	Speed	Location in Lane
1	Minimum	Left Edge
2	Minimum	Centered
3	Minimum	Right Edge
4	Maximum	Left Edge
5	Maximum	Centered
6	Maximum	Right Edge
7	Intermediate	Left Edge
8	Intermediate	Centered
9	Intermediate	Right Edge

4. Calculate the difference in the WIM-system estimate and the referenced value for each speed, wheel-load, axle-load, tandem-axle-load, GVW, and axle spacing value. Express the differences as a percent using Equation 2.1 and find a mean value for the difference for each set of values.

$$d = 100\left[\frac{(C-R)}{R}\right] \tag{2.1}$$

where: d = difference expressed as a percent of the reference value,

C = value of the data item from the WIM system, and

R = corresponding reference value for the data item.

5. Make the necessary changes, according to the vendor's recommendations, to the WIM system settings such that the mean value of the respective differences for each value is approximately zero.

The "States' Successful Practices Weigh-in-Motion Handbook" provides a procedure used in California. This procedure is used on the bending plate WIM systems, which is the predominate system in California. A two-part calibration is used: 1) acceptance testing and 2) fine tuning (*10*).

Acceptance testing is done after installation and before the system is brought on-line. It consists of three stages ():

1. The system component operation is checked. The roadway sensors should send signals to the on-site controller, and the on-site controller should convert these signals into usable data. An inconsistency here may indicate a problem with a system component or reflect an irregular traffic condition.
2. The initial calibration is performed. One Class 9 truck with air suspension for both tandem axle groups is used because it is the most predominant truck on California's highways. The truck axles are statically weighed, and the axle spacing and the overall length are measured. The initial calibration has four steps:

   Step 1. The WIM weight, axle spacing, and overall vehicle length settings are roughly adjusted using typical trucks in the traffic stream before the test truck is on-site.

Step 2. The test truck makes several runs in each lane to check the weight and spacing factors. The initial weight factor settings need to be set so that in the next step the estimated weight is within 5 percent of the actual weight. The axle spacing factor should be corrected at this time since the axle spacing is used to validate the speed readings. Because WIM estimates may be speed-dependent, speed accuracy is an important part of the calibration procedure.

Step 3. The test truck is driven over the WIM sensors in each lane at least three times at 5-mph increments usually between 45 and 65 mph for a total of 15 runs. The range of speeds should be determined to include the range at which trucks operate at the site. The GVW percent error is calculated for each run. For each lane, this information is plotted on a graph entitled "Gross Weight Percent Error by Vehicle Speed." This graph has the speed range on the x-axis and percent error on the y-axis. If the plots are inconsistent at any of the speeds, additional runs are made. These graphs are used to adjust the weight calibration factors.

Step 4. The test truck makes two additional runs at each speed after the weight factors have been adjusted. This is done to determine if the WIM system is operating at a level that meets the functional requirements for weight, axle spacing, vehicle length, and vehicle speed set by Caltrans as outlined in Section 2.4.2.5. If the requirements are not met, or a problem is detected, more diagnostic tests are performed; otherwise, the initial calibration is complete.

3. Seventy-two hours of operation is observed. The data produced during this period are reviewed using quality assurance. Once the system components are determined to be working on a continuous basis within the required specifications, the system is accepted and placed on-line.

The fine tuning or recalibration portion of the calibration takes place throughout the design life of the WIM site. The parameters are adjusted when problems are identified during the quality assurance procedures. These procedures and methods are discussed further in Section 2.5. The analyst must be knowledgeable about the site characteristics, traffic conditions, truck characteristics, and the WIM system's data processing characteristics in order to validate the data and fine-tune the calibration ().

The LTPP defines three methods for calibration. The first method is used when a static weigh station is located either upstream or downstream of the WIM sites. Random trucks are selected from the traffic stream and measured at the static weigh station. The measurements for these selected trucks are compared with the measurements taken from the WIM site. Thus, the calibration is validated, or new calibration factors are developed based on the collected data (*20*).

The remaining two methods are used in the case where a static weigh station is not located near the WIM site. The test trucks are measured and weighed on a certified static scale. Once this is accomplished, test runs may begin. Speed measurement at the site should be confirmed by using a radar gun or laser speed measurement system (*19*, *20*).

Regardless of the method used, the following points should be considered (*19*):

- The test trucks should move at a constant speed.
- Vehicle runs must be made at a variety of speeds (at least three).
- The trucks should not be operated at speeds above the posted limits and should not cause safety problems by operating too slowly.
- Note that "time of day" is actually a surrogate for temperature.
- To obtain a wide temperature variation, data may be collected for more than eight hours per day. Where possible, more than 12 test runs should be performed during each temperature range. These additional runs can be performed either by making additional runs at given vehicle speeds or by providing additional speed runs (e.g., if time is available to make one additional pass per time period/temperature condition, the additional run might be made at the speed at which the majority of trucks operate).
- Data should also be collected after the temperature has started to decline to determine whether cooling of the upper pavement layers (i.e., while the lower layer stays warm) affects WIM sensor output.

- A total of 40 runs are the minimum required to have an acceptable data set for analysis. If turnaround times are such that two trucks between them cannot complete 40 runs in a 10-hour site visit (breaks included), additional trucks should be used.

For each vehicle pass, the speed, weight of each axle, and axle spacing should be recorded ().

The classification algorithm should have been checked and assured to be functioning correctly before validation. This can be done using field tests that manually classify vehicles and check them against the scales output. In performing the analysis the recorder must manually classify the vehicle and then read the scale output. The analysis, should not be limited to heavy trucks, but all vehicles in the 13-bin classification code should be considered ().

Specific vehicles that are potentially problematic to classification algorithms should be examined carefully. These include (*19*):

- Recreational vehicles,
- Passenger vehicles (and pick-ups) pulling light trailers, and
- Long tractor semi-trailer combinations.

The scales classifier is working acceptably when (*19*):

- No more than 2 percent of the vehicles recorded are reported as "unclassified" by the WIM scale.
- The number of classification errors involving truck classification is less than 2 percent.

As previously indicated, the dynamic motion of a vehicle has an effect on the accuracy of the WIM scale. Pavement smoothness plays an important role in that dynamic motion, particularly the section of pavement 275 feet before and 30 feet after the center line of the scale. In order to obtain accurate axle load data this section must meet pavement smoothness specifications. Pavement smoothness evaluation falls into one of three categories (*19*):

1. Verification of existing WIM sites: these sites are in operation, but an evaluation will be performed to determine if the satisfy the specifications.
2. Acceptance of newly constructed WIM sites: newly constructed sites will be evaluated to determine if they meet the specifications.
3. Annual check of WIM sites: all sites in the LTPP program will be evaluated once a year to determine if they meet the specifications.

Each category has a set of procedures to follow in determining if the pavement smoothness meets the requirements. More information can be found in the literature (*19*).

The IRD Software User's Manual states that the on-site calibration is such that the computer will make the calibration adjustment calculation. A test vehicle's true length, axle weights, and spacing are entered into the computer. The vehicle is then passed over the sensors several times. After comparing the known values with those measured by the WIM system, the computer adjusts certain scaling factors used by the software to make the measured property match the vehicle's true property. A minimum of 10 runs of the test vehicle is suggested be made to determine the average measured values used for the new factor calculation. The number of runs required depends on the standard deviation of the samples obtained. If five samples are taken that are tightly grouped, or have a small standard deviation, then perhaps the scaling factor can be calculated based on the five samples. However, if the standard deviation is large, then perhaps 15 samples should be used. Statistically representative data must be used for calibration (*21*).

2.4.2.4 Verification Procedures. The ASTM Designation: E 1318-02 states that the on-site acceptance test for Type I, Type II, and Type III WIM systems is done to determine if a newly installed or modified WIM system meets or exceeds the specified requirements outlined in Table 2.5 and the data items produced, depending on type, listed previously in Table 2.3. This test is expected to be completed before the user makes final acceptance of the product or service and before final payment is made to the vendor ().

Table 2.5 ASTM Designation: E 1318-02 Functional Performance Requirements for WIM Systems at a 95 Percent Probability of Conformity (*4*)

Function	Type I	Type II	Type III
Wheel Load	± 25%	-	± 20%
Axle Load	± 20%	± 30%	± 15%
Axle-Group Load	± 15%	± 20%	± 10%
GVW	± 10%	± 15%	± 6%
Speed	-	-	± 1 mph
Axle-Spacing	-	-	± 0.5 ft

The following steps of the test are required for each instrumented lane (*4*):

1. Execute the calibration procedure as presented in the previous section. Make the adjustment to the WIM system as indicated in the fifth step of the ASTM Designation: E 1318-02 calibration procedure.
2. Have each of the two test vehicles make five or more runs over the sensors in each lane at an attempted speed approximately 5 mph less than the maximum speed, and then five or more additional runs at an attempted speed approximately 5 mph greater than the minimum speed, used during the calibration. At each speed, one or more runs should be made with the test vehicle tires near the left lane edge, and one or more runs with the test vehicle tires near the right lane edge. The other runs should be made with the test vehicle approximately centered in the lane. Also, with a radar speed meter, measure each test vehicle's speed every time it passes over the WIM system sensors.
3. Make calculations by first determining the percent difference using Equation 2.1 outlined previously. Next, determine the number of calculated differences that exceeded the tolerances in Table 2.5 and express this number as a percent of the

total number of observed values of this item by the following relationship given in Equation 2.2.

$$P_{de} = 100\left[\frac{n}{N}\right] \quad (2.2)$$

where: P_{de} = percent of differences exceeding tolerance,

n = number of differences exceeding tolerance, and

N = total number of observed values of the data item.

4. Interpret the test results and report. All specified data collection features, data-processing features, and options of the system type described above and given in Table 2.3 shall be demonstrated to function properly. If any of these fails to function properly, or if more than 5 percent of the calculated differences for any applicable data item resulting from all runs of the two test vehicles exceed the tolerance specified in Table 2.5 for that item and WIM system type, the WIM system is declared dysfunctional or inaccurate.

2.4.2.5 Performance Requirements. Several of the standards defining acceptable performance requirements for WIM system operation are outlined in this section, including: 1) ASTM, 2) "States' Successful Practices Weigh-in-Motion Handbook," and 3) the LTPP program.

The ASTM Designation: E 1318-02 performance requirements are provided in Table 2.5.

The "States' Successful Practices Weigh-in-Motion Handbook" states that the test truck makes two additional runs at each of the previously discussed speeds after the weight factors have been adjusted. This is done to determine if the WIM system is operating at a level that meets Caltrans' functional requirements for weight, axle spacing, vehicle length, and vehicle speed as shown in Table 2.6. If the requirements are not met or if a problem is detected, then more diagnostic tests are performed; otherwise, the initial calibration is complete (*10*).

Table 2.6 Caltrans States' Successful Practices Weigh-in-Motion Handbook Functional Requirements (*10*)

Variable		Mean	Standard Deviation
Vehicle Weight	Single Axle	± 5 %	8 %
	Tandem Axle	± 5 %	6 %
	GVW	± 5 %	5 %
Axle Spacing		± 6 inches	12 inches
Vehicle Length		± 12 inches	18 inches
Vehicle Speed		± 1 mph	2 mph

For the LTPP program, once the data are collected from the test runs, statistics must be computed to see if the WIM site meets the requirements set by LTPP provided in Table 2.7. The percent error for each pass must first be calculated, followed by the mean and standard deviation of the percent errors. For a large sample size (greater than 30) the formula for a 95 percent confidence level is used as given in Equation 2.3 (*19*).

$$CI = \overline{X} \pm 1.96 \cdot s \tag{2.3}$$

where: CI = confidence interval,

$\overline{X}$ = the mean percent error, and

s = the standard deviation of the percent errors.

The results of the confidence interval are compared against the values in Table 2.7. If the upper or lower boundary of the confidence interval fall outside of the upper and lower limits found in the Table 2.7, then the scale fails the basic accuracy test. Otherwise, the scale passes the basic accuracy test (*19*).

Table 2.7 LTPP WIM System Calibration Tolerances (*19*)

Variable	95 Percent Confidence Limit of Error
Loaded Single Axles	± 20 %
Loaded Tandem Axles	± 15 %
GVW	± 10 %
Vehicle Speed	± 1 mph
Axle Spacing Length	± 0.5 ft

Another two sets of tests may be performed to examine scale sensitivity to temperature and speed. First, the test vehicle runs are sorted into temperature subsets, usually cool, moderate, and hot. For each subset, the mean and standard deviation of the percent error are calculated. This is similarly done for the second test with subsets of speeds. Depending on the sample size of the subsets, a different calculation should be used. If the subset is greater than 30, Equation 2.3 can be used; otherwise, Equation 2.4 is more appropriate (*19*).

$$CI = \overline{X} \pm t \cdot s \qquad (2.4)$$

where: CI = confidence interval,

$\overline{X}$ = the mean percent error,

n = the number of samples (or runs in subset),

t = the Student's t statistic where $\alpha = 0.025$ and degrees of freedom is n-1, and

s = the standard deviation of the percent errors.

The calculated values can then be compared to the standards given, and a determination can be made on whether or not the scale fails under these conditions (*19*).

2.4.3 Auto-Calibration Methodology

IRD Software User's Manual Version 7.5.0 describes the auto-calibration feature in depth. The auto-calibration method maintains the system in constant calibration as the environmental conditions of the site change over long periods of time. Seasonal temperature changes can affect the sensor readings. Obtaining accurate data from this distorted information requires that the scaling factor be adjusted to compensate for the changes in sensor information. Generally, auto-calibration is only used for piezoelectric systems, as bending plate and single load cell systems do not change much with temperature (*21*).

The underlying principle of the auto-calibration is that the steering-axle weight of a user-selected truck type will have minimal change regardless of the load the truck is carrying. The steering-axle weight of a test truck of the chosen type can be measured and stored in the system as a referenced weight. During operation the system will keep track of all the steering-axle weights of the chosen calibration truck type, generally Class 9, and, if these begin to deviate significantly from the referenced value, the system adjusts the auto-calibration factors to bring the measured values back in line with the reference (*21*).

Based on observation, steering-axle weights may change slightly based on GVW. The system allows for the auto-calibration vehicle type to be further divided into as many as three subpopulations based on GVW. The user defines the quantity and parameters of the three potential GVW bins. Each bin has a target steering-axle weight associated with it (*21*).

The variances of weight due to temperature are also accounted for in the auto-calibration through temperature binning. This feature is critical when using piezoelectric sensors. The GVW ranges described above are grouped such that an averaged, temperature-based scaling factor is developed for each of several temperature bins. Thus, one scaling factor is associated with each temperature bin. The number and size of the bins is set by the user. Each temperature bin will have only the vehicles that pass the site when the temperature is within the bin's range to be used for the recalibration. The user may choose to have anywhere from 1 to 40 temperature bins (*21*).

The auto-calibration system will adjust the auto-calibration factors as necessary at regularly spaced intervals, every 24 hours, 48 hours, weekly, or monthly, as specified by the user. The auto-calibration system will check the gathered data at these intervals and determine if an adjustment needs to be made.

Two different ways exist for determining if the auto-calibration factor should be altered, depending on the setting: 1) the auto-calibration factor will be altered if the percent error between the mean steering-axle weight of the auto-calibration type trucks, generally Class 9, for the interval and the user-entered reference is greater than the user-entered acceptable error and 2) the number of auto-calibration type trucks and the sum of their steering-axle weights are added to a running total at the end of each interval. When the running total reaches a user-entered number of trucks before adjustment, then the population mean is checked against the reference, and an adjustment to the scaling factor is made if the error is outside the user-entered acceptable error (*21*).

One concern with having a regular interval time between updating the auto-calibration factors is that not enough trucks pass over the sensors for proper calibration to occur. Two methods are available in the system to overcome this. First, the amount of adjustment made can be based on the number of trucks that have been recorded up to a maximum of 50 percent towards the new value. For example, it can be set such that if 200 vehicles pass over within the interval the allowable change is the maximum 50 percent. However, if only 10 or 20 trucks are recorded, the allowable change may only be 20 percent. In case the small sample size produces an inaccurate average steering-axle weight, the system will only adjust the factor towards the new value, not completely changing it. Second, the amount of adjustment made can be based on the number of trucks that have been recorded and the allowable change according to an internal table. This makes it possible to allow the amount of change to be based on a user-defined internal table (*21*).

2.5 Quality Assurance Methods

Quality assurance refers to the use of methods to ensure that the quality of collected data is maintained. The following subsections explain several of these methods, including: 1) daily average steering-axle weight, 2) daily average drive tandem spacing, 3) GVW histogram, 4) vehicle class histogram, 5) left-right residual, 6) error rates, and 7) LTPP software. In the subsequent chapters, the results of many of these methods employed on the Utah 2004 WIM data are displayed and discussed.

2.5.1 Daily Average Steering-axle Weight

The weight of the steering axle for Class 9 vehicles generally varies only a few hundred pounds depending on the total GVW. The TMG recommends than if the rolling average of the steering-axle weight of the last 100 trucks changes more that a user-specified amount, then the scale should be suspected of drifting. A number of factors exist that can have an effect on the steering axle that should be considered (*1*):

- The total GVW of the vehicle (the heavier the GVW, the heavier the steering-axle weight),
- The spacing between the steering axle and the drive tandems on the tractor (the greater the distance, the lower the steering-axle weight),
- The roughness of the road (the rougher the road, the lower the steering-axle weight that can be expected), and
- State-specific weight laws and truck characteristics (create a variety of effects).

Another factor to consider is the time in which the last 100 Class 9 vehicles were recorded. If the truck volume is such that all 100 vehicles crossed the scale within the past hour, then that data set is useful in determining the health of the scale and any change in calibration. On the other hand, if the last 100 trucks were recorded over a 20-day period, temperature or other conditions may have changed during that time, and calibration adjustment would not be appropriate (*1*).

Detection of calibration drift is possible by monitoring daily averages over time. Dahlin places the distribution of steering-axle weights into three categories of GVW (*22*):

- Less than 32,000 pounds,
- 32,000 – 70,000 pounds, and

- More than 70,000 pounds.

Each of these groups has been evaluated and noted to have a different average steering-axle weight across categories, but a similar average steering-axle weight within each category. The categories may be separated and graphed against time. The dates and times that changes in this average occur can be used to pinpoint the possible causes of calibration drift. The average steering-axle weight is useful in detecting gross drifts in calibration but is not sufficient to detect minor shifts in calibration (*23*).

2.5.2 Daily Average Drive Tandem Axle Spacing

The mean drive tandem axle spacing of Class 9 vehicles has also been evaluated, and it has been determined that values are fairly consistent. This spacing is monitored to detect any changes in the scale's ability to measure speed. If the scale is not measuring speed correctly then the weights are likely also incorrect (*1*).

The expected average drive tandem axle spacing is 4.33 feet (*23*). The LTPP uses an interval between 4.10 and 4.90 feet in determining data quality. More specifically, the LTPP program proposes a precise value of 4.40 ft. Caltrans uses a value of 4.30 ft in their quality control procedures. In the United States, truck manufacturers primarily use 4.25, 4.33, 4.50, and 4.58 feet for distances between the two drive tandem axles of Class 9 vehicles. Based on the number of each type sold by manufacturers, the weighted average drive tandem axle spacing is 4.33 feet. This value is suggested by Nichols and Bullock for Indiana (*23*) and is also used in the analysis of Utah's data in this report.

If the daily average drive tandem axle spacing is graphed against time, it is possible to detect changes and the times that those changes occur. The expected values of this spacing should be 4.33 feet, and data should linger around this value. This is a useful metric to monitor the calibration of the WIM site (*23*).

2.5.3 Gross Vehicle Weight Histogram

The use of GVW histograms of Class 9 vehicles was originally developed by the Mn/DOT. It was later adopted in the LTPP program, in which a 4,000-pound bin size or increment was recommended. The basic underlying idea is to find consistent peaks in the GVW distribution. Usually, two peaks exist, one representing empty trucks (generally between 28,000 and 36,000 pounds GVW) and the other representing loaded trucks (generally between 72,000 and 80,000 pounds GVW). The characteristics of the peaks vary depending on the type of commodity and the weight law of the state in which the analysis is being performed. For most sites the location of these peaks remains constant, but the height of the peaks may change as the volumes of the loaded and empty trucks change. By comparing the current graph with those developed from new data, the reviewer must determine if the new data represent valid weights or if the scale is out of calibration.

In using the GVW histogram analysis, three main factors need to be checked (*1*):

- Both peaks shifted: if both peaks are heavier or lighter than expected, the calibration needs to be evaluated further.
- One peak shifted: if one peak is correctly located and the other has shifted, the acquisition of more data is required. Possible reasons for the shift are that the scale is classifying but not weighing the vehicles or that a change in loading of average vehicles has occured in the segment of highway and it is a valid change in the peak location.
- Number of vehicles heavier than 80,000 pounds GVW: if a dramatic change in the number or percent of vehicles heavier than 80,000-pound GVW, the scale's calibration should be questioned. This is especially useful with piezoelectric sensors when they fail because they produce extremely large and inaccurate weights.

2.5.4 Vehicle Class Histogram

A vehicle class histogram involves the evaluation of a histogram of the classes. Two measures are tracked: 1) the total volume of trucks by classification and 2) the percentage of trucks within each classification. If changes in these volumes or percentages are observed, more investigation is necessary because changes in traffic conditions may have occurred. If the distribution has not changed but the histogram shows that it has, then the scale should be evaluated and calibrated. Monitoring this distribution is very helpful, particularly if done frequently with abnormalities investigated promptly and faulty equipment repaired or replaced in a timely manner (*1*).

2.5.5 Left-Right Residual

The left-right residual is an extension of the average steering axle monitoring method that was discussed previously. The left-right residual is intended to be an accurate metric to detect small sensor drift. The premise behind the methodology is that the distribution of weight between the left and right wheel of an axle provides a fairly constant metric. In order to utilize this metric, the WIM scale must be able to collect data for each wheel (*23*). Many scales do not have the ability to weigh each wheel separately; none of the scales in Utah have this capability.

2.5.6 Error Rates

WIM sensors register warnings or errors when measurements are inconsistent with expectations. These inconsistent measurements may result from an unusual vehicle, vehicles changing lanes, or a vehicle following too close to the preceding vehicle. The number of errors can be graphed against time, and these trends can be observed. By their nature, these error warnings do not necessarily indicate a problem with the scale, but an increase or unusual patterns in the number of errors indicate a possible scale malfunction. Following the number of errors over time is another metric in determining the health of the scale and the quality of the data obtained from it (*23*).

2.5.7 LTPP Software

The LTPP program has developed software that produces graphs for the purpose of quality assurance. The software requires access to an Oracle 9i database, or more recently, a new version of the software was produced that requires a .NET framework. The software is designed to aid in monitoring WIM data by generating graphs over multiple time periods (e.g., day, week, month, year, and multiple years) to evaluate the following (*24*):

- Axle type distribution (i.e., single, tandem, tridem, quad+, and steering axles);
- GVW distribution;

- 4-card vs. 7-card;
- Vehicle distribution (4-card or 7-card);
- Axle weights;
- B-C axle weights and spacing;
- Daily average steering-axle weight;
- Classification data; and
- Average equivalent single axle load (ESAL) per vehicle.

The 4-card and 7-card title refer to measurements taken for two separate types of equipment. The number of vehicles from classification equipment may be compared against the number recorded from the WIM scale (*24*).

Many of the graphs produced by the traffic analysis software were discussed previously in this report, including their use and interpretation. The other graphs are not applicable to the analysis and are not discussed in this report.

2.6 Traffic Monitoring Guide Weight Data Collection

The TMG was published in 2001 in an attempt to offer suggestions to improve and enhance current programs with an eye to the future of traffic monitoring. The guide provides examples of statewide monitoring systems and the logic and science behind them. The information is provided to help a highway agency optimize their WIM system. This portion of the report provides a summary of the TMG section on weight data collection.

WIM systems work best when installed flush with the road surface. Two main problems are associated with sensors that sit on top of the roadway: 1) an additional dynamic motion exists in the vehicle where a horizontal component of the tire force is read and 2) the sensor measures the force of the tire deformation. Permanent installations of sensors are better for consistent accurate weighing results and are recommended. Also, calibration would be required with each move of a portable WIM device because dissimilar pavement conditions would be encountered between sites. The condition of the pavement plays an important role in the dynamic motion of vehicles and thus in the calibration of WIM equipment (*1*).

The data should be collected and analyzed frequently to ensure that the equipment is operating efficiently. The FHWA has developed software to aid in this process. FHWA's Vehicle Travel Information System (VTRIS) allows for quick examination of WIM data (*1*).

The remaining summary of the TMG covers: 1) the grouping of WIM sites, 2) site location selection, 3) total size of the weight data collection program, and 4) WIM sensor calibration.

2.6.1 Groupings

The TMG states, "[T]he objective of the truck weight data collection program is to obtain a reliable estimate of the distribution of vehicle and axle loads per vehicle for truck categories within defined roadway groups" (*1*). The idea is to place roadways into groups that experience truck traffic with reasonably similar characteristics. For example, roads that experience loads from heavy resource mining should be grouped separately from roads that carry light urban delivery. Each group should consist of several WIM sites, one or more of which should be operated continuously throughout the year to monitor seasonal changes in traffic patterns. More than one WIM site per group will help with determining whether the sites have similar load characteristics and should be in the same group (*1*).

The road groups should be based on geographic, industrial, agricultural, and commercial patterns along with knowledge of truck traffic patterns on specific roads. The key to the design of the truck weight grouping system is for the highway agency to be able to successfully recognize differences in loading patterns and to collect enough data to be able to estimate the load occurring on the different roads (*1*).

Australia has a similar grouping technique. In the Australian Pavement Design Guide, 25 different truck-loading patterns are identified. These patterns are structured both by the type of truck movement and the infrastructure linkages being served. The types of truck movement in Australia are (*1*):

- General freight,
- General freight in a heavy vehicle increased mass permit environment,
- Predominately industrial,
- Quarry products,
- Predominately farm produce,
- Livestock, and
- Logging products.

The infrastructure linkages in Australia are (*1*):

- Long-haul inter-capital,
- Long-haul inter-capital at remote sites,
- Inter-regional within state/territory or nearby region,
- Near town and/or where local freight movement occurs,
- Developing area,
- Entering and exiting port/loading sites, and
- Entering and exiting capitol city.

The TMG does not recommend specific roadway groupings. Australia's grouping plan serves as an example of how a state could develop their grouping plan. Beginning with a simple grouping and refining the grouping once more data are available is a wise approach. Where not much data available, the initial grouping should be based on the percentage of through-trucks that exist on a roadway and distinct geographical areas within the state associated with certain types of economic activity (*1*).

Several other factors exist that need to be considered when grouping roads (*1*):

- Agricultural products that produce a specific loading pattern. For example, cherry-growing areas might be grouped separately from wheat-growing areas because of the differences in the density of their loads.
- Types of industrial areas should be grouped differently depending on the materials transported.

- The distance over which the trucks are likely to travel. Areas that trucks travel for long distances are likely to be loaded heavily, while areas where short trips are made will tend to be loaded lighter.
- Urban or rural roads. Urban areas have considerably higher numbers of partially loaded vehicles and empty trucks. In rural areas, trucks tend to operate full.

A state may also be interested in separating roads because of the industrial activity that they serve. Roads leading into and out of a port will have higher loading than other roads in the same area. The use of existing data to develop logical or statistical differences can be very informative. Groups can also be established according to weight.

Washington State has developed five basic truck loading patterns in their effort to determine the total freight tonnage carried by state roads (*1*):

- Group A: serves major statewide and interstate truck travel. These routes are the major regional haul facilities.
- Group B: serves primarily inter-city freight movements, with minor amounts of regional hauling. These routes also serve as produce transfer routes, serving rail and barge-loading facilities.
- Group C: serves farm-to-market routes and regional commerce.
- Group D: serves suburban industrial activity.
- Group E: serves primarily local-goods movement and specialized products.

Table 2.8 provides a general example of truck load groupings. Each state should select the appropriate number and definition of groups based on economic and trucking characteristics. This is a good starting point, but groups should be refined as more information becomes available (*1*).

The number of groups is important because it corresponds to the number of WIM sites needed. The more groups, the more WIM sites needed. The number of current sites should be considered along with those that are planned for installation when making groups. Larger states with many WIM sites should have more groups than smaller states with fewer WIM sites (*1*).

Table 2.8 Example of Truck Loading Groups (*1*)

Rural	Urban
Interstate and arterial major through-truck routes	Interstate and arterial major truck routes
Other roads (e.g., regional agricultural with fewer through-trucks)	Interstate and other freeways serving primarily local truck traffic
Other non-restricted truck routes	Other non-restricted truck routes
Other rural roads (mining areas)	Other roads (non-truck routes)
Special cases (e.g., recreational, ports)	

Two important aspects of road grouping are: 1) checking the groupings after they have been formed and 2) determining the number of sites needed per group. These topics are discussed in the following subsections.

2.6.1.1 Checking Groups Once They Have Been Formed. Once road groups are established and data are collected within each group, the groups may be evaluated to determine if the roads that were grouped together continue to have similar truck weight characteristics. The methods that were used to form the groups initially should be used to review if the groupings are still set correctly (*1*).

One method to check groups is to check the precision of estimates from truck weight groups, where the precision of the group mean is the standard error of the mean. Precision can be estimated at a 95 percent confidence level by plus or minus 1.96 times the standard deviation divided by the square root of the number of sites. The value of 1.96 is a rough estimate and should only be used when the number of sites is greater than 30. For groups with sites less than 30, which is the case most of the time, the Student's *t* distribution should be used with degrees of freedom equal to one less than the number of sites in the group (*1*).

Two ways to increase the precision of the data collected are: 1) increasing the number of sites in the group and 2) reestablishing the group so that the variation is minimized (*1*).

2.6.1.2 Determining the Number of WIM Sites Per Group. The precision calculations discussed previously can be used to determine the number of WIM systems that should be included within each truck weight group. Two factors need to be established before determining the number of WIM sites needed. First, the agency (e.g., state DOT) needs to determine the statistic to use in the analysis. Either the mean ESAL for Class 9 vehicles or the GVW for Class 9 vehicles are recommended to be used. Second, a precision level must be established. Usually, this is expressed as a percentage of the statistic (e.g., ± 15 percent of the mean GVW) (*1*).

A few trade-offs should be considered in determining the number of WIM sites per group. The state may opt to have fewer groups but a large number of data collection sites, or, conversely, they may have more groups but a smaller number of collection sites per group depending on their emphasis for data collection (*1*).

Another trade-off to consider is the number of sites versus the precision. The state pays for the precision by installing more sites. If more sites cannot be installed due to financial or physical limitations, then precision might be increased by adjusting the groups such that the variation between group members is minimized (*1*).

The key equation in determining the number of WIM sites per group is given in Equation 2.5 (*1*).

$$n = \frac{\left(t_{\alpha/2}\right)^2 C^2}{D^2} \tag{2.5}$$

where:

n = the number of samples taken (in this case, the number of WIM sites per group);

t = the critical value associated with the Student's t distribution;

α = the selected level of confidence;

C = the coefficient of variation (COV) for the sample as a proportion; and

D = the desired accuracy as a proportion of the estimate.

The COV is the standard deviation over the mean. Solving for n is an iterative process, because an n exists on both sides of the equation (the t statistic requires degrees of freedom which is n minus 1). With this equation, different precisions, grouping variations, and number of sites may be considered. Changing the road groupings has a dramatic effect on the number of sites needed (*1*).

As the number of sites increase, the incremental benefit of adding additional sites decreases. Research has found that after six sites the benefit of adding more diminishes quickly. Therefore, the TMG recommends six sites per group (*1*).

A general recommendation of the TMG is that a least one site in a group is operated continuously to be able to detect any changes in truck weights for daily or seasonal variations. The sites that are not operated continuously are recommended to be operated for seven continuous days each year (*1*).

2.6.2 Site Selection

Selection of a new site for a WIM scale should be based on the weight data collection program and on the characteristics of the roadway section. The needs of the weight data collection program are (*1*):

- The need to obtain more vehicle weight data on roads within a given truck weight roadway group,
- The need to collect data in geographic regions that are poorly represented in the existing WIM data collection effort,
- The need to collect data on specific facilities of high importance (e.g., interstate highways or other national highway system routes),
- The need to collect data for specific research projects or other special needs of the state, and
- The need to collect weight information on specific commodity movements of importance to the state.

Even if the site meets the criteria above, it still may not be suitable for a WIM site. The physical characteristics of the section of highway play a large role in the accuracy of the data provided at the site. The physical requirements of the site vary depending of the vendor, but in general WIM sites should have (*1*):

- Smooth, flat (in all planes) pavement;
- Pavement that is in good condition and that has enough strength to adequately support axle weight sensors;
- Vehicles traveling at constant speeds over the sensors; and
- Access to power and communications (although these can be supplied from solar panels and through various forms of wireless communications).

2.6.3 Total Size of the Weight Data Collection Program

The weight data collection program is a function of the size of the variability of the truck weights and the accuracy and precision desired. A small state with only two road groups will need only 12 sites with two to four operating continuously. A larger state may have 10 to 15 road groups requiring 60 to 90 WIM sites. The number of continuously operating sites would also increase. Most states will find themselves between these two examples. Between 12 and 90 sites are expected to be needed per state (*1*).

2.6.4 WIM Sensor Calibration

As indicated previously, the most common approach to WIM sensor calibration is to use test trucks of known weight. One or more trucks make multiple runs over the WIM scale. The performance of the WIM scale is then compared to the known weight of the test trucks, and adjustments are made to the calibration as needed. Following the adjustments additional runs may be made to ensure the level of accuracy desired. A number of variations exist to the use of test trucks. The methods differ in the use of additional vehicles, environmental conditions, truck speeds, and number of truck runs (*1*).

The problem with the test truck method is that the use of a single (or even two vehicles) can create a bias in the calibration. This comes from the fact the different trucks interact with the road in a dynamically different way. As a truck bounces down the roadway, the vehicle may weigh more or less at a given point than it would statically, as depicted previously in Figure 2.1. This cyclical pattern changes depending on the truck (*1*).

Five approaches to overcome this potential bias in the calibration are (*1*):

1. A scale sensor can be used that physically measures the truck weight for a long enough time period to be able to account for the truck's dynamic motion (this is true of the bridge WIM system approach where the truck is on the "scale" the entire time it is on the bridge deck).
2. Multiple sensors can be used to weigh the truck at different points in its dynamic motion either to average out the dynamic motion or to provide enough data to predict the dynamic motion (so that the true mean can be estimated accurately).
3. The relationship of the test truck to all other trucks can be determined. This is often done by mathematically modeling the dynamic motion of the truck being weighed in order to predict where in the dynamic cycle it is when it reaches the scale.
4. More than one type of test truck can be used in the calibration effort (where each test truck has a different type of dynamic response) in order to obtain a sample of the vehicle dynamic effects at that point in the roadway.
5. Independent measurement can be used to ensure that the data being collected are not biased as a result of the test truck being used.

The first approach has a number of other technical problems associated with it. The use of multiple sensors is a technically promising approach; however, most states do not like the added cost of additional sensors. The third approach requires extensive knowledge of the vehicle's dynamic motion, which is difficult to obtain. In the fourth approach, the LTPP program recommends the use of multiple test trucks. This was a compromise of the simplicity of using one test truck and the increased confidence of using larger numbers of trucks. The fifth approach uses independent measures such as running trucks at different speeds and using consistent weight characteristics to confirm the accuracy of the scale (*1*).

2.7 AASHTO Pavement Design Guide

The long awaited "Guide for Mechanistic Empirical Design of New and Rehabilitated Structures" is currently being prepared for use by highway agencies. Many agencies have been preparing for this guide since 2002. This guide replaces the earlier versions of the AASHTO Pavement Design Guide. It is a data-intensive method that uses a mechanistic-empirical approach to pavement design (*3*).

A summary of the document is provided in the following sections, which include: 1) an overview, 2) a discussion of the levels of data input, 3) the data requirements of the guide, and 4) the WIM data importance.

2.7.1 Overview

The overall objective of the AASHTO Pavement Design Guide is to provide the highway community with a state-of-the-practice tool for the design of new and rehabilitated pavement structures based on mechanistic-empirical principles. This is done through the guide itself and software developed to accompany the guide (*3*).

This guide represents a substantial change in the way that pavement is designed. In the new design, environmental and construction conditions are considered, including traffic, climate, subgrade, and existing pavement condition for rehabilitation. Based upon these inputs a trial design is developed and evaluated through a prediction of key distresses and smoothness. If the design does not meet the criteria, it is revised and evaluated again. This iterative process is continued until the design meets the criteria specified (*3*).

2.7.2 Levels of Data Input

Most of the data inputs may be of three quality levels depending on the criticality of the roadway and the data available. The levels include (*3*):

- Level 1: where very good knowledge of past and future traffic characteristics,
- Level 2: where modest knowledge of past and future traffic characteristics, and
- Level 3: where poor knowledge of past and future traffic characteristics.

Good knowledge of traffic loads can be obtained where past traffic volume and weight data have been collected along or near the roadway segment to be designed. The designer has a high level of confidence in the accuracy of the truck traffic data used in the design (*3*).

Modest knowledge consists of knowledge where only regional/statewide truck volume and weights data are available for the design section of roadway. In this case, the designer can predict with reasonable certainty the basic pattern of loads the trucks will carry (*3*).

Poor knowledge of past and future traffic characteristics is where the designer must rely on default values computed from a national database and/or relatively little truck volume and weight data available (*3*).

2.7.3 Data Requirements

Traffic data are essential to the design of pavements. The load and frequency of loading must be known. The typical data required for pavement design are (*3*):

- Base year truck-traffic volume,
- Vehicle (truck) operational speed,
- Truck-traffic directional and lane-distribution factors,
- Vehicle (truck) class distribution,
- Axle-load distribution factors,
- Axle and wheel base configurations,
- Tire characteristics and inflation pressures,
- Truck lateral distribution factor, and
- Truck growth factors.

These data are gathered through WIM, Automatic Vehicle Classification (AVC), and vehicle counts. These may be extended through traffic forecasting models. The design guide describes the data needed and also has default values if the data are unavailable (*3*).

Four basic types of traffic data are needed for pavement design (*3*):

- Traffic volume including base year information;
- Traffic volume adjustment factors including monthly adjustment, vehicle class distribution, hourly truck distribution, traffic growth factors;
- Axle-load distribution factors; and
- General traffic inputs including number of axles/trucks and wheelbase.

These four traffic data types are discussed in the following sections in connection with the three levels of data input and the requirements for the new design method.

2.7.3.1 Traffic Volume – Base Year Information. The base year refers to the first year that the roadway segment under design was opened to traffic. The base year information required includes (*3*):

- Two-way annual average daily truck traffic (AADTT),
- Number of lanes in the design direction,
- Percent trucks in design direction,
- Percent trucks in design lane, and
- Vehicle (truck) operating speed.

Two-way AADTT is the total truck volume (Class 4 through Class 13) in the traffic stream passing a single point or segment of a road to be designed in both directions during a 24-hour period. These data can be gathered using WIM, AVC, vehicle counts, or traffic forecasting and trip generation models. Simply, the AADTT is the total truck traffic divided by the number of days the data cover. The assignment of the level of this data input is as described previously, where Level 1 is site-specific data, Level 2 is regional or statewide, and Level 3 is that the AADTT is estimated from Annual Average Daily Traffic (AADT) using an estimate of the expected truck percentage (*3*).

The number of lanes can be obtained based on the design specifications. The number of lanes represents the total number of lanes in one direction (*3*).

The percent trucks in the design direction are also referred to as the directional distribution factor (DDF). The AADT and the AADTT is generally assumed to have a

DDF of 50 percent in each direction when a two-direction value is given, but this is not always the case. The levels of input for the percent trucks in the design direction range from site-specific to regional/statewide to national average. This can be determined from WIM, AVC, and vehicle count data (*3*).

Percent trucks in the design lane, also called the truck lane distribution factor (LDF), accounts for the distribution of truck traffic between lanes in one direction. The factor is 1.0 on a two-lane, two-way highway (i.e., one lane in each direction). On roadways with multiple lanes in one direction, the factor depends on the AADTT and other geometric and site-specific conditions. The input levels are the same as discussed before, where Level 1 is site-specific coming from WIM, AVC, or vehicle count data; Level 2 is a regional/statewide factor that comes from WIM, AVC, or vehicle count data; and Level 3 is where a national average or a traffic forecasting and trip generation model is used (*3*).

Vehicle (truck) operating speed or the average travel speed depends on a number of factors. The determination of this speed is given in the TRB "Highway Capacity Manual" (*25*) or AASHTO's "A Policy on Geometric Design of Highways and Streets" (often called the "Green Book") (*26*). The software designed in connection with the design guide uses a default speed of 60 mph (*3*).

2.7.3.2 Traffic Volume Adjustment Factors. The truck-traffic volume adjustment factors required of traffic characterization are (*3*):

- Monthly adjustment factors,
- Vehicle class distribution factors,
- Hourly truck distribution factors, and
- Traffic growth factors.

A truck traffic monthly adjustment factor (MAF) is the proportion of the annual truck traffic for a specific truck class that occurs in a particular month. It is equal to the monthly truck traffic of the given class for the month divided by the total truck traffic for that class for the entire year. This factor could vary over the years of the life of the pavement, but this design method assumes that the factor remains constant throughout the design life of the pavement. The input levels are similar to what has been discussed, where Level 1 is site-specific, Level 2 is regional/statewide, and Level 3 is national; the use of estimates based on local experience may also be considered under Level 3 data. For all levels, the MAF is computed from WIM, AVC, or vehicle count data. The calculation of the MAF can be found in the literature with a default factor of 1 for each month and each class (*3*).

Vehicle class distribution is computed from data obtained from vehicle classification counting programs such as AVC, WIM, and vehicle counts. Normalized vehicle class distribution represents the percentage of each truck class (Class 4 through Class 13) within the AADTT for the base year. The sum of the percent AADTT of all truck classes should equal 100, with the levels of input consistent with that previously discussed (*3*).

Hourly truck distribution factors (HDF) are the percentages of the AADTT within individual hours of the day. The default values of this factor are given in the design guide, while WIM, AVC, or vehicle counts may be used to compute the HDF. The input levels for this factor are consistent with those previously discussed (*3*).

Traffic growth factors are best estimated at a particular site or segment when continuous traffic count data are available. Substantial amounts of data are needed to generate growth factors because growth factors computed from limited data collected from a limited number of locations may be biased. Data gathered using WIM or AVC is particularly useful in computing traffic growth factors.

2.7.3.3 Axle Load Distribution. Axle load distribution factors represent the percentage of the total axle applications within each load interval for a specific axle type (i.e., single, tandem, tridem, and quad) and vehicle class (i.e., Class 4 through Class 13). The load intervals for each axle type are (*3*):

- Single axles: 3,000 pounds to 40,000 pounds at 1,000-pound intervals,
- Tandem axles: 6,000 pounds to 80,000 pounds at 2,000-pound intervals, and
- Tridem axles and quad axles: 12,000 pounds to 102,000 pound at 3,000-pound intervals.

The normalized axle-load distribution or spectra can only be determined from WIM data. The input levels are similar to those discussed previously where: Level 1 is the distribution factors determined from site- or segment-specific WIM data, Level 2 is from regional/statewide WIM data, and Level 3 is from national default values (*3*).

2.7.3.4 General Traffic Inputs. The general traffic inputs include (3):

- Mean wheel location,
- Traffic wander standard deviation,
- Design lane width,
- Number of axle types per truck class,
- Axle configuration,
- Wheelbase, and
- Tire dimensions and inflation pressures.

Mean wheel location is defined as the distance from the outer edge of the wheel to the pavement marking. The input levels are: Level 1 is measured on site-specific segments, Level 2 is a regional/statewide average, and Level 3 is a national average value or estimate based on local experience. For the design guide software, the default (Level 3) mean wheel location is 18 inches (*3*).

Traffic wander standard deviation is the standard deviation of the lateral traffic wander. This parameter is used to determine the number of axle load applications over a point for predicting distress and performance. Level 1 is determined through direct measurements on site-specific segments, Level 2 is a regional/statewide average measured on similar roadways, and Level 3 is a national average or estimate based on local experience. The default value is 10 inches (*3*).

Design lane width is defined as the distance between lane markings on either side of the design lane. The default value for the standard-width lanes is 12 feet (*3*).

Number of axle types per truck class is the average number of axles for each truck class (i.e., Class 4 to Class 13) for each axle type (i.e., single, tandem, tridem, and quad). Level 1 values are determined from direct analysis of site-specific traffic data (e.g., AVC, WIM, or traffic counts), Level 2 values are determined through direct analysis of regional/statewide traffic data (e.g., AVC, WIM, or traffic counts), and Level 3 (i.e., default values) are based on analysis of national databases (*3*).

Axle configuration represents a series of data elements that describe the configurations of the typical tire and axle. Among these are the average axle-width, dual tire spacing, and axle spacing. These may be measured site-specific, or typical values may be used (*3*).

Wheelbase is a series of data elements that are needed to describe the detail of the vehicle's wheelbase used for computing pavement responses. These data may be collected through field measurement or from the manufacturer's database. Typical values are provided in the design guide, but site-specific values may be used if they are available. The particular way that these values are input into the software is provided in the design guide (*3*).

Tire dimensions and inflation pressures are important inputs in the performance prediction models. Many trucking industry associations were consulted to verify tire dimensions and pressures, the results of which are provided in the design guide (*3*).

2.7.4 WIM Data Importance

WIM data are essential in determining normalized axle load spectra and may be used to obtain all of the other hierarchal data inputs on a Level 1 or Level 2 analysis. WIM scales may also help in determining other non-hierarchal data inputs (*3*). With the emergence of the new guide, the importance of having sufficient accurate and functional WIM data collection locations will increase dramatically.

2.8 Concluding Remarks

The primary areas of focus discussed in the literature review chapter include: 1) WIM history, 2) basic concepts of WIM, 3) WIM technologies and application, 4) calibration results of WIM data collection systems, 5) weight data collection programs throughout the United States, 6) TMG weight data collection guidelines and recommendation, and 7) the new AASHTO Pavement Design Guide. The purpose of this chapter was to review existing publications that may contribute to this study.

Now that a discussion of the current literature has been accomplished, the current condition of the Utah WIM data is explored in the following chapter. An understanding of the literature leads to an understanding and evaluation of the Utah case study.

3 Utah WIM Data Summary

The purpose of this chapter is to provide background information about the current situation of Utah's CMV population. The CMV size and weight regulations will be outlined, followed by a description of Utah's WIM data set. Lastly, the preliminary analysis of the data will be discussed and examples given.

3.1 Utah CMV Size and Weight Regulations

Operators of vehicles that exceed the weight and size limits should obtain a permit prior to operating on Utah's public highways. These limits are in place to safeguard Utah highways, structures, and highway facilities from damage. UDOT is empowered to construct ports of entry for the purpose of enforcing these limits. UDOT's size and weight regulations, along with fees for obtaining permits, are outlined in the following sections (*27*).

3.1.1 Legal Size Regulations

Utah's size regulations, including width, height, length, overhang, and towing, are summarized in Table 3.1. The width, height, towing, and overhang parameters do not vary based on vehicle type; however, the length parameter does change based on the vehicle configuration (*27*).

3.1.2 Legal Weight Regulations

Utah's weight regulations are divided into two parts: 1) tire weight limitations and 2) vehicle weight limitations.

Table 3.1 Utah Size Regulations (*27*)

Parameter	Legal Requirement	Interpretation
Width	8.5 feet	The width measured from the outmost extremities
Height	14 feet	Measured from the road surface to the top of the load or vehicle
Length	45 feet	Single Vehicle: including front and rear bumpers
	48 feet	Semi-trailer: no length limit exists on tractor-trailer combinations where the trailer is less than or equal to 48 feet
	61 feet	Double Trailer Combinations: measured from the front of the first trailer to the back of the second trailer Stinger-Steered Automobile Transporters: measured bumper to bumper
	75 feet	Saddle Mount[1]: allows for a max of three Saddle mount vehicles Truck-Trailer Combinations: measured bumper to bumper
Overhang	3 feet in front and 6 feet in rear	Measured beyond the rear of the bed or the body of the vehicle
Towing	15 feet	Connection between the two vehicles must be less than 15 feet

[1]A saddle mount vehicle is a truck or trailer towing other vehicles with the steering axle of each towed vehicle mounted on top of the frame of the preceding vehicle

3.1.2.1 Tire Weight Limitations. The regulations for tires are as follows (*27*):

1. No tire is to carry more than the manufacturer's rating or 600 psi per inch of tire width.
2. Permitted divisible configurations with 11 inch wide tires or greater will be allowed 500 psi per inch of tire width. Divisible refers to a load that can reasonably be dismantled or disassembled to smaller loads to be within legal dimensions of size and weight.
3. Permitted divisible configuration with less than 11 inches of tire width will be allowed 450 psi per inch of tire width.

4. All axles weighing more than 10,000 pounds must have at least four tires per axle with the exception of steering, self-steering Variable Load Suspension (VLS)/retractable, or wide-base single tires (at least 14 inches wide).
5. Single tires on single axles will not be allowed except for steering axles, self-steering VLS/retractable axles, or axles with wide-base single tires (at least 14 inches wide).

3.1.2.2 Axle and Vehicle Weight Limitations. The weight regulations for axles and vehicles are summarized in Table 3.2. The parameters are displayed and the requirements provided along with and interpretation of the requirements. The maximum legal GVW is 80,000 pounds, however, even a vehicle weighing less than this may still be in violation of one of the other parameters of Bridge Table B discussed below (*27*).

Table 3.2 Axle and Vehicle Weight Limitations (*27*)

Parameter	Legal Requirement	Interpretation
Single Wheel	10,500 pounds	As long as tire rating is not exceeded
Single Axle	20,000 pounds	Dual tires or equivalent are required except for steering axles
Tandem Axle	34,000 pounds	Dual tires or equivalent are required
Tridem axle	(see Table 3.3)	
GVW	80,000 pounds	Must comply with Table 3.3

The Utah Weight Table Bridge Table B given in Table 3.3 provides the maximum load in pounds carried on any groups of two or more consecutive axles. All combinations of vehicles that weigh more that 80,000 pounds must be in compliance with this table and obtain an overweight permit before operating on Utah’s public highways. The values in the Table 3.3 are based on the weight formula in Equation 3.1 (*27*).

$$W = 500\left[\frac{L \cdot N}{N-1} + 12N + 36\right] \qquad (3.1)$$

where: W = maximum load in pounds that can be carried on a group of two or more axles to the nearest 500 pounds,

L = distance in feet between the outer axles of any two or more consecutive axles, and

N = number of axles being considered.

Table 3.3 Utah Weight Table Bridge Table B (*27*)

(N)	2 Axles	3 Axles	4 Axles	5 Axles	6 Axles	7 Axles	8 Axles	9 Axles	10 Axles	11 Axles	12 Axles	13 Axles
(L)												
4	34,000											
5	34,000											
6	34,000											
7	34,000	34,000										
8	34,000	42,500										
9	39,000	43,500										
10	40,000	44,000										
11		45,000										
12		45,500	50,000									
13		46,500	50,500									
14		47,000	51,500									
15		48,000	52,000									
16		48,500	52,500	58,000								
17		49,500	53,500	58,500								
18		50,000	54,000	59,000								
19		51,000	54,500	60,000								
20		51,500	55,500	60,500	66,000							
21		52,500	56,000	61,000	66,500							
22		53,000	56,500	61,500	67,000							
23		54,000	57,500	62,500	68,000							
24		54,500	58,000	63,000	68,500	74,000	79,500					
25		55,500	58,500	63,500	69,000	74,500	80,500					
26		56,000	59,500	64,000	69,500	75,000	81,000					
27		57,000	60,000	65,000	70,000	75,500	81,500					
28		57,500	60,500	65,500	71,000	76,500	82,000					
29		58,500	61,500	66,000	71,500	77,000	82,500					
30		59,000	62,000	66,500	72,000	77,500	83,000					

Table 3.3 (Continued)

(N)	2 Axles	3 Axles	4 Axles	5 Axles	6 Axles	7 Axles	8 Axles	9 Axles	10 Axles	11 Axles	12 Axles	13 Axles
(L)												
31		60,000	62,500	67,500	72,500	78,000	83,500					
32			63,500	68,000	73,000	78,500	84,000	90,000				
33			64,000	68,500	74,000	79,000	85,000	90,500				
34			64,500	69,000	74,500	80,000	85,500	91,000				
35			65,500	70,000	75,000	80,500	86,000	91,500				
36			68,000	70,500	75,500	81,000	86,500	92,000	98,000			
37			68,000	71,000	76,000	81,500	87,000	93,000	98,500			
38			68,000	71,500	77,000	82,000	87,500	93,500	99,000			
39			68,000	72,500	77,500	82,500	88,500	94,000	99,500			
40			68,500	73,000	78,000	83,500	89,000	94,500	100,000	106,000		
41			69,500	73,500	78,500	84,000	89,500	95,000	101,000	106,500		
42			70,000	74,000	79,000	84,500	90,000	95,500	101,500	107,000		
43			70,500	75,000	80,000	85,000	90,500	96,000	102,000	107,500		
44			71,500	75,500	80,500	85,500	91,000	965,000	102,500	108,000	114,000	
45			72,000	76,000	81,000	86,000	91,500	97,500	103,000	108,500	114,500	
46			72,500	76,500	81,500	87,000	92,500	98,000	103,500	109,500	115,000	
47			73,500	77,500	82,000	87,500	93,000	98,500	104,000	110,000	115,500	
48			74,000	78,000	83,000	88,000	93,500	99,000	104,500	110,500	116,000	122,000
49			74,500	78,500	83,500	88,500	94,000	99,500	105,000	111,000	116,500	122,500
50			75,500	79,000	84,000	89,000	94,500	100,000	106,000	111,500	117,500	123,000
51			76,000	80,000	84,500	89,500	95,000	100,500	106,500	112,000	118,000	123,500
52			76,500	80,500	85,000	905,000	95,500	101,000	107,000	112,500	118,500	124,000
53			77,500	81,000	86,000	91,000	96,500	102,000	107,500	113,000	119,000	124,500
54			79,000	81,500	86,500	91,500	97,000	102,500	108,000	113,500	119,500	125,000
55			78,500	82,500	87,000	92,000	97,500	103,000	108,500	114,000	120,000	126,000
56			79,500	83,000	87,500	92,500	98,000	103,500	109,000	115,000	120,500	126,500
57			80,000	83,500	88,000	93,000	98,500	104,000	109,500	115,500	121,000	127,000
58				84,000	89,000	94,000	99,000	104,500	110,000	116,000	121,500	127,500
59				85,000	89,500	94,500	99,500	105,000	111,000	116,500	122,000	128,000
60				85,500	90,000	95,000	100,500	105,500	111,500	117,000	122,500	128,500
61				86,000	90,500	95,500	101,000	106,500	112,000	117,500	123,500	129,000
62				86,500	91,000	96,000	101,500	107,000	112,500	118,000	124,000	
63				87,500	92,000	96,500	102,000	107,500	113,000	118,500	124,500	
64				88,000	92,500	97,500	102,500	108,000	113,500	119,000	125,000	
65				88,500	93,000	98,000	103,000	108,500	114,000	119,500	125,500	
66				89,000	93,500	98,500	103,500	109,000	114,500	120,500	126,000	
67				90,000	94,000	99,000	104,500	109,500	115,000	121,000	126,500	
68				90,500	95,000	99,500	105,000	110,000	116,000	121,500	127,000	
69				91,000	95,500	100,000	105,500	111,000	116,500	122,000	127,500	
70				91,500	96,000	101,000	106,000	111,500	117,000	122,500	128,000	
71				92,500	96,500	100,500	106,500	112,000	117,500	123,000	128,500	
72				93,000	97,000	102,000	107,000	112,500	118,000	123,500	129,000	

Table 3.3 (Continued)

(N)	2 Axles	3 Axles	4 Axles	5 Axles	6 Axles	7 Axles	8 Axles	9 Axles	10 Axles	11 Axles	12 Axles	13 Axles
(L)												
73				93,500	98,000	102,500	107,500	113,000	118,500	124,000		
74				94,000	98,500	103,000	108,500	113,500	119,000	124,500		
75				95,000	99,000	103,500	109,000	114,000	119,500	125,000		
76				95,500	99,500	104,500	109,500	114,500	120,000	126,000		
77				96,000	100,000	105,000	110,000	115,500	121,000	126,500		
78				96,500	101,000	105,500	110,500	116,000	121,500	127,000		
79				97,500	101,500	106,000	111,000	116,500	122,000	127,500		
80				98,000	102,000	106,500	111,500	117,000	122,500	129,000		
81				98,500	102,500	107,000	112,500	117,500	123,000	129,500		
82				99,000	103,000	108,000	113,000	118,000	123,500	129,000		
83				100,000	104,000	108,500	113,500	118,500	124,000			
84					104,500	109,000	114,000	119,000	124,500			
85					105,000	109,500	114,500	120,000	125,000			
86					105,500	110,000	115,000	120,500	126,000			
87					106,000	110,500	115,500	121,000	126,500			
88					107,000	111,500	116,500	121,500	127,000			
89					107,500	112,000	117,000	122,000	127,500			
90					108,000	112,500	117,500	122,500	128,000			
91					108,500	113,000	118,000	123,000	128,500			
92					109,000	113,500	118,500	123,500	129,000			
93					110,000	114,000	119,000	124,500				
94					110,500	115,000	119,500	125,000				
95					111,000	115,500	120,500	125,500				
96					111,500	116,000	121,000	126,000				
97					112,000	116,500	121,500	126,500				
98					113,000	117,000	122,000	127,000				
99					113,500	117,500	122,500	127,500				
100					114,000	118,500	123,000	128,000				
101	40,000	60,000	80,000	100,000	114,500	119,000	123,500	129,000	129,000	129,000	129,000	129,000

3.1.3 Permit Fees

An oversized or overweight vehicle must obtain a permit. Table 3.4 provides the fees based on the duration of the permit, the weight of the load, and the type of load. The duration of the permit can be a single trip, semi-annual, or annual. The weight is classified into three weight groups with the exception of single trips and oversized loads. Finally, the types of loads include: 1) divisible loads and 2) non-divisible loads.

Divisible loads refer to a load than can reasonably be dismantled or disassembled into smaller loads to be within legal dimensions of size and weight. A non-divisible load is a load that exceeds limits of size or weight, which, if separated into smaller loads, would (*27*):

1. Compromise the intended use of the load or vehicle and make it unable to perform its intended function,
2. Destroy the value of the load or vehicle, or
3. Require more than eight hours to dismantle using the appropriate equipment.

Table 3.4 General Permit Fees (*27*)

Oversize Divisible/Non-Divisible Loads		
Single Trip		$25
Semi-Annual (180 days)		$60
Annual (365 days)		$75
Overweight/Oversize Divisible Loads		
Single Trip		$50
Semi-Annual (180 days)	80,001 – 84,000 pounds	$150
	84,001 – 112,000 pounds	$260
	112,001 – 129,000 pounds	$350
Annual (365 days)	80,001 – 84,000 pounds	$200
	84,001 – 112,000 pounds	$400
	112,001 – 129,000 pounds	$450
Overweight/Oversize Non-Divisible Loads Up to 125,000 Pounds GVW		
Single Trip		$50
Semi-Annual (180 days)	80,001 – 84,000 pounds	$150
	84,001 – 112,000 pounds	$260
	112,001 – 125,000 pounds	$350
Annual (365 days)	80,001 – 84,000 pounds	$200
	84,001 – 112,000 pounds	$400
	112,001 – 125,000 pounds	$450
Overweight/Oversize Loads Exceeding 125,000 Pounds GVW		
Single Trip	Minimum	$65
	Maximum	$450

Overweight/oversize permit fees for vehicles with a GVW in excess of 125,000 pounds are determined by Table 3.5. These fees are for a single trip and increase both with length of the trip in miles and GVW of the vehicle in pounds. The combination of the two parameters determines the fee, which is a minimum of $65 and a maximum of $450 as also outlined in Table 3.4 (*27*).

Table 3.5 Fee Table for Non-Divisible Loads Exceeding 125,000 Pounds (*27*)

Miles:	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
Pounds:												
150,000	$65	$70	$110	$140	$180	$210	$250	$280	$320	$350	$390	$420
175,000	$65	$100	$140	$190	$240	$290	$330	$380	$430	$450	$450	$450
200,000	$65	$120	$180	$240	$300	$360	$420	$450	$450			
225,000	$70	$150	$220	$290	$360	$440	$450					
250,000	$90	$170	$260	$340	$430	$450						
275,000	$100	$200	$290	$390	$450							
300,000	$110	$220	$330	$440								
325,000	$120	$250	$370	$450								
350,000	$140	$270	$410									
375,000	$150	$300	$440									
400,000	$160	$320	$450									
425,000	$170	$350										
450,000	$190	$370										
475,000	$200	$400										
500,000	$210	$420										
525,000	$220	$450										
550,000	$240											
575,000	$250											
600,000	$260											
625,000	$270											
650,000	$290											
675,000	$300											
700,000	$310											
725,000	$320											
750,000	$340											
775,000	$350											
800,000	$360											
825,000	$370											
850,000	$390											
875,000	$400											
900,000	$410											
925,000	$420											
950,000	$440											
975,000+	$450											

3.2 Utah's WIM Data Set

This section discusses Utah's WIM data set, including: 1) the locations and characteristics of the WIM sites and 2) a description of the data set and the manipulation of it. The data for the analysis was obtained from 10 sites during the year 2004.

3.2.1 Utah WIM Site Locations and Characteristics

Utah currently has 15 permanent WIM sites. The WIM sites consist of nine piezoelectric sites and six load cell sites. Figure 3.1 provides a map of the locations of the WIM sites in Utah. All sites are under the jurisdiction of UDOT with the exception of the I-80 Evanston and I-70 Loma sites, which are maintained by the Wyoming and Colorado Departments of Transportation, respectively. Figure 3.2 provides a more detailed view of the WIM sites located in Salt Lake County.

The permanent WIM sites in the state of Utah are grouped into three categories based on the manufacturer and type of the WIM system. These categories include Peek (i.e., Peek Traffic manufacturer), IRD, and port of entry (POE). Table 3.6 shows how the sites within the state are grouped according to manufacturer and location.

Table 3.6 Utah Categories of WIM sites

Peek	IRD	POE
SR-10 Huntington MP 54	I-15 10600 South MP 293.3	I-15 St. George MP 1.8
I-15 Nephi MP 206.7	I-15 5300 South MP 300.3	I-15 Perry MP 360
I-15 Plymouth MP 385.7	I-15 1300 South MP 306.3	I-70 Loma Colorado
SR-35 Woodland MP 10.4	I-15 400 North MP 309	I-80 Evanston Wyoming
US-40 Midway MP 12.8		I-80 Wendover MP 2.6
		I-80 Echo MP 165.9

The Peek sites are all piezoelectric and manufactured by Peek Traffic (*28*). They are used in the rural areas of the state. The Peek sites auto-calibrate by redeveloping the calibration factors based on the last 100 Class 9 vehicle steering-axle weights. If less than 100 Class 9 vehicles pass over the site, then the scale does not recalibrate. Some exceptions to the Class 9 auto-calibration exist. At the SR-10 Huntington site, for example, Class 13 vehicles are more prevalent than Class 9. Thus, Class 13 steering-axle weights are used for the calibration (*29*). Of the sites listed, only a small amount of data were available from the Peek sites. These sites are Type II according to the ASTM Designation: E 1318-02 classification outlined in Section 2.4 of this report.

The IRD sites are manufactured by International Road Dynamics (*30*). These sites were installed in 2001 in conjunction with the I-15 reconstruction. They are also all piezoelectric, but not auto-calibrated. Calibration factors based on steering-axle weight

Figure 3.1 WIM sites in Utah.

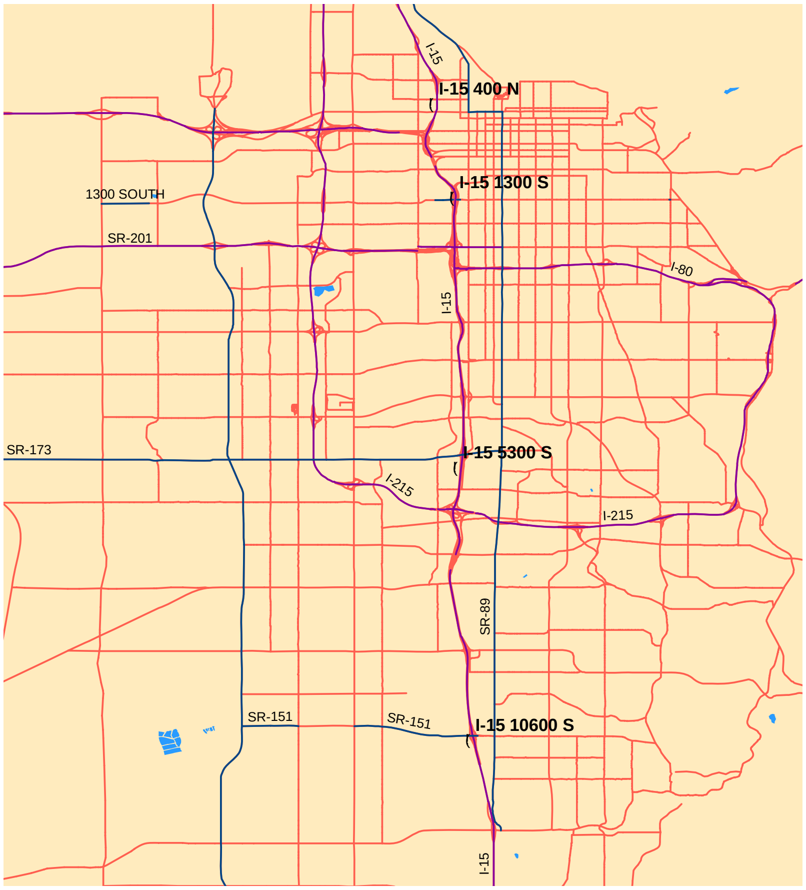

Figure 3.2 WIM sites in the Salt Lake City area.

are adjusted manually in the scale on a weekly basis. These sites have the capability of auto-calibration, but currently the system will not support it. The IRD sites are Type II according the ASTM Designation: E 1318-02 classification outlined in Section 2.4 of this report.

The POE sites consist of WIM scales both off the roadway in the POE and located in the roadway. These WIM scales are used for bypass to minimize the number of trucks that need to be weighed on the static scales. The POE sites on I-80 have WIM scales in the roadway, while the POE sites on I-15 are located off the roadway in the POE (i.e., in the off-ramp). These sites are Type III according the ASTM Designation: E 1318-02 classification outlined in Section 2.4 of this report.

3.2.2 Constitution of the Data Set

The data collected at each of the WIM sites include a listing of time and date for each vehicle, as well as detailed classification data, vehicle length, aggregate vehicle weight, disaggregate axle spacing, and disaggregate axle weight for each vehicle that crosses the WIM location. The original data set was modified for the analysis to include the route and the direction of travel for each vehicle.

To aid in analysis and reporting of data, a portion of the data set was removed based on practical constraints. Three constraints were used to remove data: 1) vehicles with GVW less than or equal to 10,000 pounds, 2) vehicles with total length less than or equal to 11 feet, and 3) vehicles that have a distance between the first and second axle less than or equal to 10 feet. Vehicles with a GVW less than or equal to 10,000 pounds were removed from the data set because the focus of the collection and analysis is truck data rather than light vehicles. The constraint based on total length and axle spacing was done based on the characteristics of design vehicles given in the AASHTO Green Book (*26*). The Green Book gives the passenger car a total length of 19 feet, which indicates that a vehicle in the data set with a total length less than or equal to 11 feet is likely an error in the reporting of data. These short vehicles made up 16.2 percent of the total data set. In like manner, the shortest distance between the first and second axle of any vehicle in the AASHTO Green Book is 10.1 feet, which indicates that a vehicle with a distance less than or equal to 10 feet in this study would also likely be an error (*26*). These vehicles comprised 29.7 percent of the data set. Many cases where the total length was less than 11 feet also had distances between the first and second axle less than 10.1 feet; as a result, only 30.3 percent of the total data set was removed.

The data columns obtained differ from site to site, but they all provide the following basic data items:

- Year (e.g., 2004),
- Month (e.g., 11),
- Day (e.g., 29),
- Hour (e.g., 13),
- Minute(e.g., 59),

- Second (e.g., 58),
- Error Number: a number that represents the type of error in the data gathered,
- Record Type,
- Lane (lane number),
- Speed (mph),
- Truck Class (FHWA Class 1 through Class 13),
- Length (feet),
- GVW (pounds),
- ESALs,
- Weight 1: the weight of the first axle of the vehicle (pounds),
- 1-2 Length: the distance between the first and second axle of the vehicle (inches),
- Weight 2: the weight of the second axle of the vehicle (pounds),
- 2-3 Length: the distance between the second and third axle of the vehicle (inches),
- Weight 3: the weight of the third axle of the vehicle (pounds),
- 3-4 Length: the distance between the third and fourth axle of the vehicle (inches),
- Weight 4: the weight of the fourth axle of the vehicle (pounds),
- 4-5 Length: the distance between the fourth and fifth axle of the vehicle (inches),
- Weight 5: the weight of the fifth axle of the vehicle (pounds),
- 5-6 Length: the distance between the fifth and sixth axle of the vehicle (inches),
- Weight 6: the weight of the sixth axle of the vehicle (pounds),
- 6-7 Length: the distance between the sixth and seventh axle of the vehicle (inches),
- Weight 7: the weight of the seventh axle of the vehicle (pounds),
- 7-8 Length: the distance between the seventh and eighth axle of the vehicle (inches),
- Weight 8: the weight of the eighth axle of the vehicle (pounds),
- 8-9 Length: the distance between the eighth and ninth axle of the vehicle (inches),
- Weight 9: the weight of the ninth axle of the vehicle (pounds),
- 9-10 Length: the distance between the ninth and tenth axle of the vehicle (inches),
- Weight 10: the weight of the tenth axle of the vehicle (pounds),

- 10-11 Length: the distance between the tenth and eleventh axle of the vehicle (inches),
- Weight 11: the weight of the eleventh axle of the vehicle (pounds),
- 11-12 Length: the distance between the eleventh and twelfth axle of the vehicle (inches),
- Weight 12: the weight of the twelfth axle of the vehicle (pounds),
- 12-13 Length: the distance between the twelfth and thirteenth axle of the vehicle (inches), and
- Weight 13: the weight of the thirteenth axle of the vehicle (pounds).

The differences among data columns produced at different sites include temperature, Automatic Vehicle Identification (AVI) tag, and additional axle spacing and weights. The temperature and AVI tag data appear not to be working correctly, and, because 14-axle vehicles are rare, the loss of these data columns is of little consequence.

The data obtained from UDOT were segmented further in order to complete the analysis. The next sections discuss the two data sets used and how they were created, beginning with the total data set and then the reduced data set.

3.2.2.1 Total Data Set. As the analysis began, it was determined that data could not be obtained from each site. From the sites where data were available only portions of a given year could be obtained due to construction, equipment malfunction, and other reasons. Table 3.7 provides a summary of the sites and directions of travel for which data were available in the study year (2004). An "X" in the table indicates that some data were obtained during that month. Only quarterly data were available for the Nephi site and only the first two quarters were available for the Plymouth site. The 10600 South site was unavailable for the second half of the year due to construction. The other vacancies in the data could not be explained.

As illustrated in Figure 3.3, the majority of the data, over 25 percent, comes from the I-15 5300 South site, with the other IRD sites also contributing significantly with the exception of the I-15 10600 South. The sites with the smallest contributions of data are I-15 Plymouth and I-15 Nephi because only quarterly data were available at these sites.

Table 3.7 Months in 2004 When Data Were Obtained from Each Direction at Each Site

	Wendover		Echo	Perry		St George		10600S		5300S		1300S		400N		Nephi		Plymouth	
	EB	WB	WB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
Jan	X		X	X	X	X	X	X	X	X		X	X	X					
Feb	X		X	X	X			X	X	X		X	X	X		X	X	X	X
Mar	X	X	X	X	X	X	X	X	X	X	X	X	X	X					
Apr	X	X	X	X	X	X		X	X	X	X	X	X	X	X				
May	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X
Jun	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				
Jul	X	X	X	X	X	X	X			X	X	X	X	X	X				
Aug	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
Sep	X	X	X	X	X	X	X			X	X	X	X	X	X				
Oct	X	X	X	X	X	X	X			X	X	X	X	X	X				
Nov	X		X	X	X					X	X					X	X		
Dec	X	X	X	X	X	X	X			X	X	X	X	X	X				

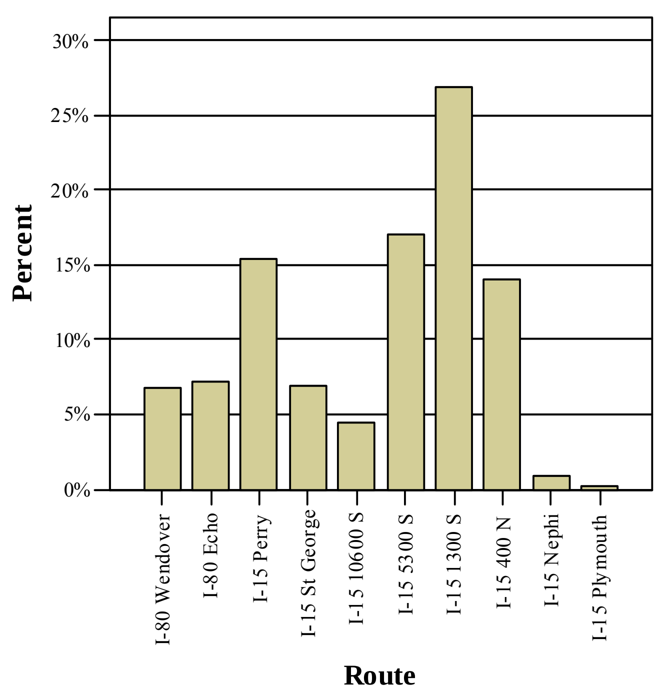

Figure 3.3 Percent of data from each site in the total data set.

As part of the analysis of the total data set, a histogram of the GVW for the vehicles was also developed. Figure 3.4 is the GVW histogram of the total data set with the bin size set at 4,000 pounds, which is consistent with the LTPP requirements. The population is made up primarily of lighter trucks, but a small peak is found between 72,000 and 80,000 pounds. As discussed in Section 2.5.3, full Class 9 vehicles create a peak in this range. Empty Class 9 vehicles weigh between 28,000 and 36,000 pounds, between which another small peak is seen in Figure 3.4. Even though all vehicle classes are included in this histogram, these small peaks tend to indicate that the system is in good health. The overall mean GVW is 44,663 pounds, and the standard deviation is 28,922 pounds.

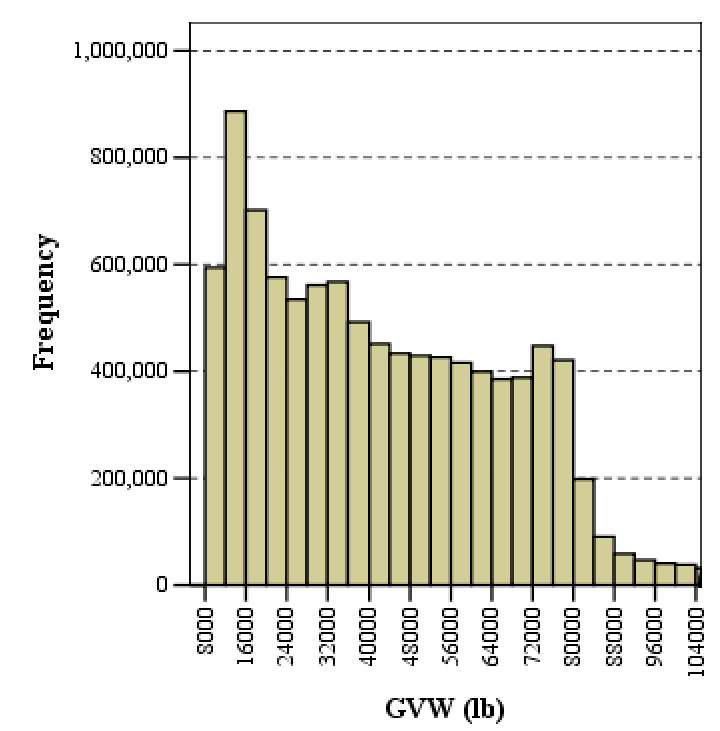

Figure 3.4 GVW histogram from the total data set.

A similar analysis was done looking at the total spacing or total length of the vehicles in all classes. The bin width used on this histogram was 5 feet, covering a range from 0 to 120 feet. Figure 3.5 displays the results of this histogram. As can be seen from the figure, two distinct groups exist: 1) vehicles with lengths from 20 to 25 feet and 2) vehicles with lengths from 70 to 75 feet. These groups correspond to Class 5 vehicles and Class 9 vehicles, the primary classes of vehicles on the roadway.

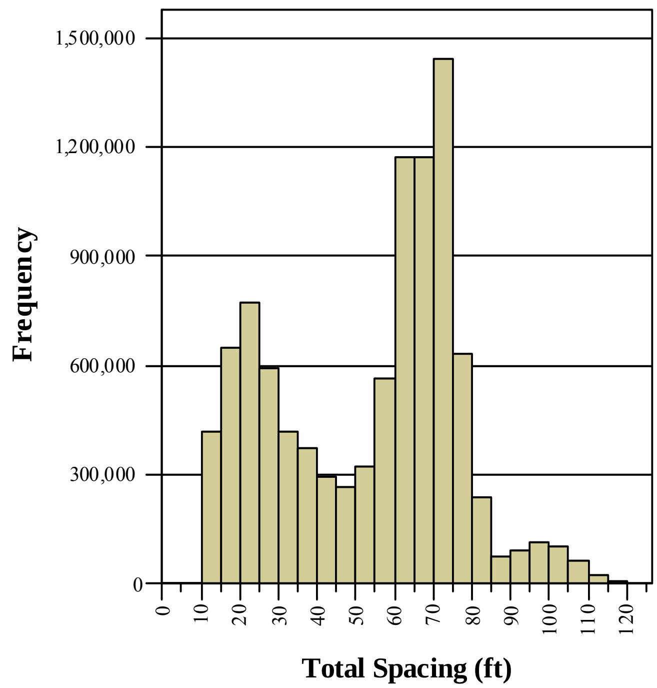

Figure 3.5 Total spacing histogram from the total data set.

Figure 3.6 provides a histogram of the truck classes. As was noted in the total spacing discussion, the most prevalent truck class in the total data set was Class 9 with Class 5 being the second most prevalent. The large proportion of Class 9 vehicles is the source of the visible empty and full peaks illustrated in the GVW histogram in Figure 3.4. A significant number of Class 0 vehicles were present, where Class 0 refers to vehicles that are either the result of an error or are not definable (*21*). A large number of Class 0 vehicles can indicate a potential problem with the system. In this case the number is relatively low (<10 percent); therefore, the data are generally assumed acceptable.

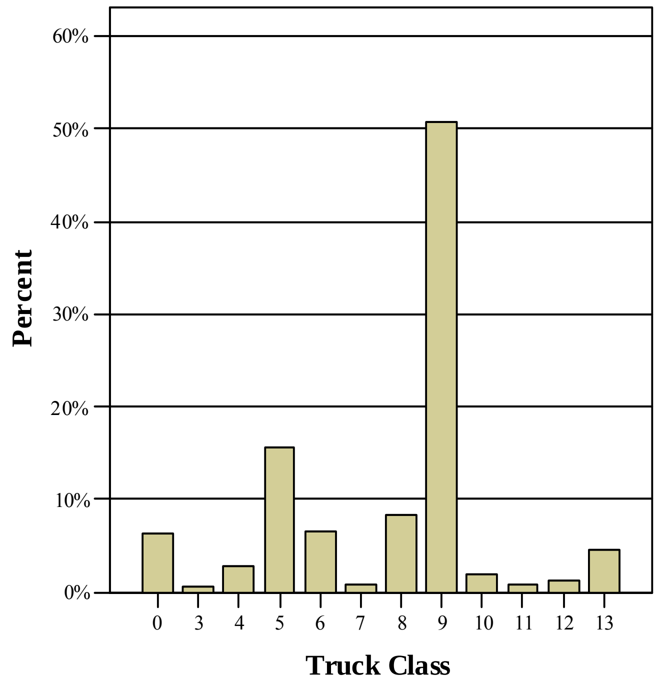

Figure 3.6 Truck class histogram from the total data set.

The total data set represents all the data obtained, and the figures in this section describe this data set. Working with such a large data set requires great computing power. As a result, certain analyses were not possible to perform. For this reason, a reduced data set was developed, from which the majority of the analysis was completed.

3.2.2.2 Reduced Data Set. The data set size was reduced in order for the analysis software to analyze the data and output the desired results. The nearly 10-million-vehicle data set was reduced to just over 1 million vehicles by reducing the data set to one week per quarter. Not all of the data came from consecutive days in a single week, but in several cases data from days in adjacent weeks were used to fill gaps. Table 3.8 shows the days of the week for which data were available in each quarter for each site and direction of travel. Again, the “X” indicates that some data from that weekday are included in the reduced data set.

Table 3.8 Data from Days of the Week in Each Quarter of the Year

		Wendover		Echo	Perry		St George		10600S		5300S		1300S		400N		Nephi		Plymouth	
		EB	WB	WB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
1ST Quarter	Sun		X						X	X	X	X	X	X	X		X	X	X	X
	Mon	X	X	X	X	X	X	X				X	X	X	X		X	X	X	X
	Tue	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X	X	X
	Wed	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
	Thu	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X
	Fri		X						X	X	X	X	X	X	X				X	X
	Sat		X						X	X	X	X	X	X	X					
		Wendover		Echo	Perry		St George		10600S		5300S		1300S		400N		Nephi		Plymouth	
		EB	WB	WB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
2nd Quarter	Sun	X	X	X	X	X	X	X			X	X	X	X	X	X			X	X
	Mon	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
	Tue	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
	Wed	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
	Thu	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Fri	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Sat	X	X	X	X	X	X	X			X	X	X	X	X	X				
		Wendover		Echo	Perry		St George		10600S		5300S		1300S		400N		Nephi		Plymouth	
		EB	WB	WB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
3rd Quarter	Sun	X	X		X	X	X	X			X	X	X	X	X	X				
	Mon	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Tue	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Wed	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Thu	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Fri	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Sat	X			X	X	X	X			X	X	X	X	X	X	X	X		
		Wendover		Echo	Perry		St George		10600S		5300S		1300S		400N		Nephi		Plymouth	
		EB	WB	WB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
4th Quarter	Sun	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Mon	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Tue	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Wed	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Thu	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Fri	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		
	Sat	X	X	X	X	X	X	X			X	X	X	X	X	X				

The reduced data set gives a more balanced representation of the WIM sites because each site's contribution is more nearly equal. Figure 3.7 displays a histogram of the data from each site as a percentage of the reduced data set. Plymouth is still the smallest contributor, but Nephi is now supplying as much data as some sites where the whole year's data were available. The greatest portion of data comes from I-15 1300 South, with I-15 5300 South following.

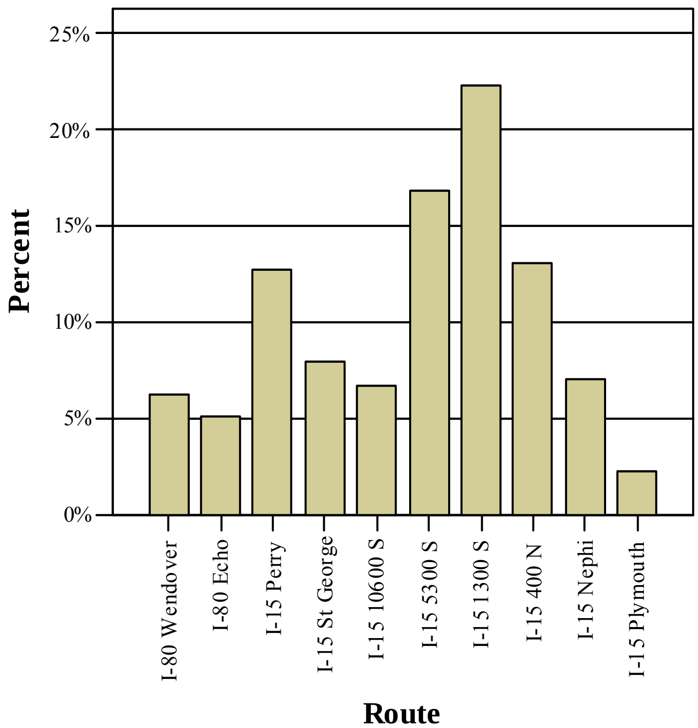

Figure 3.7 Percent of data from each site in the reduced data set.

Figure 3.8 illustrates the GVW Histogram for all classes of the reduced data set. This histogram is analogous to its counterpart from the total data set. Three peaks are found in the same locations as in the total data set GVW histogram. The reductions made to the total data set did not appear to change the overall distribution of GVW. The mean GVW increased slightly to 45,065 pounds, a 1 percent increase, while the standard deviation also increased slightly to 29,764 pounds, a 3 percent increase.

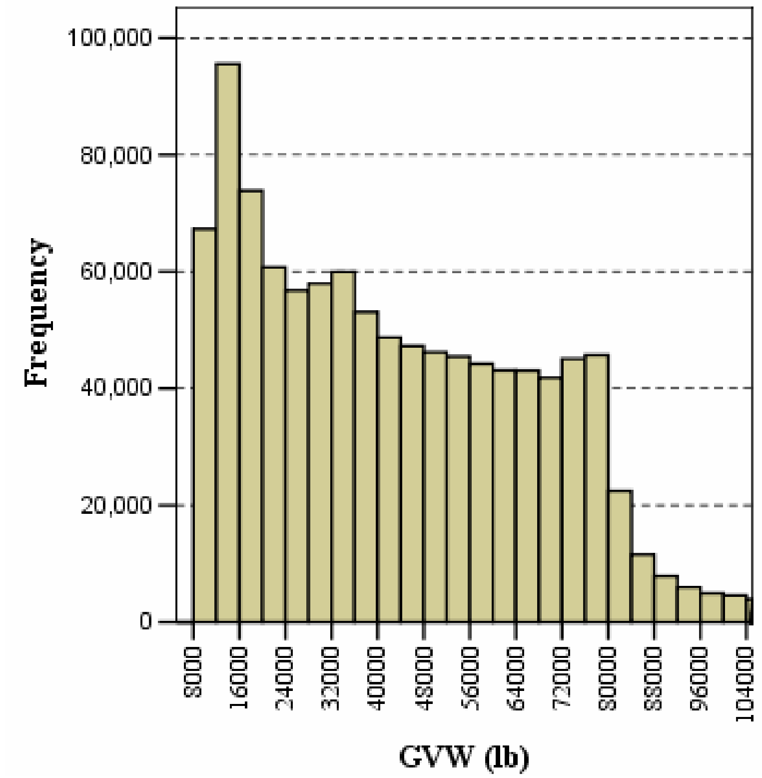

Figure 3.8 GVW histogram for the reduced data set.

The total spacing histogram for the reduced data set is found in Figure 3.9. Two peaks are again seen, indicating groups of long vehicles (e.g., Class 9) and groups of shorter vehicles (e.g., Class 5). Again, the distribution of total length does not appear to be different from that of the total data set.

Figure 3.10 displays the proportions of vehicles represented in the reduced data set. The distribution of class is nearly identical to that of the total data set. The reduced data set is still comprised of about 6 percent Class 0 vehicles. The distribution of truck class did not change with the creation of the reduced data set. The Class 9 vehicles make up just over 50 percent of the data set, while Class 5 vehicles make up just over 15 percent, which is identical to the total data set.

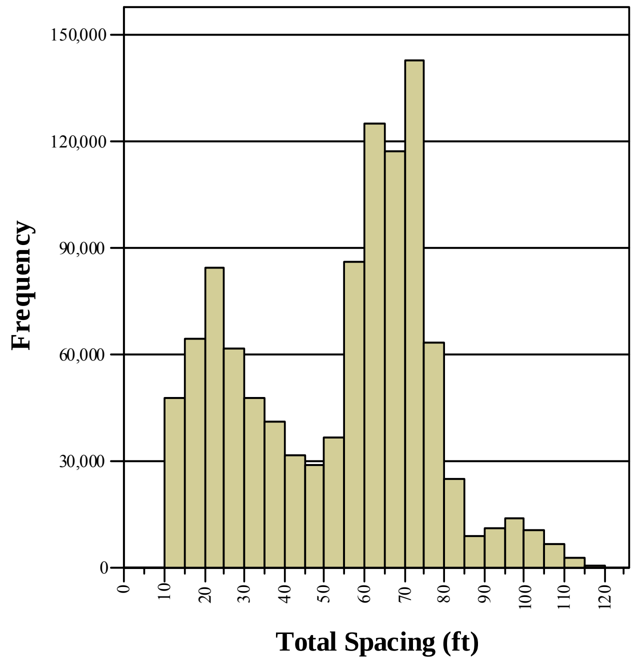

Figure 3.9 Total spacing histogram for the reduced data set.

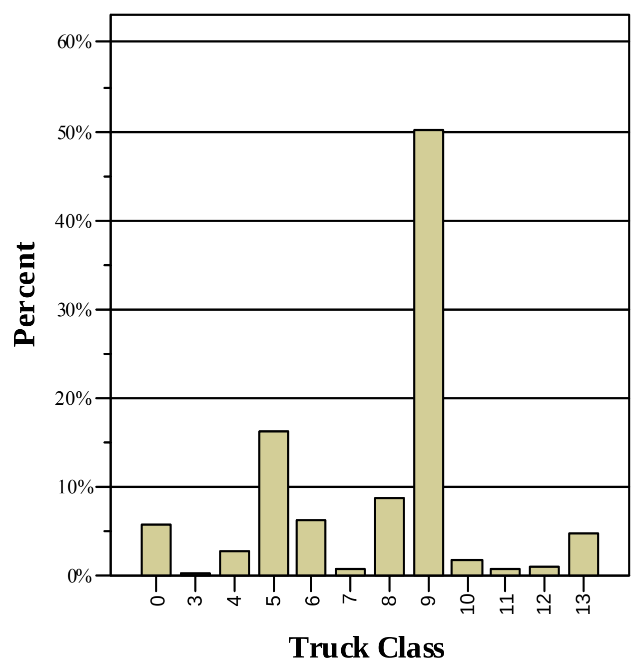

Figure 3.10 Truck class histogram for the reduced data set.

3.3 Site GVW, Truck Class, and Total Length Histograms

In addition to the total and reduced data sets, consideration was also provided to each WIM site individually. A quarterly analysis for each site is provided in Appendix A. The analysis includes GVW, truck class, and total length histograms for each site for each quarter of the year. These graphs were made with the quarterly proportions of the reduced data set. Each graph comes from approximately one week of data from the respective quarter. Changes in these graphs over time can be an indication of a problem with the WIM system or a seasonal change in truck traffic characteristics.

The results of this preliminary analysis show that all the WIM sites generally demonstrate the same distributions regardless of the time of year. This is a promising result that shows the current calibration methodology is producing relatively consistent results.

3.4 Concluding Remarks

This chapter provided a summary of the Utah WIM data, including: 1) a discussion of the CMV size and weight regulations; 2) a description of Utah's WIM data set; and 3) a site-by-site analysis including GVW, truck class, and total length histograms. With the data set obtained and prepared and a preliminary analysis complete, the next chapter describes the analysis and discusses the results.

4 Analysis of Data

This chapter discusses the analyses performed with the data provided from the UDOT WIM sites during 2004. Several analyses were explored in an effort to evaluate the consistency of the data, including box plots, error bar charts, steering-axle weight, drive tandem axle spacing, and an over/under weight limit analysis. A correlation with weather conditions and the daily average metrics was also explored.

Calibration is done on a lane-by-lane basis for WIM systems because each lane has independent calibration factors. Ideally, the analysis would also be on a lane-by-lane basis. However, this quickly becomes very complicated to both accomplish and interpret. Thus, the analysis contained here begins by considering site-by-site characteristics, and, in the case where anomalies exist, a more detailed analysis is explored.

The analyses identified previously will be discussed in the remaining sections of this chapter following a description of the lane naming convention.

4.1 Lane Naming Convention and Percent Trucks in Lane

All the WIM sites in Utah are located on divided highways. The numbering of the lanes begins with one on the outside lane and increases toward the median. Figure 4.1 shows the typical lane numbering. This figure depicts the configuration of the IRD sites. The other sites are similar, but with fewer lanes and no High Occupancy Vehicle (HOV) lane.

The percent of trucks (i.e., Class 5 and greater) in each lane is important when determining if a lane needs to be calibrated or validated. This information was analyzed

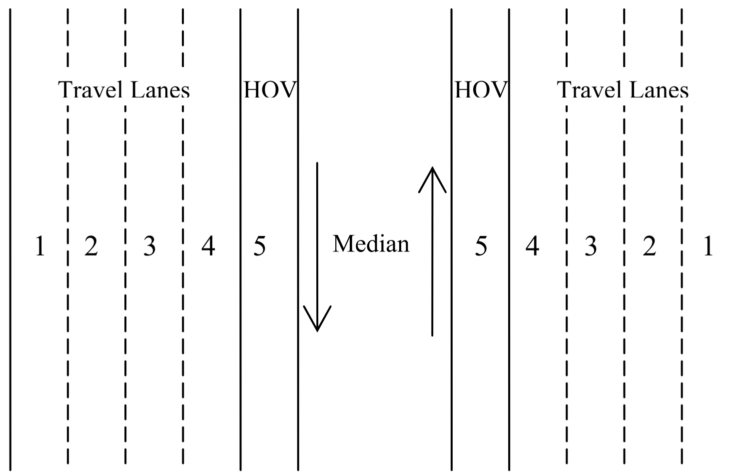

Figure 4.1 Lane numbering convention.

for each lane for each site. Graphical representations of these distributions are found in Appendix B.

4.2 Box Plot Analysis

Box plots describe several of the main features of a data set, including the (*31*, *32*):

- Median,
- Spread,
- Extent and nature of any departure from symmetry (i.e., skewness), and
- Identification of outliers.

Box plots are based on measures that are resistant to outliers. For instance, box plots are not based on the mean and standard deviation, which are dramatically affected by outliers. The box portion of the plot has the first quartile (25^{th} percentile) as the bottom and the third quartile (75^{th} percentile) as the top. The line across the box between the top and the bottom represents the median or second quartile (50^{th} percentile). The difference between the third quartile and the first quartile is the interquartile range and is represented by the height of the box. The lines that extend from the box in either direction are referred to as whiskers and extend to the smallest and largest value that does not exceed 1.5 times the interquartile range. Any values beyond 1.5 times the interquartile range are outliers, and values that exceed three times the interquartile range are extreme outliers. Side-by-side box plots are an effective way of revealing similarities and differences between two or more data sets (*31*, *32*). The box plots in this document represent outliers as open circles and extreme outliers as asterisks.

Figure 4.2 is a box plot comparing the GVW data sets of the 10 WIM sites considered in the analysis. The box plot was made with a 3 percent random sample taken from the reduced data set consisting of one week of data taken from each quarter. The sample size was limited by the computing power of the program to produce box plots. All of the sites show a skew toward heavy vehicles; thus, the data appear not to be normally distributed. One of the most noticeable features is the large number of outliers at the 5300 South and 400 North sites. The numbers labeling the outliers are the vehicle classes. Most of the outliers are made up of Class 13 and Class 0 vehicles. Class 13 vehicles are vehicles with seven or more axles consisting of three or more units, one of which is the tractor as illustrated previously in Figure 2.1. Class 0 represents vehicles that are either an error or not definable (*21*). The large number of Class 0 outliers at 5300 South is a potential indication of a problem with the site. If these vehicles were actually included in the traffic stream, similar outliers would be expected at the adjacent 1300 South and 10600 South sites.

Another box plot with the Class 0 vehicles removed is displayed in Figure 4.3 and shows the details of the box and whiskers. The median and quartiles of the IRD sites are lower than the other sites. This is understandable due to the urban nature of the IRD sites, as urban areas are expected to have more short-haul vehicles, which often operate empty or close to empty. Rural sites record more long-haul vehicles that tend to operate full.

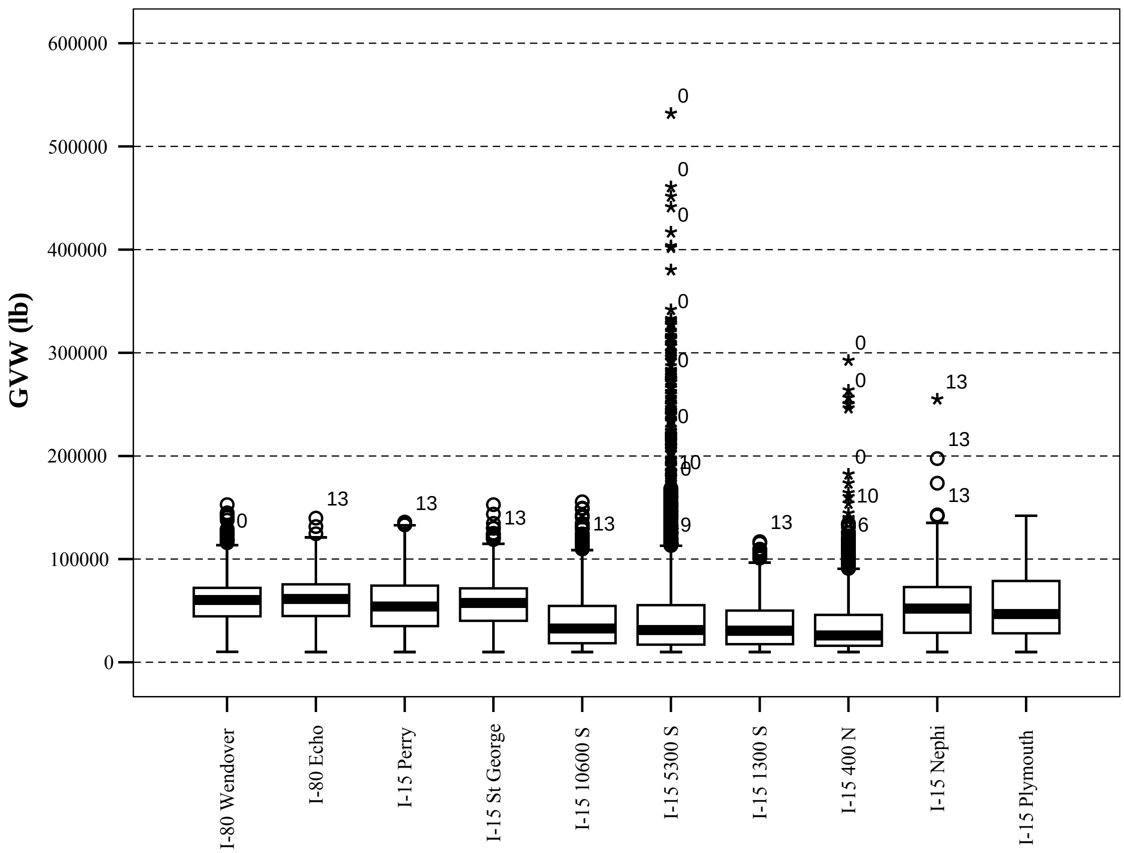

Figure 4.2 Side-by-side box plots of the GVW from a three percent random sample of the reduced data set.

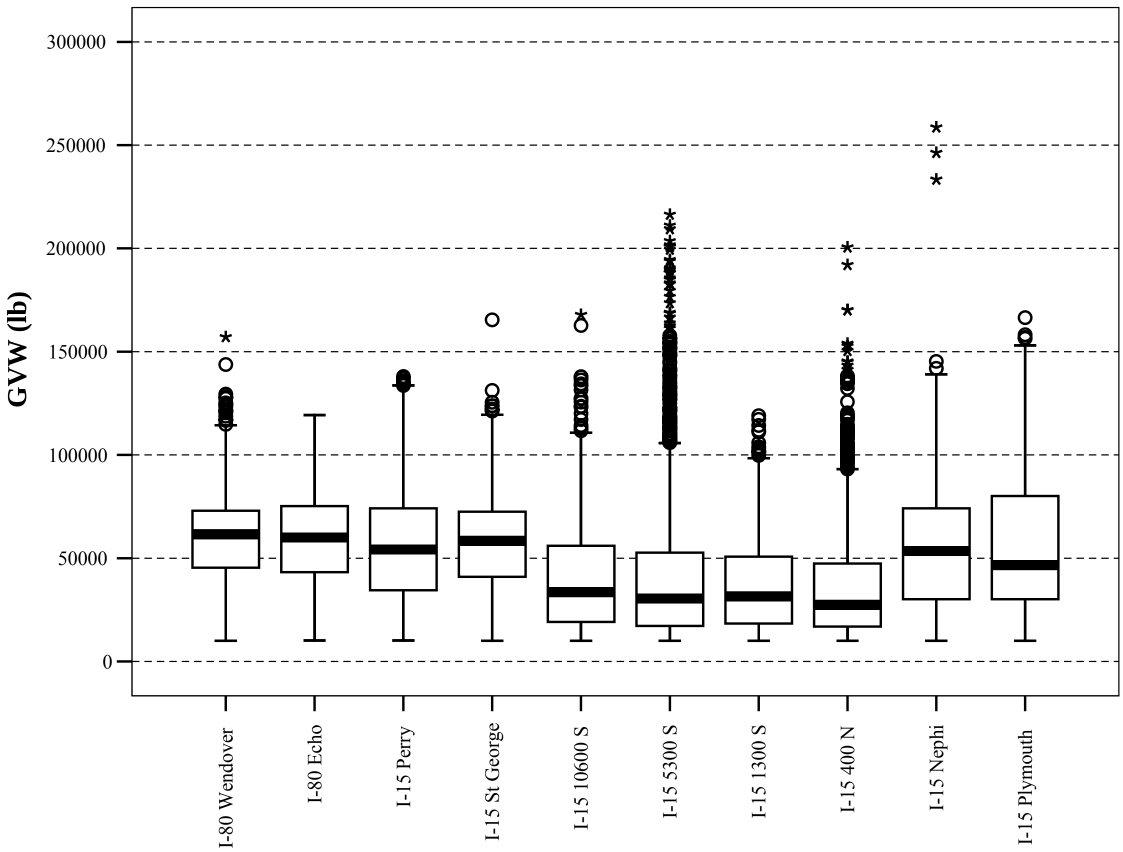

Figure 4.3 Class 0 removed side-by-side box plots of the GVW from a 3 percent random sample of the reduced data set.

Another data set of interest is the GVW of only Class 9 vehicles. Figure 4.4 shows a side-by-side box plot of the GVW of Class 9 vehicles. To form the data set for this figure, a 7 percent random sample was taken of the Class 9 vehicles in the reduced data set. The median and interquartile ranges are varied, but again the IRD sites are generally lower than the other sites. Almost all of the outliers are seen in the IRD sites. The 5300 South site has the most outliers; however, the 1300 South and 400 North sites have similar outliers.

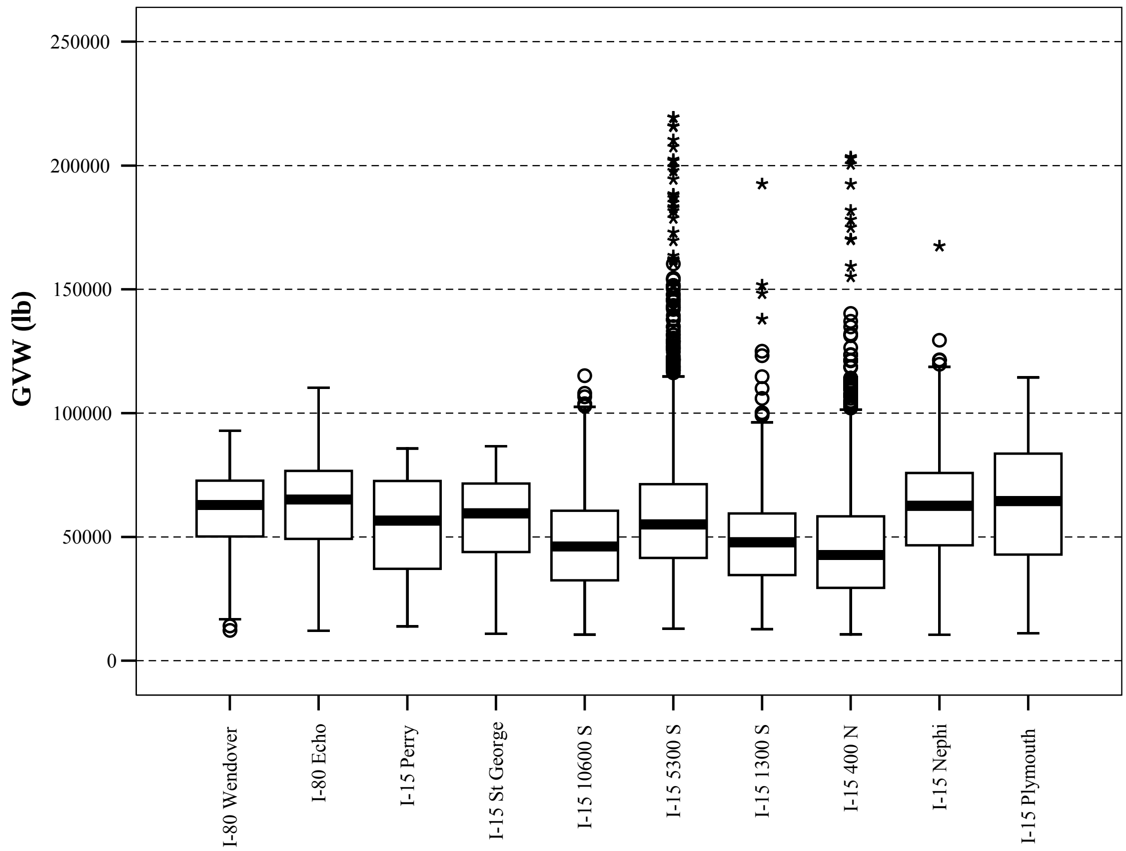

Figure 4.4 Side-by-side box plots of the GVW of Class 9 vehicles from a 7 percent random sample of the Class 9 vehicles in the reduced data set.

4.3 Error Bar Chart Analysis

Error bar charts are similar to box plots in that they display the center and spread of the data. The chart consists of a circle placed at the mean and whiskers extending a certain number of standard errors or standard deviations from the mean. Figure 4.5 is an error bar chart showing the mean and spread of one standard deviation (SD) both up and down. The error bar chart is based on the total data set in this case since the computing power required for the analysis is not as extensive. The IRD sites have a mean that is generally lower than the other sites. The standard deviation is similar among most of the sites, with the exception of the 5300 South and Plymouth. The 5300 South site has the largest variation, which is likely due to the large number of outliers. Both the mean and the standard deviation are dramatically affected by outliers.

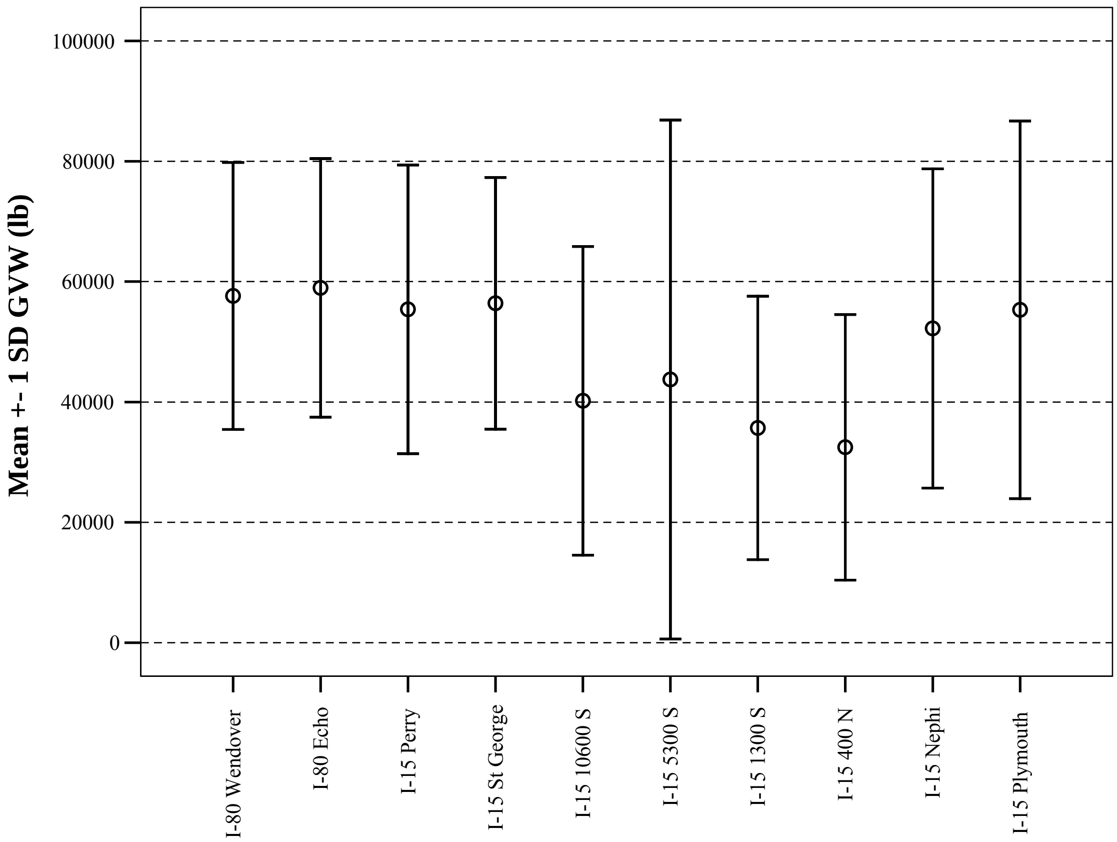

Figure 4.5 Error bar chart of GVW from the total data set.

The error bar chart for only the Class 9 vehicles based on the total data set was also considered and is shown in Figure 4.6. As is expected, the variation is reduced when considering only Class 9 vehicles. A larger variation is still seen at the 5300 South and Plymouth sites. Also, 5300 South has a much larger mean than the other IRD sites. The mean and variation of all the IRD sites are expected to be similar. This is an indication of a potential problem at the 5300 South site that should be explored in more detail by UDOT personnel.

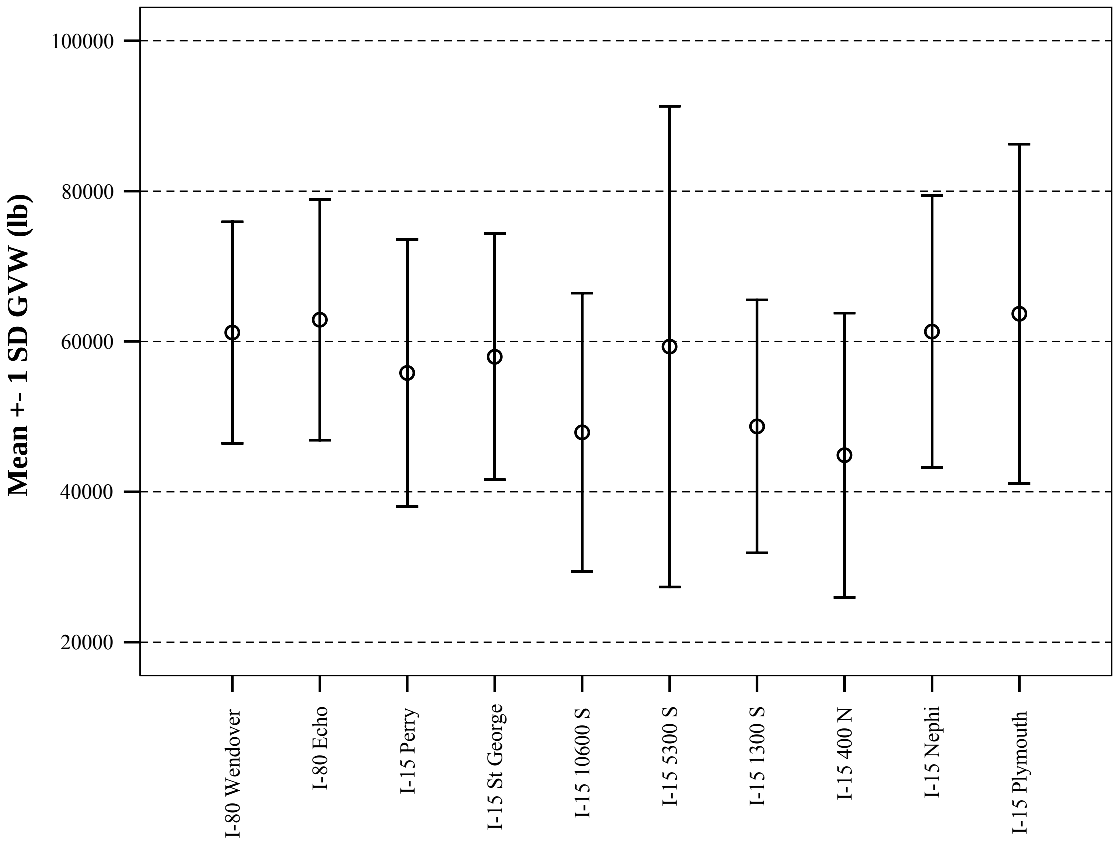

Figure 4.6 Error bar chart of GVW from the Class 9 vehicles in the total data set.

4.4 Steering-Axle Weight Analysis

The daily average steering-axle weight is a useful comparison used for quality assurance and is discussed in detail in Section 2.5.1 of this report. For this analysis, the daily average steering axle of Class 9 vehicles is graphed against the days of the year. The average weight is expected to be approximately 11,000 pounds based on UDOT POE averages.

A daily average steering-axle weight graph was created for each site based on the overall contribution to the total data set and is found in Appendix C. An example graph of 400 North is given in Figure 4.7. The results of this analysis for all the WIM sites are summarized in Table 4.1 and can be verified by viewing the graphs in Appendix C.

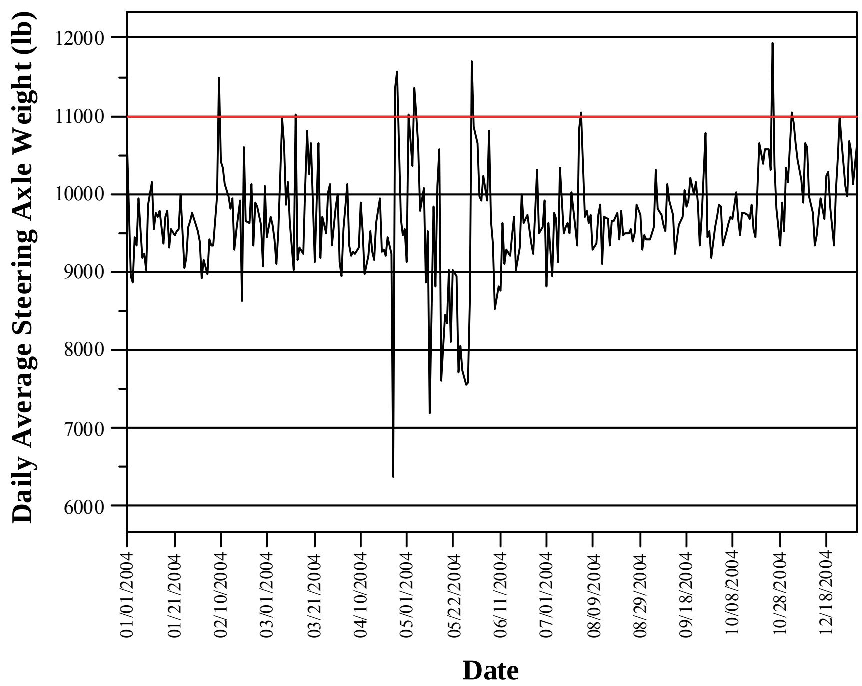

Figure 4.7 I-15 400 North daily average steering-axle weight.

As indicated in Table 4.1, several of the mean front axle weights are lower than expected. These are primarily at the IRD sites, with the exception of the 5300 South site. The 5300 South site is also of concern because of the large variation occurring throughout the whole year. Again, all of the IRD sites are expected to have similar characteristics. The POE sites, Perry and St. George in particular, show a pattern of peaks on weekends and valleys during weekdays. One theory is that this is due to the loss of short-haul trucks on the weekends, which often operate empty. This lack of short-haul trucks could drive the average steering-axle weight up on the weekends.

Correlation of steering-axle weight to temperature and precipitation were also considered. WIM sensors have been known to be sensitive to temperature and precipitation. The effort was made to determine if Utah's WIM scales had problems in this regard. The results of the steering-axle graphs were compared with these weather metrics; however, no obvious correlations were found. The temperature and precipitation graphs are found in Appendix D.

The main concern is that the daily average steering-axle weight should stay around 11,000 pounds. Departures from this may be due to calibration changes, weather, or malfunctions of the system's components. These graphs provide the ability to determine the time that departures occurred. In this way, the search for the cause can be aided.

Table 4.1 Steering-axle Weight Analysis Results Summary

Site	Summary Results
400 North	Mean steering-axle weight approximately 9,700 pounds Large variation from end of April to June
1300 South	Mean steering-axle weight approximately 9,700 pounds Large variation in April, May, June, July, and December
5300 South	Mean steering-axle weight approximately 11,500 pounds Large variation throughout the whole year
10600 South	Mean steering-axle weight approximately 9,600 pounds Little variation, although only January through June data available
Nephi	Mean steering-axle weight approximately 11,000 pounds Limited data available (quarterly)
Plymouth	Mean steering-axle weight approximately 11,000 pounds Limited data available (1st and 2nd quarters only)
Perry	Mean steering-axle weight approximately 10,800 pounds Pattern of peeks on weekends and valleys during weekdays Sharp rise in August and steady decline from October to December
St. George	Mean steering-axle weight approximately 10,900 pounds Pattern of peaks on weekends and valleys during weekdays Large variation occurring in June, followed by a steady decline until August followed by a series of large jumps
Echo	Mean steering-axle weight approximately 11,300 pounds Pattern of peaks on weekends and valleys during weekdays Little variation with jumps occurring at the beginning of June and at the end of August
Wendover	Mean steering-axle weight approximately 11,100 pounds Some variation occurring throughout the year Jumps occur in January, May, August, and September

4.5 Drive Tandem Axle Spacing Analysis

The drive tandem spacing graph is another quality assurance measure and is discussed thoroughly in Section 2.5.2 of this document. The drive tandem axle spacing refers to the distance between the second and third axles on the tractors. These are the axles driven by the engine of the truck to move the vehicle. On Class 9 vehicles, the spacing is fairly constant and is expected to be approximately 4.33 feet on average, based on information from truck manufacturers (*23*). Reviewing these graphs is a good way to check the ability of the WIM systems to measure speed. If speed is being measured incorrectly, other aspects of the system or calibration may also be functioning incorrectly.

A drive tandem spacing graph was made for each WIM site based on its contribution to the total data set. An example of this type of graph from 400 North is found in Figure 4.8. A line has been placed at 4.33 feet to indicate where the drive tandem spacing is expected to be. The results of this analysis are summarized in Table 4.2 and can be verified by viewing the graphs in Appendix E.

The mean drive tandem spacing is slightly high for all the WIM sites, with the exception of 10600 South. Echo has the highest mean drive tandem spacing at approximately 0.5 feet longer than expected. Generally, the mean drive tandem spacing does not deviate far from the expected value of 4.33 feet. As indicated in Section 2.5.2, the LTPP program uses an interval between 4.10 and 4.90 feet in determining data quality. All sites fall within this range.

Again, correlation of drive tandem spacing to temperature and precipitation were considered. The results of the drive tandem graphs were compared with these weather metrics, and no obvious correlations were found. As indicated previously, the temperature and precipitation graphs can be found in Appendix D.

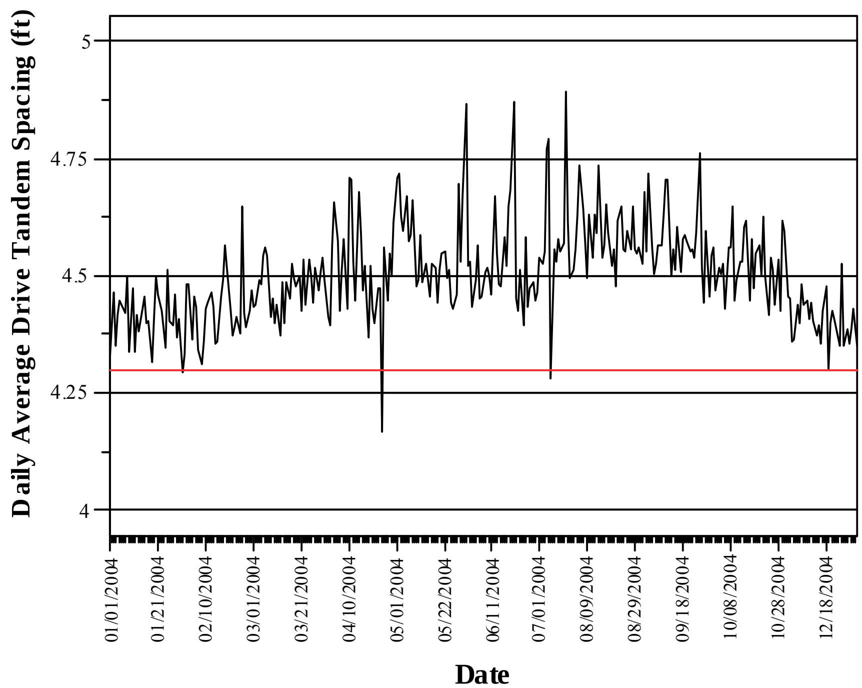

Figure 4.8 I-15 400 North daily average drive tandem spacing.

Table 4.2 Drive Tandem Spacing Analysis Results Summary

Site	Descriptions of Graph
400 North	Mean spacing approximately 4.51 feet Rises in March and goes back down in October Jumps occurring in April, May, June, and July
1300 South	Mean spacing approximately 4.57 feet Rises in April and stays fairly constant
5300 South	Mean spacing approximately 4.54 feet Jumps occurring in April, May, September, and November
10600 South	Mean spacing approximately 4.33 feet Data only available from January to June Jumps occurring in March and May
Nephi	Mean spacing approximately 4.68 feet Only quarterly data available Jumps down at beginning of May and back up in August
Plymouth	Mean spacing approximately 4.51 feet Only 1st and 2nd quarter data available
Perry	Mean spacing approximately 4.38 feet No jumps
St. George	Mean spacing approximately 4.60 feet Wide variation compared to the other sites
Echo	Mean spacing approximately 4.74 feet Jumps down occurring in September Wide variation compared to the other sites
Wendover	Mean spacing approximately 4.46 feet Steady decline beginning in June

4.6 Over/Under Weight Limit Analysis

The maximum legal weight limit for UDOT roads is 80,000 pounds. Table 4.3 provides a summary of the percent of trucks (Class 5 and above) over the weight limit and the percent under the weight limit. As can be seen from the table, Plymouth and Nephi have a very high percentage of overweight vehicles. The Nephi data set consists of data from every quarter, and the Plymouth data set consists of data from the first two quarters. The small data set may contribute to the atypical percentages. Investigation of the reason the smallest data sets have the highest percent of trucks overweight may be revealing. Another interesting analysis would be to investigate a correlation between the number of overweight permits issued and the number of vehicles overweight.

Table 4.3 Percent Over/Under Weight Limit

Site	Percent Trucks Over Weight Limit	Percent Trucks Under Weight Limit
400 North	3.0	97.0
1300 South	2.4	97.6
5300 South	9.5	90.5
10600 South	7.3	92.7
Nephi	14.3	85.7
Plymouth	27.0	73.0
Perry	10.3	89.7
St. George	7.6	92.4
Echo	13.3	86.7
Wendover	10.6	89.4

4.7 Summary and Conclusions of the Analysis

In general, the data appear to be consistent with expectations. The average steering-axle weight for each WIM site is within 13 percent of the 11,000-pound target. This percentage is not alarming given that the performance requirement for a single axle is ± 20 percent for both the ASTM Designation: E 1318-02 and the LTPP program (*4*, *19*). The average drive tandem axle spacing for each WIM site is within 10 percent, or 0.41 feet, of the 4.33 feet target. Again, this is not alarming, as the performance requirement for axle spacing is ± 0.5 feet based on the ASTM Designation: E 1318-02, "States' Successful Practices Weigh-in-Motion Handbook," and the LTPP Program (*4*, *10*, *19*). The WIM data appear to be consistent with expectations; however, potential for improvement to the data collection process exists. The data from several WIM sites illustrate possible concerns that should be addressed. These sites and the reasons for the potential for concern are summarized in Table 4.4 and discussed in the following paragraph.

Table 4.4 UDOT WIM Sites Requiring Attention

Site	Reason
5300 South	Large number of outlying Class 9 and Class 0 vehicles Larger mean and standard deviation than other IRD sites Large variation in daily average steering-axle weight
400 North	Large number of outlying Class 9 and Class 0 vehicles Low mean steering-axle weight (12% deviation from target)
1300 South	Low mean steering-axle weight (12% deviation from target)
10600 South	Low mean steering-axle weight (13% deviation from target)
Nephi	Large percent over weight limit (14%)
Plymouth	Large percent over weight limit (27%)

As outlined in Table 4.4, 5300 South and 400 North have several outlying Class 0 and Class 9 vehicles. All of the IRD sites are expected to have similar distributions, which is not the case when considering these outliers. The error bar charts show 5300 South having a higher mean and standard deviation than the other IRD sites. This is especially evident when considering only Class 9 Vehicles. The daily average steering-axle weights at the 5300 South site also vary over the year. The 400 North, 1300 South, and 10600 South sites have mean steering-axle weights slightly lower than expected. Finally, both Nephi and Plymouth tend to have a large percentage of trucks over the weight limit.

Overall, the data falls within expectations, and the calibration method currently in use is generally producing data of regular quality. However, potential for improvement exists. In particular, the sites in question, which are discussed above, should be evaluated further by UDOT personnel.

Calibration standards have been explored in Section 2.4 of this report. The following chapter will explore current practices in selected states. In an effort to bring

UDOT in line with the standard and current practices of other states, a calibration procedure based on both the standards and the practices of other states is presented.

5 Calibration Methodology

This chapter will explore a calibration methodology for the state beginning with consideration of the current practices of other states in the maintenance of WIM systems. The current practice in the state of Utah will also be explored, including the IRD procedure at the POE sites and the UDOT procedure at the IRD and Peek sites. Finally, a recommended procedure will be outlined for WIM calibration, verification, and quality assurance programs.

5.1 Current Practices in Other States

To facilitate better understanding of current practices in WIM calibration, a survey was conducted of 10 states concerning WIM system calibration and maintenance. The results of this survey are summarized in Table 5.1 and discussed further on a state-by-state basis in the sections that follow.

5.1.1 California

Currently 106 WIM sites are in use in California, 85 of which are solely for data collection; the remainder are for data collection and enforcement. More are under construction and planned to be added to the state's system (*33*). All of California's WIM sites are IRD bending-plate types, with the exception of one Kistler sensor. California uses both field and office calibration for their WIM sites (*34*).

In order to prepare the scale for the initial field calibration after installation, the calibration factors are adjusted until Class 9 vehicle steering-axle weights in the traffic stream average near 10,500 pounds. The loop spacing distance setting in the WIM

Table 5.1 Summary of Current Practices in Selected States

State	# of Permanent WIM Sites	Calibration Procedure	Calibration Frequency
California	106	Test trucks and office calibration	Test trucks at least every 3 years Office calibration at least annually
Florida	40	Test trucks	Data are monitored, and calibration is done based on need
Idaho	16	Auto-calibration features and steering-axle weights tracked	Constantly monitor steering-axle weights
Montana	28	Test trucks and auto-calibration	Test truck calibration bi-annually
Oregon	24	Traffic stream trucks	At least annually
Nevada	3	Test trucks if away from POE and traffic stream trucks scale if near POE	Annually
South Dakota	13	Data from traffic stream	2 to 3 years
Texas	21	Test trucks	At least annually
Washington	10	Traffic stream trucks	At least annually
Wyoming	7	Test trucks if away from POE and traffic stream trucks scale if near POE	At least annually

system is also set by adjusting the distance until the Class 9 drive tandem axle spacing averages between 4.2 feet and 4.5 feet. This brings the scale close to proper calibration, and the scale can now be more finely calibrated using test trucks.

Field calibration continues with the use of a Class 9 test truck loaded between 70,000 and 80,000 pounds. The test trucks are carefully weighed and measured including weights and spacing for all axles. California's IRD scales have three speed bins with calibration factors associated with each of them. Therefore, the test truck makes runs over the scales at three different speeds: 45, 55, and 65 mph, with two runs made per speed bin. After each run is made, a value is added to a plot of the known reference weight against the WIM system weight. The plots are checked for trends associated with speed in case a need exists to adjust the factors based on speed. Once the scale is calibrated, more runs are made to verify the calibration. The required accuracy is set at ± 5 percent of the GVW. Using test trucks poses the problem of time and expense. At one California site, only one pass could be made every 40 minutes (*34*).

Office calibration includes the use of a program developed by Caltrans. The CTWIM Suite is a collection of Windows- based programs that are designed to aid in tasks such as onsite calibration, accuracy validation of WIM systems, and day-to-day monitoring of calibration (*33*). The office calibration starts with an ASCII file of the data, which CTWIM analyzes and summarizes in reports. CTWIM displays reports regarding the difference in wheel weights on the steering-axle and the total length of the vehicle versus the distance between the first and last axle. A difference of 6 to 7 feet between the two parameters is expected. These reports are checked against the site history to determine what changes need to be made at the site (*34*).

The frequency of field calibrations is based on priority levels. The sites that are used for Prepass, a system that allows trucks to bypass weigh stations, and the Sharp LTPP sites, sites from which data are sent to a national data base, are field calibrated annually. Other sites are field calibrated as needed about every two to three years. Office calibrations are performed about every six months or at least annually (*34*).

5.1.2 Florida

Of the 40 WIM sites that exist in the state of Florida 12 are bending plate, 15 are quartz piezoelectric, and 13 are piezoelectric types (*35*). Two procedures are provided for the maintenance of existing and newly-installed sites. Since the procedures only differ slightly the existing-site case will be described with a comment on the changes made for the newly-installed-site case. The procedure includes both calibration and validation (*36*).

The calibration includes pre-calibration procedures and four steps in the actual calibration. The purpose of the pre-calibration is to determine whether or not to proceed to calibration. The candidate site must be functioning well before calibration. To determine if the sites are functioning well, the existing site conditions should be described quantitatively and made a matter of record. This includes an inspection of the following (*36*):

- Physical aspects of the sensors in the road,
- Road surface conditions,
- Electrical characteristics of the WIM system electronic hardware,
- Various sensors being used, and
- Utilities at the site.

An ASCII log file is used in recording the initial calibration factors of the WIM system, the classification table, and the different sensor set-up configurations. Once this is complete, the analyst must determine whether to continue and calibrate the WIM site. If the analyst determines to proceed, the calibration is recommended to take place within two to three weeks. During the interim period, the site is monitored, and three days of data are gathered to determine the speed points, or the speeds at which runs should be conducted. At least one Class 9 test truck is used and loaded with a non-liquid load to a minimum of 90 percent of its legal limit. The remainder of the calibration is outlined in the following four steps (*36*):

1. The test truck is measured according to the ASTM Designation: E 1318-02. Measurements are taken of the spacing of all axles from center to center. Next, the load on each wheel is measured three times with the brakes released. The averages of the three measurements are used as the reference values or the "static weight values." At this point, some type of communication (e.g., two-way radio) is set up with the driver of the test vehicle.
2. The calibration software is set up with a history log file application, which will create a chronological record of events occurring during the calibration. This history should include, but not be limited to:

    - The initial calibration factors,
    - The calibration runs,
    - The final calibration factors, and
    - Any changes made to the calibration factors during the calibration runs.

3. The test truck shall make at least one run for each speed point over the sensors. During these runs the axle spacing factors are corrected. The axle spacing is very important because it is used to validate speed readings. Changes are made to the calibration factors to get the weights in the "ball park" of the static values.
4. The test truck makes a run over each WIM lane a minimum of two times for each speed point and once for each increment of 5 mph between the first and the third speed points (e.g., if the first and third speed points are 40, 55, and 70 mph, then a run is made at 40, 45, 50, 55, 60, 65, and 70 mph, followed by additional runs at 40, 55, and 70 mph). The GVW percent error is calculated, and the information is plotted on a "Gross Weight Percent Error by Vehicle Speed" graph for each WIM lane. These graphs are used to determine the adjustments made to the calibrations factors. If more runs are needed to make final adjustments, they should be made in sequence starting at the lowest speed point and continuing to the highest.

Final adjustments to the calibration and axle spacing factors must be made before the validation procedure. The validation is recommended to be done on a different day than the calibration. Like the calibration, the validation has four steps (*36*):

1. Repeat step one of the calibration.
2. Start the history log just as in step two of the calibration.
3. Conduct three runs made at each 5 mph increment between the first and last speed point. The runs should be made in sequence, one at each increment beginning with the lowest to the highest; then start over again and do it two more times. The GVW percent error is calculated and plotted on a "Gross Weight Percent Error by Vehicle Speed" graph. These graphs are analyzed to make final adjustments to WIM factors if needed. If changes are made to the WIM factors, the validation runs will need to be repeated.
4. Download and provide a copy of all data files, history files, and graphs to the department's statistics office. For the calibration to be accepted, the GVW percent error of the validation will have to be evenly distributed around the zero axis of the "Gross Weight Percent Error by Vehicle Speed" graph for each speed point in each WIM lane. The specifications of the ASTM Designation: E 1318-02 for Type I and Type II systems should be met as provided in Section 2.4.

The calibration and validation procedures for newly-installed WIM sites is identical to that outlined previously with the exception of a statement indicating that the vendor is responsible to prove that the system is able to be calibrated and that it meets the requirements in the ASTM Designation: E 1318-02 (*36*).

The WIM sites are calibrated and validated after installation, after sensors or electronics are changed, or if weights are observed to change. Florida's experience is that the bending-plate and quartz-piezoelectric systems are very stable, while the regular piezoelectric sites are very temperature-dependent and the weights are sometimes questionable (*35*).

5.1.3 Idaho

There are 16 permanent WIM sites in the state of Idaho, 13 of which are Electrical Control Measure (ECM) and three of which are manufactured by IRD. Typically, the calibration is done with a Class 9 test truck loaded to 80,000 pounds GVW. Most procedures require 10 runs on each lane followed by a comparison between the system weight and the actual truck weight. The thresholds are adjusted, and the test truck makes

10 more runs. The process is then repeated until the weights match within predefined limits set by the Idaho Transportation Department (ITD). Due to the rural nature of the WIM sites in Idaho, the use of this method is impractical. Not enough time, staff, or funding is available to calibrate in this manner. At some of the sites, the turn-around points are 10 to 15 miles from the scales. Calibration would take all summer using test trucks. As a result, a different tactic is used. Each of the scales is equipped with auto-calibration. To monitor the effectiveness of the auto-calibration, the steering-axle weights of the Class 9 trucks at each site are recorded and charted for a time sensitive comparison. Through this monitoring, ITD is confident that the performance of the WIM systems is consistent and accurate (*37*).

5.1.4 Montana

Montana's State Truck Activities Reporting System (STARS) consists of 28 permanent WIM sites and 62 sites that are intermittently activated on a 3-year cycle (portable WIM). Four of these sites are automated weigh stations that utilize WIM and AVI. The data collected from the AVI system are treated just as data collected from a standard WIM site. Of the 28 permanent sites, 25 are piezoelectric, and three are bending-plate types. More sites are currently being installed (*12, 38*).

The locations of the WIM sites are chosen based upon the volume of commercial vehicle traffic carried and the location of existing static weigh stations. Since most of the static weigh stations are located on interstates, the focus of the STARS WIM systems is on the non-interstate national highway system (NHS) network. The portable systems are focused further on the less traveled routes in consideration of the recommendations of the TMG (*1*, *38*).

The Montana Department of Transportation (MDT) calibrates the permanent sites on a bi-annual basis with the use of a Class 9 test truck of a known weight. Some sites in Montana use other classes for their target values, such as passenger cars and pick-up trucks. MDT also performs standard quality control checks on the raw and processed data (*12, 38*).

The majority of the WIM sites are piezoelectric types manufactured by ECM. These systems have the ability to auto-calibrate, which changes the way the systems are monitored and calibrated. The machine is given four targets: 1) class, 2) GVW, 3) steering-axle weight, and 4) minimum GVW. If the scale records a vehicle within plus or minus a predefined percentage (set by the user) of the listed parameters, it will use that vehicle in the auto-calibration procedure. As vehicles are saved for the calibration, they are put into three groups of three vehicles each (i.e., nine total vehicles). At any time, the three groups determine the calibration of the scale through their average GVW. As a new group of three vehicles is completed, the oldest group is deleted, and the process continues. The scale turns itself up or down depending on the current three groups (*12*).

In addition to the auto-calibration, MDT performs a bi-annual calibration to establish target values for the auto-calibration. First, the scale is given default targets. For example, if Class 9 is the target class, the default targets could include GVW of 78,000 pounds, steering-axle weight of 10,800 pounds, and minimum weight of 60,000 pounds. After this, a waiting period is implemented, the duration of which is dependent on the traffic conditions (i.e., the lower the traffic volumes, the longer the duration and vice versa). After the waiting period has passed, a Class 9 vehicle of known weight and configuration makes a minimum of five runs over the WIM scale, and the axle weights for each run are recorded. These values are entered into a spreadsheet, and, with averages and standard deviations, new targets are determined. The standard deviation determines how much to adjust the target. If a large standard deviation is observed, then the target should be adjusted less than in the case where a small standard deviation. These parameters are then checked against historic data. After the new targets are entered into the scale, another period of time is needed to gather data. These gathered data are used to make a GVW histogram of the Class 9 vehicles with a true tandem axle on the trailer. This means the distance between the axles on the trailer is in the range of 4 to 5 feet, not 10 to 12 feet, which is becoming more common due to its ability to carry a heavier load. This GVW histogram is made on a monthly basis to track potential calibration drift. These graphs are stored for diagnostic purposes. By viewing the graphs over time, the observer can readily discern any drift (*12*). These types of graphs are discussed in Section 2.5 of this report.

In addition to the piezoelectric sensor, which is sensitive to temperature, MDT uses Kistler WIM systems that are not as temperature sensitive. Since they are not as temperature sensitive as other WIM devices, the auto-calibration feature is not needed. These sites are calibrated on a bi-annual basis with the use of a test truck. The process alternates between groups of three runs and adjustments made to the scales. This process is continued until the average measurement of three runs is within a specified tolerance to the known weight. This process has been known to take 15 to 21 runs (*12*).

Software was developed especially for the MDT for the purpose of automatically analyzing the collected WIM data. The Measurement of Enforcement Activities Reporting System (MEARS) generates reports on commercial vehicle activity by site and by month for the entire year. Most of the software's outputs have to do with enforcement, but some deal with quality control and calibration tracking (*38*).

MDT is having success with the piezoelectric system. Comparing a piezoelectric and a bending plate to a static scale, the piezoelectric was found to be closer to the static scale than the bending plate (*12*).

5.1.5 Oregon

In Oregon, 24 WIM sites are in use: 22 at weigh stations and two used solely for data collection. The sensors are single-load cell sensors manufactured by IRD. Calibration of the WIM scales is accomplished through comparison with static scales since all of the WIM scales are located in the vicinity of a static scale. Generally, 20 consecutive trucks from the normal stream of traffic are used for calibration. The WIM weight is compared with the static weight, and adjustments are made to the WIM scale as needed. This calibration is done annually or when an enforcement officer notices discrepancies (*39*).

5.1.6 Nevada

Three permanent WIM sites are used in the state of Nevada, one bending plate and two Kistler sensors. Two more sites are expected to be added in 2006. When the sites are located near POEs, 100 Class 9 trucks from the traffic stream are used to calibrate each WIM lane. The WIM weights are compared against the static weights, and adjustments are made. If the WIM sites are located away from static scales, then 77 to

100 runs are made with a Class 9 test truck of known weight. Only the slow lanes are calibrated because they carry most of the truck traffic. Calibration is done annually (*40*).

5.1.7 South Dakota

The state of South Dakota has 13 WIM sites, including 12 bending plate and one Kistler quartz site. Test trucks are used during the initial installation and setup but are not used during the recalibration process. The recalibration is done in-house and uses a large sample of trucks from the main stream of traffic. The weights of the trucks are not known; however, constant aspects of the trucks are used, such as steering-axle weights and drive tandem spacing, to conduct the calibration. The WIM sites are calibrated every two to three years (*41*).

5.1.8 Texas

The concept of WIM was first considered in Texas in the early 1960s. Studies led to the implementation of a program that used permanent WIM stations to replace the use of static weigh stations. The number of static weigh stations was reduced as the WIM sites were added (*6*).

Over the years the WIM sites in Texas have gone in and out of service due to equipment failure, construction, and the ability of the highway agency to support the system. The majority of the sites in Texas are piezoelectric, but some bending-plate types are also in service. Many of the original bending-plate systems have been changed to piezoelectric. As of 2002, 21 permanent sites were in service that collect data for at least 48 hours every quarter of the year. The number of sites from which data are collected varies from year to year due to construction, equipment failure, and road conditions (*6*). In August 2002, only 17 WIM sites were functioning, 12 piezoelectric and five bending plate (*42*).

At the time of this document, Texas Department of Transportation (TxDOT) engineers were evaluating their data collection systems in an effort to conform to the TMG and prepare for the 2002 AASHTO Pavement Design Guide. In connection with this evaluation, the state was carrying out a goal of adding 133 new WIM sites over the next several years. This would lead to a total of 150 WIM sites in Texas. Road groupings have been determined according to the TMG, and a desired precision was set at ± 10 percent of the actual GVW at a 90 percent confidence level. The TMG and the 2002 AASHTO Pavement Design Guide were discussed previously in Section 2.6 and Section 2.7 of this report (*1*, *3*, *6*, *42*).

TxDOT uses a technique similar to that outlined in the ASTM Designation: E 1318-02 for calibration of WIM scales. This involves test trucks of known weight making multiple runs over the WIM scales. TxDOT uses 2-, 3-, and 5-axle vehicles with focus on the Class 9 truck for the test trucks. The trucks make multiple runs over the scale at low, intermediate, and high speeds. The equipment is then adjusted according to manufacturer specifications (*6*, *43*).

5.1.9 Washington

The state of Washington has eight functioning WIM sites, with two WIM sites currently out of service due to construction and two to be added to the system in the design phase. All of the systems are comprised of single load cells manufactured by IRD. All of the sites are in proximity of a static scale, so a 10-truck statistical method is used where the WIM weights are compared against the static weights. Adjustments are then made as needed. The static scales are calibrated once a year. Calibration of the WIM scales is also done at least annually and more frequently if operators notice a discrepancy between the WIM and static scales. The complete procedures can be found in ASTM Designation: E 1318-02 for Type III scales. The first calibration of a new site begins using 100 trucks from the traffic stream. These are Class 9 vehicles in good condition and loaded stably to 75 percent of the legal GVW. A test truck is used as part of the initial calibration to verify the tracking and transponder systems. Logistically, several problems are faced in Washington with the use of test trucks (*44*):

- Safety: the trucks are required to do combinations of lane changes in heavy traffic;
- Communication: letting the truck know which lane to take (e.g., cell phones, CB radios, and even hand signals); and

- Personnel: obtaining a good truck and driver willing to drive in circles for several days. Most companies do not have spare trucks and drivers available. If these trucks are available, they usually are not of ideal quality.

After the site is accepted, the calibration is done at least bi-annually (*44*).

5.1.10 Wyoming

The state of Wyoming has seven permanent WIM sites, all of which are load-cell scales manufactured by IRD. Ideally, they are calibrated with the use of a single Class 9 truck with air ride suspension loaded to 80 percent of its maximum capacity. The test truck makes 10 runs over the scale at several different speeds. Because all of the sites are located at a POE, a simpler approach is often employed where trucks from the traffic stream are used. The WIM measurements are compared against the static measurements, and adjustments are made to the WIM scale. Calibration is done at least annually. The main problem that Wyoming faces with the use of test trucks is turn-around time. At one site 10 hours were needed to make 10 runs (*45*).

5.2 Current Practice in Utah

UDOT has contracted with IRD to maintain the WIM scales at the POE sites, while UDOT maintains the IRD and Peek sites internally. The procedures currently employed by IRD and UDOT are discussed in the next two sections.

5.2.1 International Road Dynamics Inc. Calibration Procedure

IRD uses a calibration methodology for the POE WIM scales developed for use when the WIM scale is located near a static scale. The methodology is developed so that the POE WIM sites are calibrated bi-annually. In this procedure, 10 to 20 trucks are weighed statically and compared to their WIM scale measurements. Adjustments are made to the WIM scale accordingly. Following this, 10 to 15 trucks are weighed to verify that the WIM scale is weighing properly. Speed ranges may or may not be used depending on the layout of the site. A ramp system with a posted limit of 20 mph usually does not require the use of speed ranges (*46*).

5.2.2 UDOT Calibration Procedure

The Peek and IRD sites are both calibrated by UDOT, but each site is calibrated in a different manner. Two calibrations are performed on the IRD site data, and only one on the Peek site data in addition to its auto-calibration process. These calibration processes are given in the following paragraphs (*29*).

Currently, the IRD site data are calibrated on a bi-weekly basis and on a yearly basis. The IRD sites have weight factors for three speed bins: 1) less than 60 mph, 2) 60 mph to 70 mph, and 3) greater than 70 mph. A set of three speed bins exist for each lane. The speed of the vehicle determines which of the three factors is applied to the axle weights (*29*).

Calibration is performed bi-weekly to correct for seasonal factors. Adjustment factors are developed based on the steering-axle weights. When the data are collected, the Class 9 steering-axle weight for each lane and speed group is tracked and averaged. An adjustment factor is determined by dividing the POE Class 9 average steering-axle weight (11,000 pounds), by the average steering-axle weight for the lane and speed group. This adjustment factor is only applied if at least 10 Class 9 vehicles exist for the lane and speed group. The weight factors currently used in the WIM system are multiplied by this adjustment factor to determine new weight factors. These new weight factors are input into the system at the site (*29*).

The annual calibration corrects for daily temperature variation. In this calibration, the actual scale is not calibrated, but the data are adjusted by factors in a "rolling calibration." The axles and GVW of each data point are multiplied by a factor consisting of the average of the 25 previous and subsequent 25 steering-axle weights divided by the steering-axle weight associated with the given data point. This process is called a rolling calibration because it continues through the data set with a different factor being applied to each data point. This process corrects for daily temperature variations. For data sets with greater than 50 Class 9 vehicles, the annual calibration works as a rolling calibration as described above. In the case where sites have less than 50 but greater than 30 Class 9 vehicles, one correction factor is used. For sites with less than 30 Class 9 vehicles, the data are not changed (*29*).

The Peek WIM data sites automatically calibrate themselves based on the last 100 Class 9 vehicles to pass over the site. On these sites, the bi-weekly calibration is not performed, but the annual calibration outlined previously is. The site will not auto-calibrate until 100 Class 9 vehicles have passed over the site. For example, SR-35 Woodland has not had enough Class 9 vehicles in order to auto-calibrate. SR-10 MP 35 Huntington has more Class 13 vehicles than Class 9, so the Class 13 trucks are used to calibrate using the same approach (i.e. steering-axle weight) (*29*).

5.3 Recommended Procedure

The current UDOT calibration is producing reasonably accurate data based on the analysis described in Chapter 4 of this report. Therefore, the recommended procedure given here is not necessary to repair major errors found in the data but to bring UDOT practices in line with the current WIM standards and the practices of other states, to help maintain better consistency in the data, and to potentially minimize the inconsistencies identified in Chapter 4. The recommended procedure includes a calibration, verification, and quality assurance program. These aspects of scale maintenance are seen in LTPP, ASTM, and several other procedures (*4*, *19*, *20*). Recommended calibration, verification, and quality assurance methods for the POE, IRD, and Peek sites are given in the following sections.

5.3.1 Calibration

The current method in use for maintenance of the POE WIM sites is adequate and in line with the ASTM Designation: E 1318-02 for calibration of Type III systems (*4*). IRD should continue to maintain the WIM scales as they are currently doing.

The IRD and Peek sites have auto-calibration capability, and this method should begin to be used at the IRD sites and continue to be used at the Peek sites. The current calibration of the Peek sites is adequate; however, the auto-calibration utilities at the IRD sites are not currently functioning. Repairs to the thermometers and other necessary modifications to the program should be made so that the auto-calibration will function as described in the IRD Users Manual. The manual states that the temperature-binning feature of the auto-calibration is critical when using piezoelectric systems (*21*).

The auto-calibration requires that a target steering-axle weight be given. This target should be 11,000 pounds based on the averages from the POE static scales, as is currently being used in UDOT's calibration of the IRD sites. This value should be reviewed on a bi-annual basis. Other details about the auto-calibration settings are fairly arbitrary but should be set consistently among all the IRD sites. A detailed description of the auto-calibration aspects is given in Section 2.4 of this report.

5.3.2 Verification

A verification method is currently in use at the POE sites where 10 to 15 trucks are used to verify the calibration. No change should be made to this verification method.

The IRD and Peek sites currently have no verification method in practice. A verification process should be implemented and that it include runs with a single test truck to verify the auto-calibration systems of these sites. The recommended verification procedure will be outlined here in a series of steps detailed in the following subsections.

5.3.2.1 Step 1: Site Evaluation. Before runs are made, an evaluation of the physical characteristics of the site and the components of the WIM system should be made. The following should be evaluated and problems corrected prior to test truck runs:

- A survey of the pavement condition 275 feet before and 30 feet after the WIM sensor should be conducted. This involves looking for anomalies in the pavement that may cause vehicles to bounce. If such anomalies are found, then efforts to correct the problem should be taken because the bouncing will affect the WIM sensor readings. This recommendation is based on the "Data Collection Guide for SPS WIM Sites Version 1.0" (*19*).
- Threshold settings for both the piezoelectric sensors and the inductive loops should be set as recommended in the IRD Users Manual. Setting the piezoelectric threshold includes an iterative trial-and-error process. Two competing objectives need to be met: 1) the threshold needs to be low enough that the axles of trucks register properly by the system and 2) the threshold needs to be set high enough

such that background noise does not cause the system to register non-existent axles. In like manner, the loop sensor threshold must be set such that it will trigger when a vehicle passes over it but not trigger when vehicles pass close by (*21*).

- Speed calibration should be done with the use of a radar gun. The speed is calibrated by adjusting the sensor distance setting. This is important because the axle spacing and vehicle speed are determined based on this parameter. An individual should make use of a radar gun and measure the speed of vehicles selected from the traffic stream. The WIM sensor output for the speed of the same vehicle should be obtained by another individual or remotely via a laptop with the first individual. If a second individual is needed, then some type of communication needs to be put into place to ensure that the same vehicle is measured by the radar gun and the WIM sensor. This procedure should be done during times of light traffic to ensure a clear line of sight to the vehicle for the radar gun. Corrections for the angle at which the speeds were collected should be made to the radar gun readings. The difference between the radar gun reading and the output of the WIM sensor for the same vehicle should be calculated, and the setting of the distance between the sensors should be adjusted based on an average of the differences. This is done using vehicles in the traffic stream (*23*).
- A general check of the components of the system should be also accomplished.

5.3.2.2 Step 2: Obtain Test Truck and Reference Values. A test truck should be obtained with the following characteristics:

- The predominate truck class at that site (e.g., Class 9),
- Loaded with a non-shifting load, and
- Loaded to within 90 percent of the legal limit.

The reference values to be compared against the values of the runs over the WIM sensors should be obtained from static measurements. The recommended method to obtain the static reference values is consistent with the ASTM Designation: E 1318-02 procedure for weighing and measuring test vehicles to obtain reference values. The steps include (*4*):

1. Measure center-to-center spacing between successive axles on the test vehicle and record the data to the nearest 0.1 foot as axle spacing references.
2. Weigh the test vehicle a minimum of three times with brakes released using a certified static scale. Measure the tire loads of the wheels on each and every axle of the vehicle. Move the vehicle completely away from the scale before beginning a new set of tire-load measurements, always approaching the weighing devices from the same direction. Sum the applicable tire loads to determine wheel, axle, and tandem-axle loads as well as GVW each time the vehicle is weighed.
3. Calculate the arithmetic mean for all wheel load, axle-load, tandem-axle-load, and GVW values that resulted from weighing each test vehicle three or more times. These means are the reference values that will be used.

5.3.2.3 Step 3: Test Truck Runs. This section describes the number of runs, the speed distribution of the runs, and the location in the lane where the vehicle passes. This step also discusses an option for conducting the runs in an efficient manner. During this step, a check or calibration should be done on the sensor spacing setting, as this will affect the speed and axle spacing output.

Three runs should be made at maximum, intermediate, and minimum speeds for a total of nine runs. The maximum should be less than the speed limit. The maximum and the minimum should differ by more than 20 mph. The maximum should be greater than, and the minimum less than, the intermediate speed. The intermediate speed should be representative of the prevailing speed of truck traffic at the site. One run in each speed group should be made at the left edge, center, and right edge of the lane. These recommendations are based on the ASTM Designation: E 1318-02 (*4*).

Lanes carrying less than 10 percent of the truck traffic going the same direction, (i.e., Class 5 and above) do not necessarily need to be verified, as they contribute little to the truck data. The analysis of each lane and its contribution to the traffic data in the same direction is included in Appendix B for all WIM sites studied in this document. The lane numbering convention was shown previously in Figure 4.1.

Several options are available to accomplish this step depending on the site location and characteristics. The IRD sites located on I-15 seem particularly challenging logistically. One solution is displayed in Figure 5.1. In this example, four test trucks are used to make the runs, and the WIM sensor in each lane is passed almost simultaneously. A Utah Highway Patrol (UHP) vehicle drives before and after the test vehicles to keep other traffic from interfering with the procedure. The same truck should make all the runs over a particular WIM lane, (i.e., Test Truck #3 should make all the runs over the WIM sensor in lane 3). All four IRD sites will be tested before the caravan turns around. The lanes in the other direction are then tested until all four sites have been evaluated. The caravan turns around again, and the process is repeated until all the necessary runs are completed. In the case of the IRD sites, lanes 4 and 5 generally need not be verified because they carry less than 10 percent of the truck traffic.

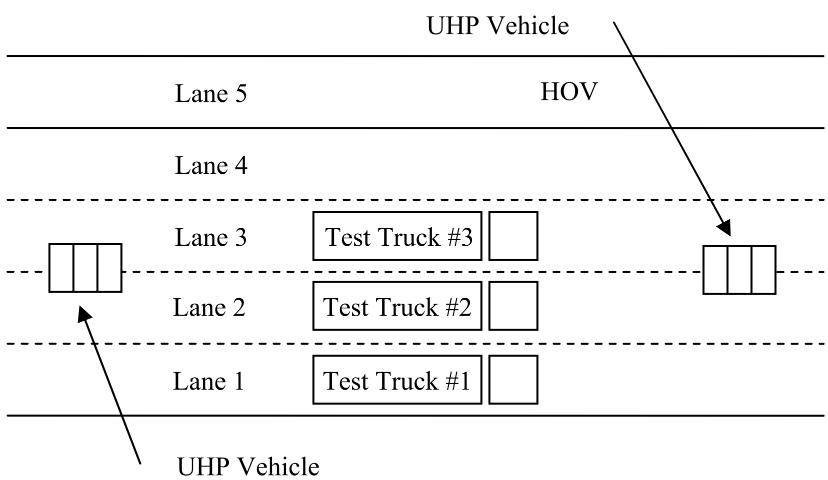

Figure 5.1 Diagram for test truck run scenario over the IRD sites.

5.3.2.4 Step 4: Calculations. To determine the status of the lane's WIM sensor, certain calculations should be made based on the acceptance test given in the ASTM Designation: E 1318-02 (*4*). First, the percent difference between the data produced by the WIM system and the corresponding reference value for the data item needs to be calculated using Equation 5.1 (*4*).

$$d = 100\left[\frac{(C - R)}{R}\right] \tag{5.1}$$

where: d = difference expressed as a percent of the reference value,
C = value of the data item produced by the WIM system, and
R = corresponding reference value for the data item.

Next, it is necessary to determine the number of calculated differences that exceed the tolerances summarized in Table 5.2 and then to express this number as a percent of the total number of observed values of the item in question (i.e., axle load, axle group load, or GVW) utilizing the relationship outlined in Equation 5.2 (*4*).

$$P_{de} = 100\left[\frac{n}{N}\right] \tag{5.2}$$

where: P_{de} = percent of calculated differences that exceeded the specified tolerance value,
n = number of calculated differences that exceeded the specified tolerance value, and
N = total number of observed values of the data item.

5.3.2.5 Step 5: Interpretation of Results. If any item in Table 5.2 fails to function properly, or if more than 5 percent of the calculated differences for any applicable data item resulting from all runs of the test vehicle exceed the tolerance specified for that item, the WIM system should be declared dysfunctional or inaccurate. If a lane fails to meet the requirements, then appropriate measures should be taken to improve or repair the failing components of the lane's WIM system.

Table 5.2 Functional Performance Requirements for the IRD and Peek Site at a 95 Percent Probability of Conformity (*4*)

Function	Type II
Axle Load	± 30 percent
Axle Group Load	± 20 percent
GVW	± 15 percent

5.3.2.6 Step 6: Verification Results Report. The health of the system is largely aided if changes over time can be observed. Detailed reports will make this possible. These reports should include:

- Description of the pavement condition,
- Description of changes to the system settings (e.g., threshold settings and sensor distance settings),
- The results of the test truck runs, and
- Report on the overall results of the verification.

Verification should take place at least on an annual basis. The calibration of every WIM lane should be verified, with the exception of lanes that contribute less than 10 percent of the truck traffic at the site. In addition to the annual verification, checks should be done on a more frequent basis through a quality assurance program as outlined in the following section.

5.3.3 Quality Assurance

Quality assurance refers to methods that assess the data quality and in turn the WIM system performance. Quality assurance involves the production of graphs and histograms including the creation of the following graphs:

- Vehicle class histogram,
- Daily average steering-axle weight,

- Daily average drive tandem axle spacing, and
- GVW histogram.

The details of the use and creation of these graphs are given in Section 2.5. The graphs should be made on a quarterly basis to evaluate the data collected during that quarter. They should be made from the combined data from each lane and direction of a site. However, if the graphs indicate a problem, a lane-by-lane analysis should be considered to narrow the source of the abnormality. Examples of such graphs are provided in this section using I-15 5300 South WIM data from the first quarter of 2004. These graphs were made with the use of the SPSS® 13.0 for Windows software, which is capable of managing large data files. Microsoft® Excel is limited to only 65,000 rows of data, while the first quarter data set for 5300 South contained over 200,000 rows. Thus, some sort of statistical or database software with a large capacity to handle data should be used to produce these graphs.

5.3.3.1 Vehicle Class Histogram. A vehicle class histogram provides an easy look at the type of traffic using the roadway. It is recommended that FHWA classification system be used. Figure 5.2 shows the FHWA vehicle class histogram for the first quarter of 2004 at I-15 5300 South.

5.3.3.2 Daily Average Steering-Axle Weight. The steering-axle weight does not change considerably for Class 9 vehicles regardless of the load being hauled. This makes the steering-axle weight a good metric for monitoring data. Only Class 9 vehicle data should be included when making this graph. Figure 5.3 provides a daily average steering-axle weight graph for the first quarter of 2004 at I-15 5300 South. The average steering-axle weight for each day is plotted from January 1, 2004, to March 31, 2004. The average should be 11,000 pounds.

5.3.3.3 Daily Average Drive Tandem Spacing. The spacing between the drive tandem axles (i.e., the second and third axles) of Class 9 vehicles is also very consistent. Again, only Class 9 vehicles should be included in this graph. The average distance should be 4.33 feet. Figure 5.4 is a graph of the daily average tandem axle spacing for the first quarter of 2004 at I-15 5300 South. The average drive tandem axle spacing for each day is plotted from January 1, 2004, to March 31, 2004.

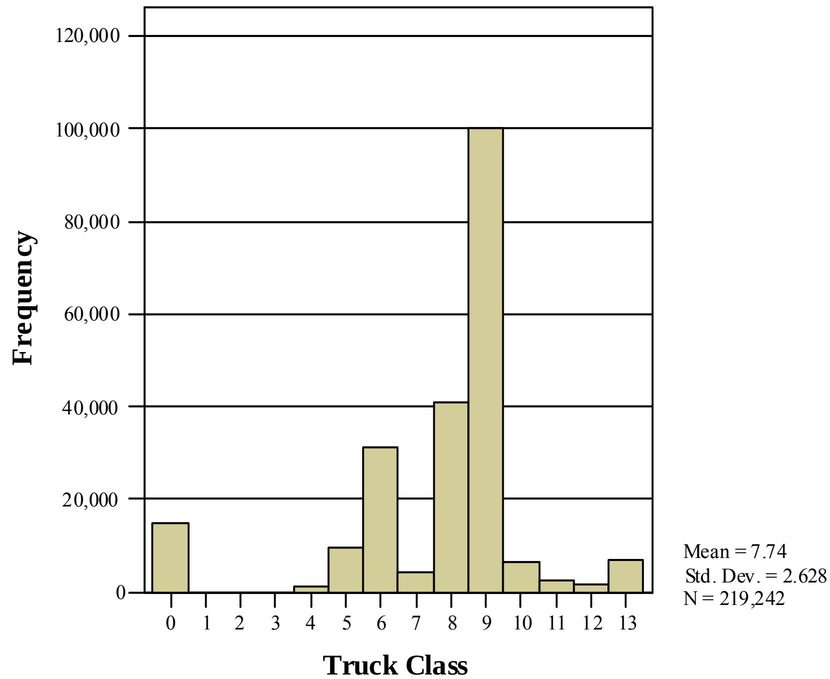

Figure 5.2 First quarter I-15 5300 South vehicle class histogram.

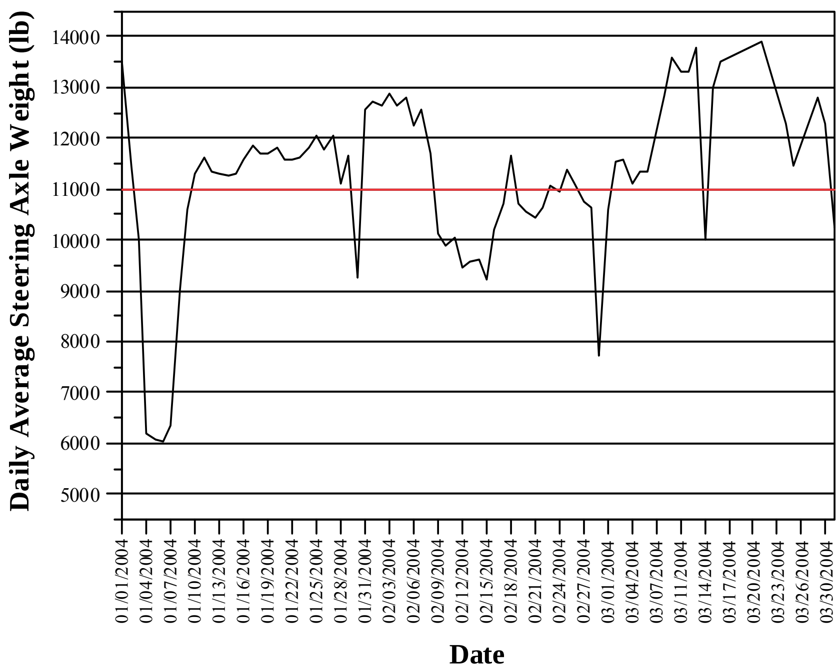

Figure 5.3 First quarter I-15 5300 South daily average steering-axle weight.

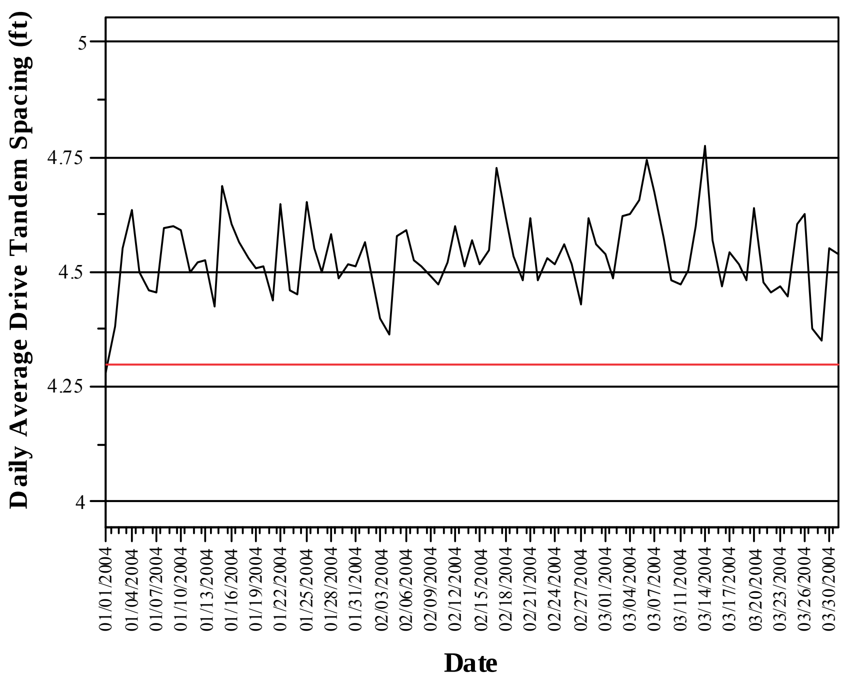

Figure 5.4 First quarter I-15 5300 South daily average drive tandem spacing.

5.3.3.4 GVW Histogram. The final graph is a GVW histogram of Class 9 vehicles. Two peaks are expected, one for empty trucks and one for full trucks. However, this is not always the case. The usefulness of this graph in observing changes in the distribution. If only one peak exists as in Figure 5.5, then a similar distribution is expected to continue. In the case where a change in the distribution occurs, an investigation of the cause should be undertaken.

The purpose of the quality assurance is to become familiar with the output of the individual sites and be able to identify changes and anomalies in the data. The results of the quality assurance should be made a matter of record. In this way, changes to the characteristics of the graphs can be observed. Thus, changes in the expected characteristics of the graphs would indicate a problem with the WIM system. A quality assurance program is recommended to evaluate the quality of data being produced and to monitor the health of the WIM system.

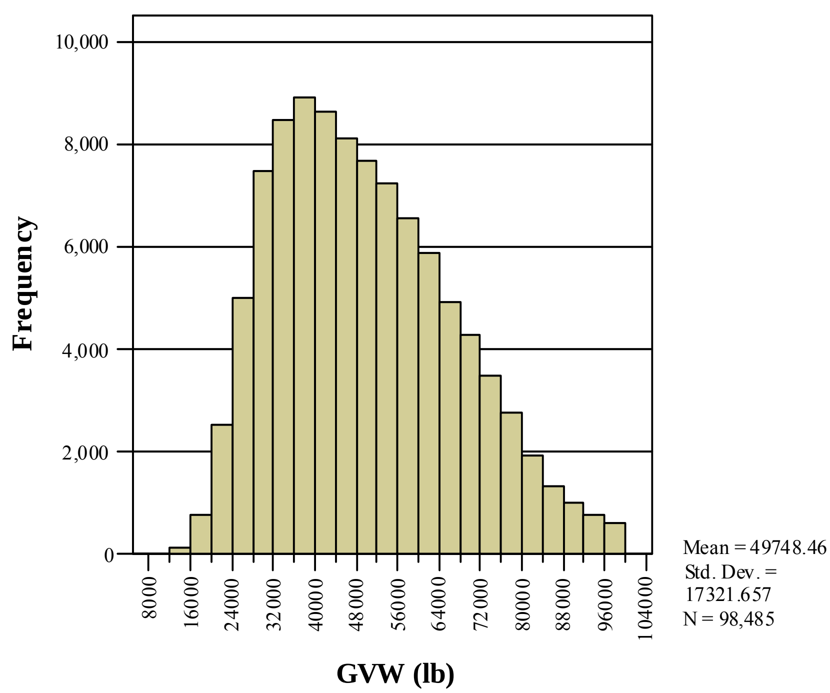

Figure 5.5 First quarter I-15 5300 South Class 9 GVW histogram.

5.4 Summary and Conclusions

This chapter has explored calibration improvement, including current practices of other states. The degree of compliance to the standards discussed in Section 2.4 varies from state to state. The current practice in the state of Utah was also explored, including the IRD procedure at the POEs and the UDOT procedure at the IRD and Peek sites. A procedure based on both current practices of other states and on standards was described, including recommendations about calibration, verification, and quality assurance programs.

The current calibration methods used at the POE and Peek sites is adequate; however, the auto-calibration capability of the IRD sites should be made functional. This will make temperature-binning and other options of the system available for use.

The verification process being done at the POE sites is adequate, while a new process is recommended for the IRD and Peek sites. Verification is to be done on an annual basis with the use of test trucks.

Finally, a quality assurance method is recommended for all the WIM sites. This includes the production of graphs on a quarterly basis for the purpose of assessing the quality of the data and the heath of the WIM system. A statistical or database software package that can handle large data sets will be needed for the quality assurance process.

The recommendations outlined in this chapter will improve the functionality of the Utah WIM sites and ensure the quality of their output. It will also bring the maintenance of the WIM sites in line with standards and current practice.

6 Conclusions and Future Research

This chapter provides conclusions from the research, including the results of the commercial motor vehicle (CMV) program evaluation and the recommended improvements to that program. Also, a discussion of future research is provided, particularly concerning the second phase of this research project.

6.1 Conclusions

The problem statement identified the need to evaluate current CMV data statewide and to develop a more accurate and succinct methodology for the collection and interpretation of CMV data that can be used throughout the Utah Department of Transportation (UDOT) for design and analysis purposes. The objective of this research was to evaluate the CMV data collection program in the state of Utah and to recommend potential improvements and changes that will aid in more detailed and accurate CMV data collection across the state.

6.1.1 Evaluation of the CMV Data Collection Program

Based on the analysis of the Weigh-in-Motion (WIM) data that were provided by UDOT, the current methodology is functioning fairly well and is producing data that are consistent with expectations. The results of the analysis do show, however, that room for improvement exists. Several WIM sites were shown to be somewhat inconsistent with other similar WIM sites. Among these were 5300 South, 400 North, 1300 South, 10600 South, Plymouth, and Nephi. The severity of the inconsistency is greatest at the 5300 South site, followed by the 400 North site due to Class 0 vehicles and outliers. Variation also exists in the data from these sites. All of the International Road Dynamics (IRD) sites, with the exception of 5300 South, have lower-than-expected mean steering-axle weight, and the Plymouth and Nephi WIM sites tended to exhibit large percentages of trucks over the legal weight limit (80,000 pounds). Ultimately, the data obtained from Utah's WIM sites are of consistent quality; however, several areas exist that should be evaluated further by UDOT personnel.

6.1.2 Recommended Improvements to the CMV Data Collection Program

The recommended improvements to the CMV data collection program include the implementation of a calibration procedure outlined in Section 5.3 of this report. This recommended procedure consists of three parts: 1) calibration, 2) validation, and 3) quality assurance. The calibration currently in use at the Port of Entry (POE) and Peek sites should continue, while the IRD sites are recommended to be enabled to use an auto-calibration function. A validation procedure that is currently used at the POE sites is adequate; however, no validation procedure being used at the Peek or IRD sites. The validation procedure outlined in Section 5.3.2 of this report should be implemented, which includes the use of test trucks. Finally, a quality assurance method is recommended that involves the production of several graphs on a quarterly basis. This should be done to monitor the health of the WIM sites and to ensure that quality data are being produced.

6.1.3 Summary of Conclusions

The primary questions that this research answers are twofold: 1) "What is the state of the Utah's current CMV data collection system?" and 2) "What changes can be made to improve the CMV data collection system?" Through analysis and research, both questions were addressed.

The analysis of the data provided by UDOT answers the first question. Utah's WIM data generally meet the expectations of the analysis. Thus, the current methods appear to be fairly reliable at producing accurate data. Yet, some problem areas were observed that should be addressed as noted previously.

The second question was answered through research of standards about WIM system maintenance and through a survey of selected states. Based on this research, a WIM calibration procedure was developed for the Utah sites. The procedure consists of three parts: 1) calibration, 2) verification, and 3) quality assurance. The calibration included the use of auto-calibration for the piezoelectric WIM systems. The verification includes the use of test trucks. Quality assurance refers to the periodic use of graphs to ensure the quality of the data and the proper functioning of the WIM system.

6.2 Future Research

The research project described in this report has a second phase that may be completed at a future date. The second phase builds upon the results found in this document. The purpose of the second phase is to outline recommended changes to the current program and to identify new methodologies and ideas to provide better estimates of vehicle weight data that can be used in pavement damage estimates, truck distributions, and simulation.

The second phase consists of several tasks, including: 1) identifying truck and road groupings based on recommendations found in the Traffic Monitoring Guide (TMG); 2) analyzing the WIM data collection program, which will consist of a broad review of the program including enforcement, truck percentage development, and steps to establishing a new citation fee structure; and 3) providing recommendations and conclusions.

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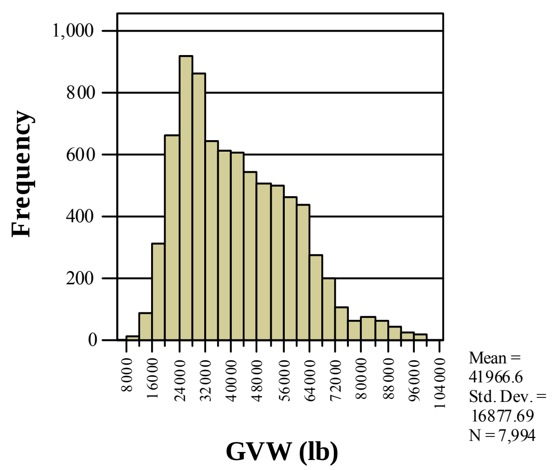
Appendix A Quarterly Analysis Histograms



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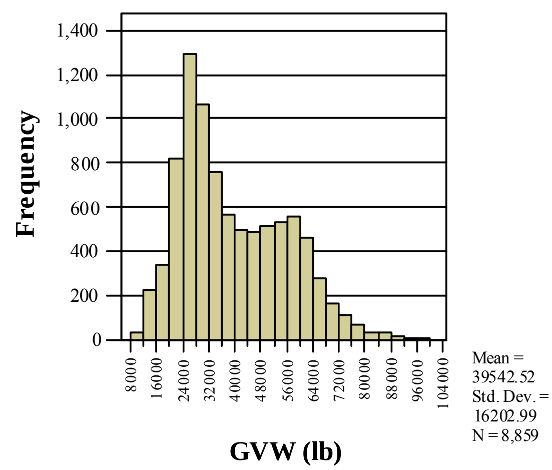

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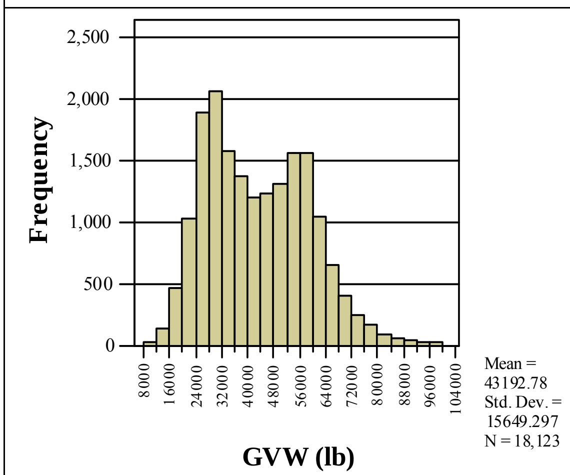

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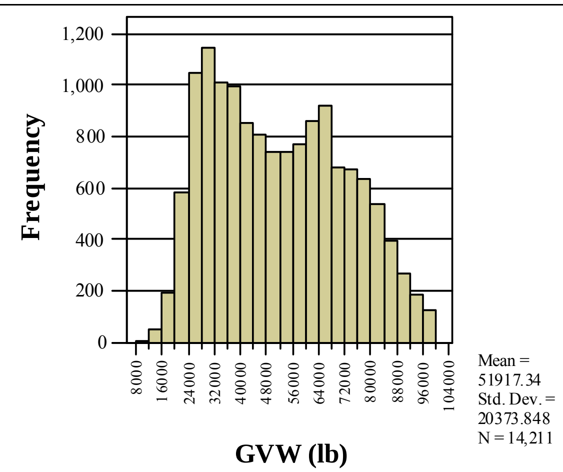

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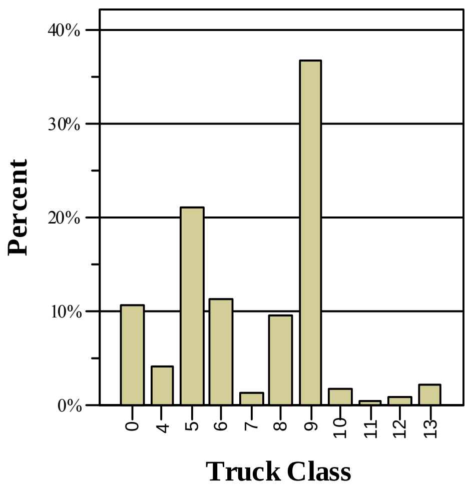
Figure A.1 I-15 400 North quarterly GVW histograms of Class 9 vehicles.



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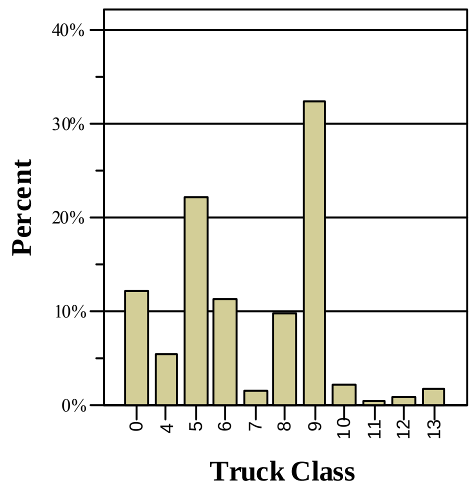

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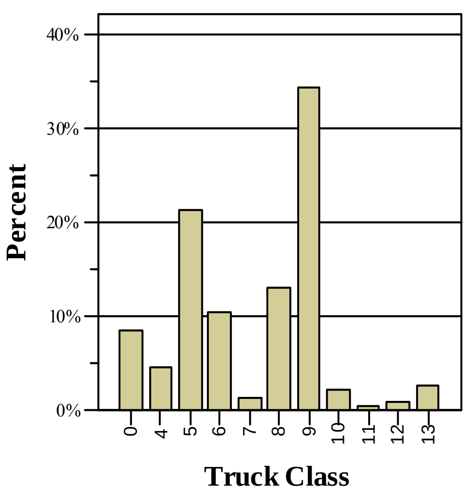

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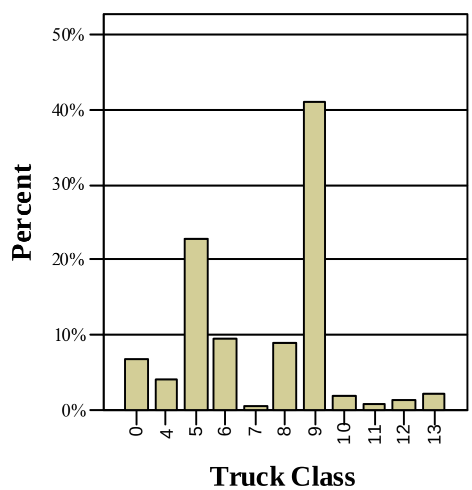

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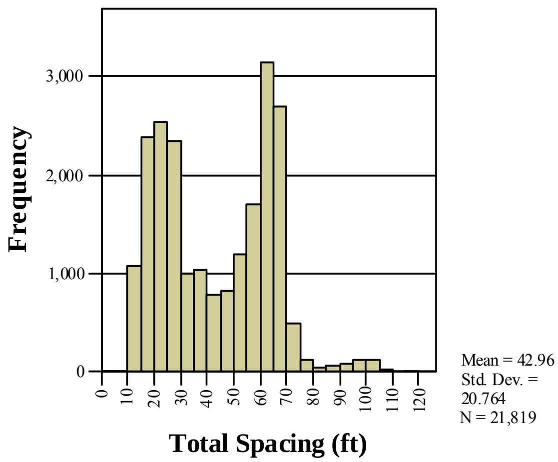
Figure A.2 I-15 400 North quarterly truck class histograms.



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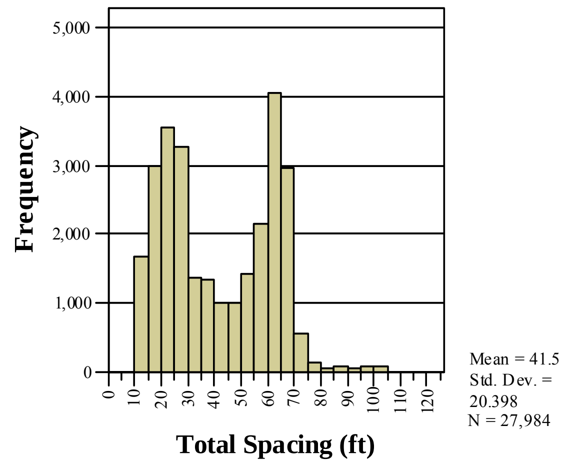

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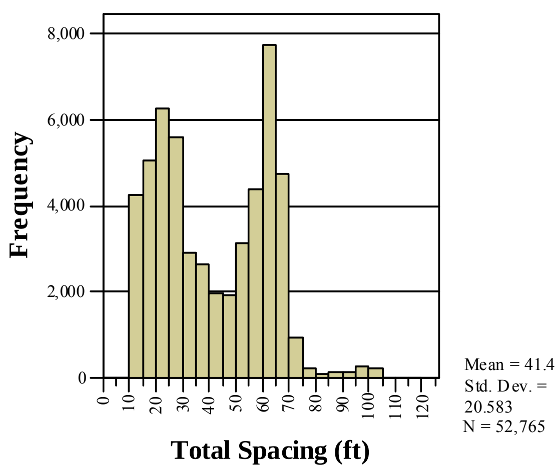

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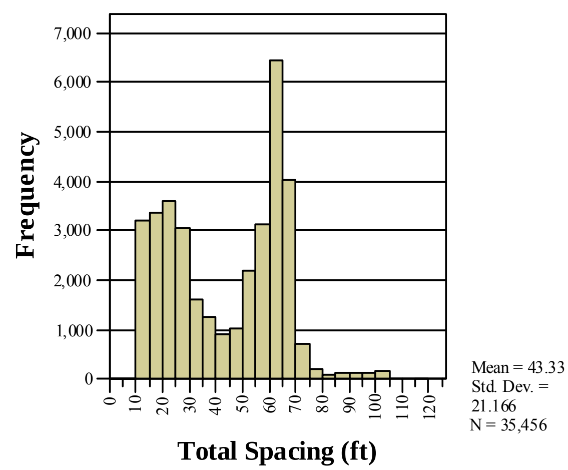

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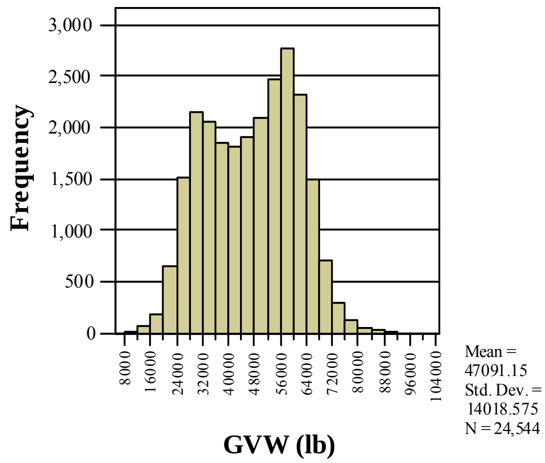
Figure A.3 I-15 400 North quarterly total spacing histograms of all vehicle classes.



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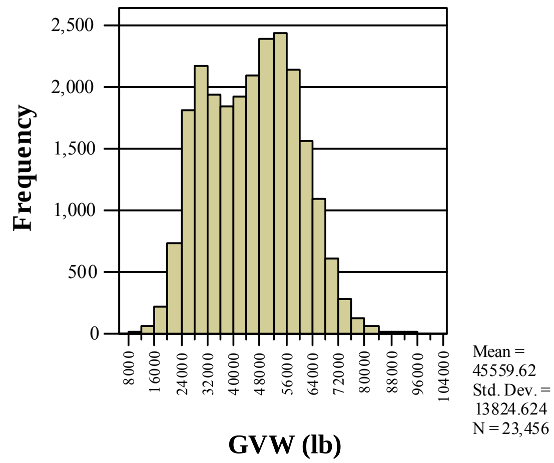

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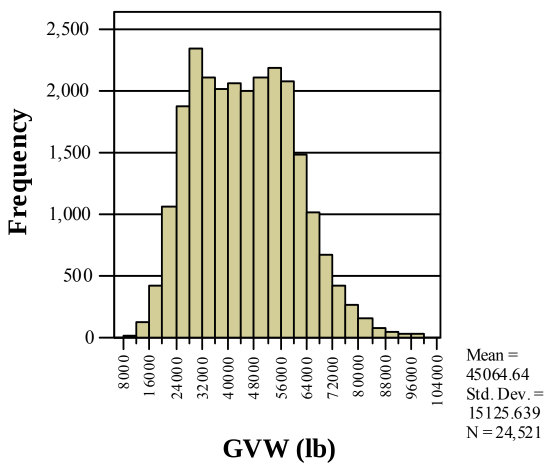

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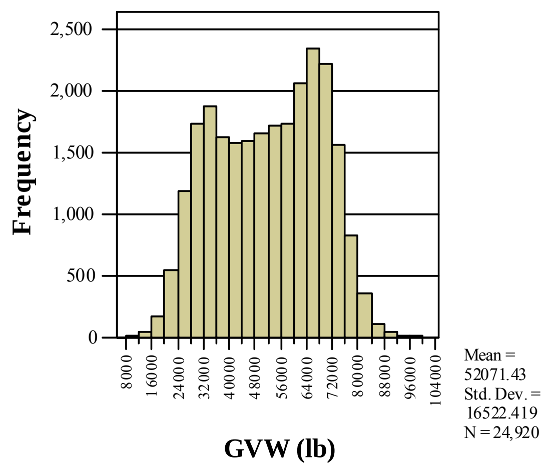

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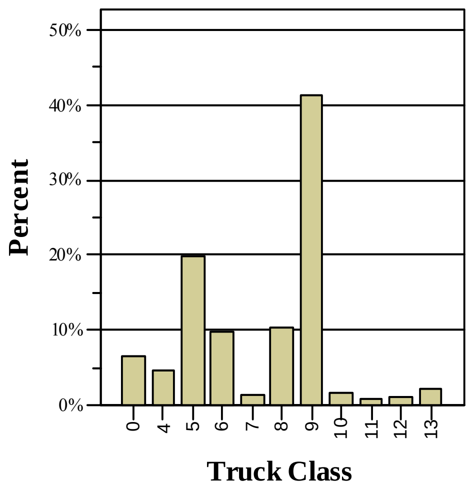
Figure A.4 I-15 1300 South quarterly GVW histograms of Class 9 vehicles.



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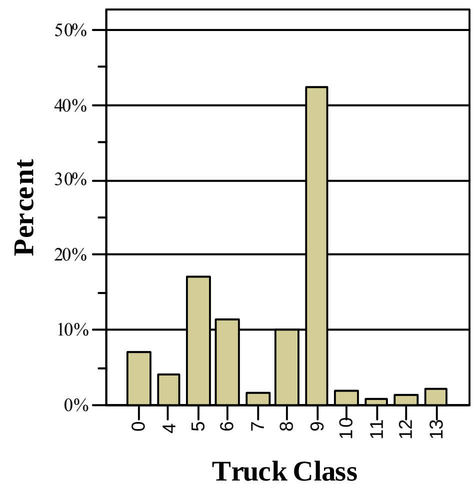

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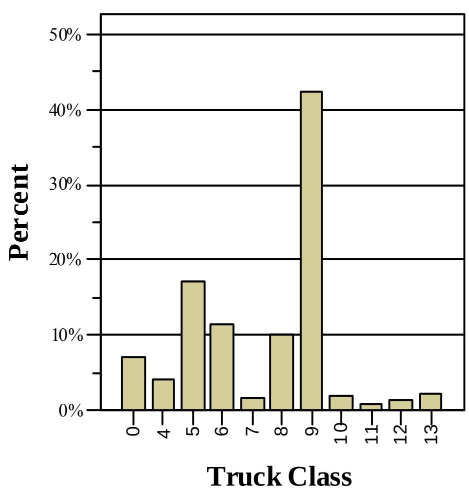

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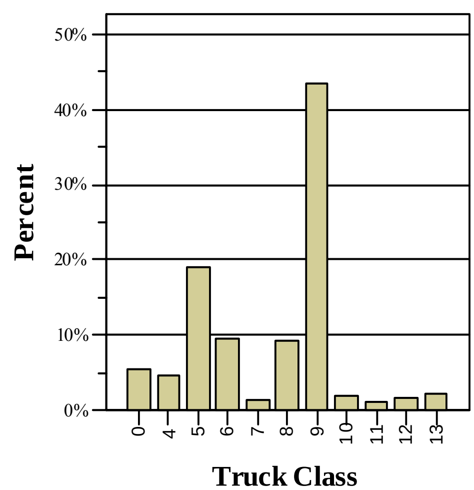

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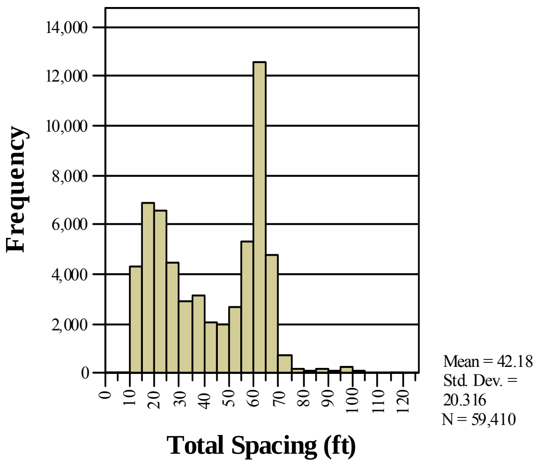
Figure A.5 I-15 1300 South quarterly truck class histograms.



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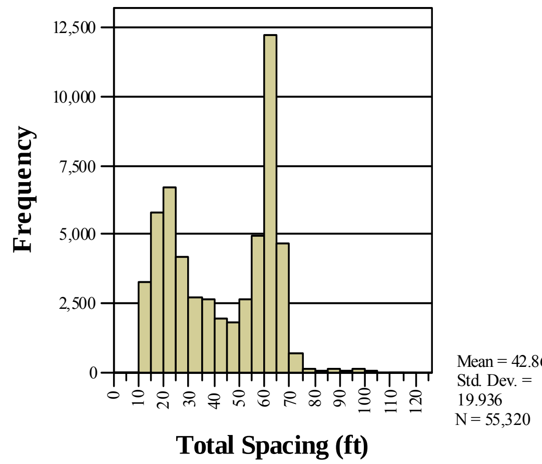

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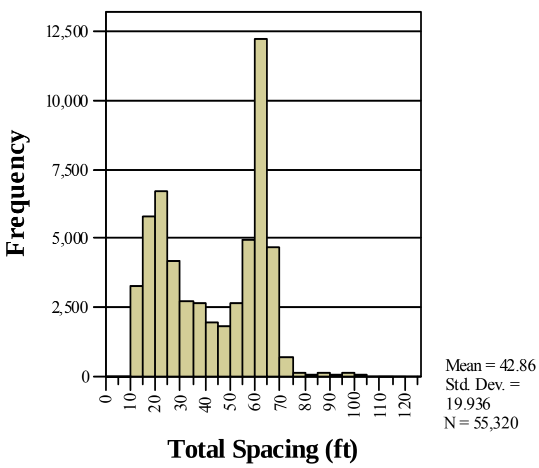

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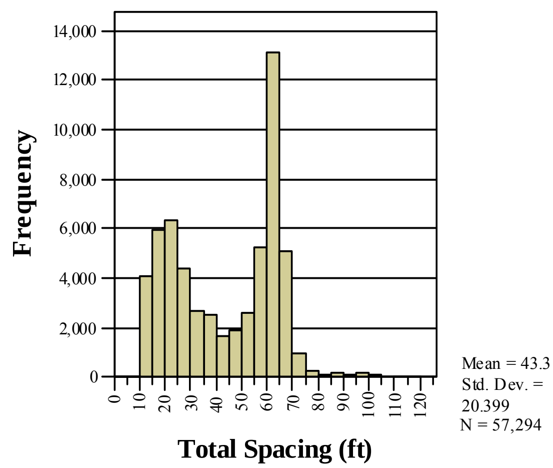

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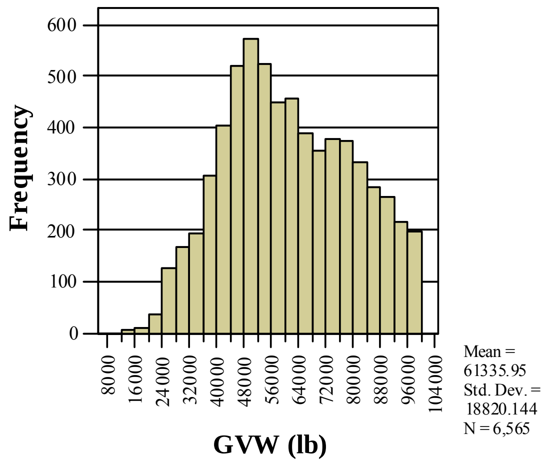
Figure A.6 I-15 1300 South quarterly total spacing histogram of all vehicle classes.



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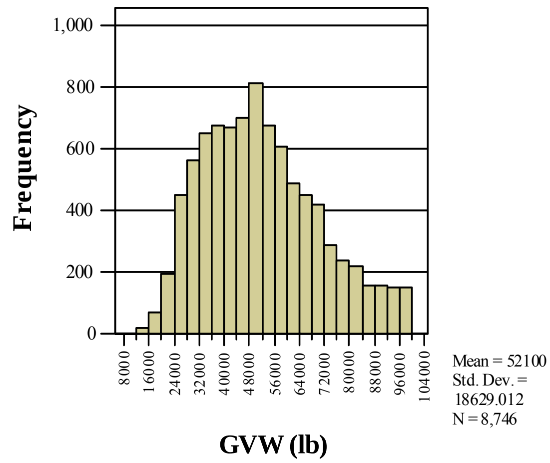

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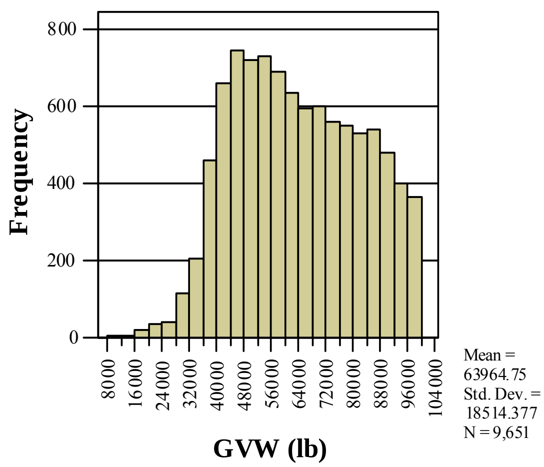

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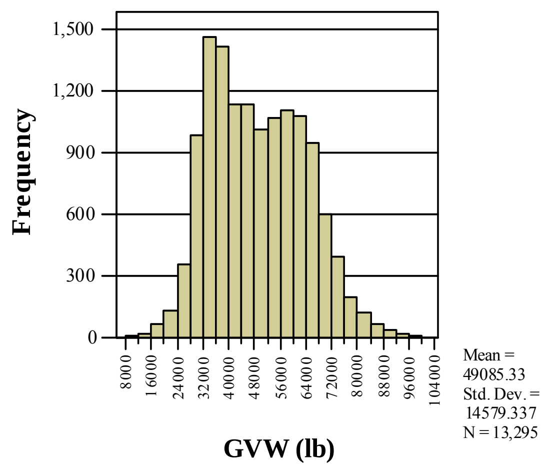

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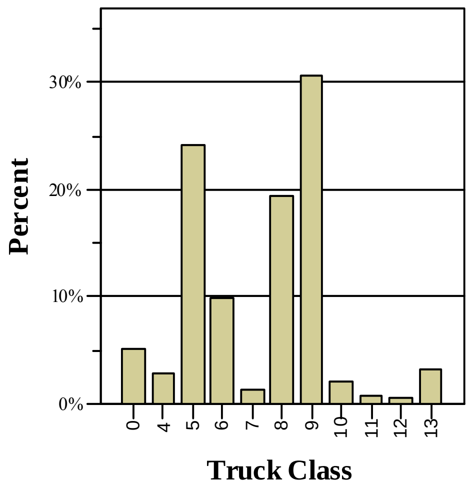
Figure A.7 I-15 5300 South quarterly GVW histograms of class 9 vehicles.



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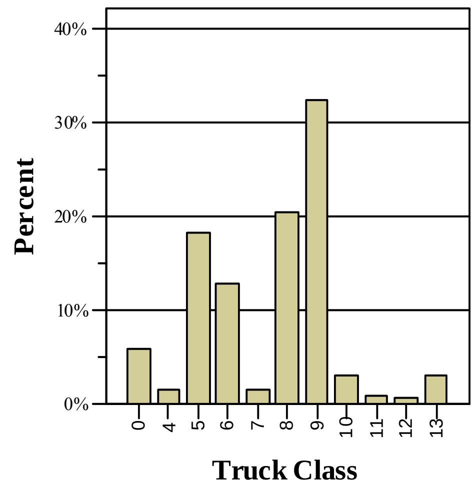

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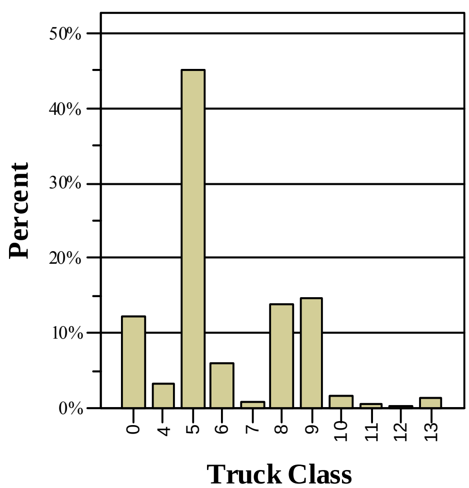
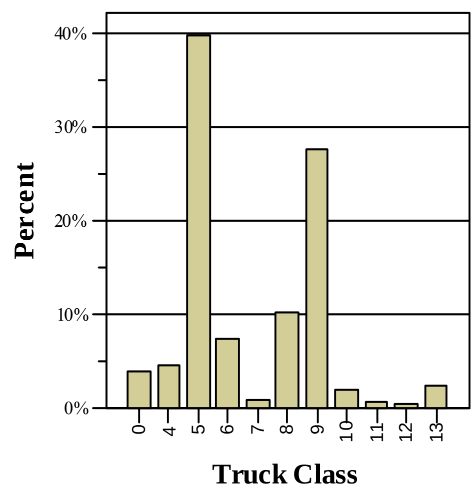
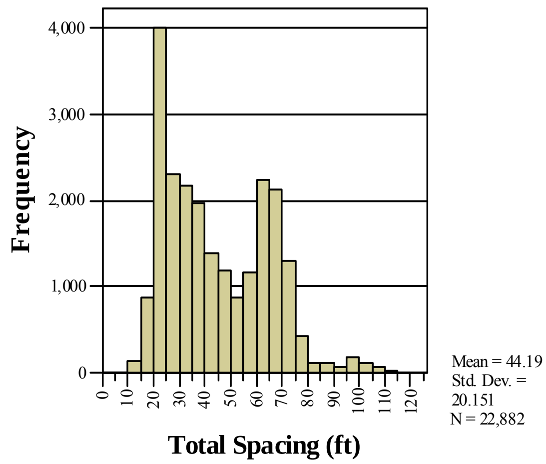


(c) Third Quarter

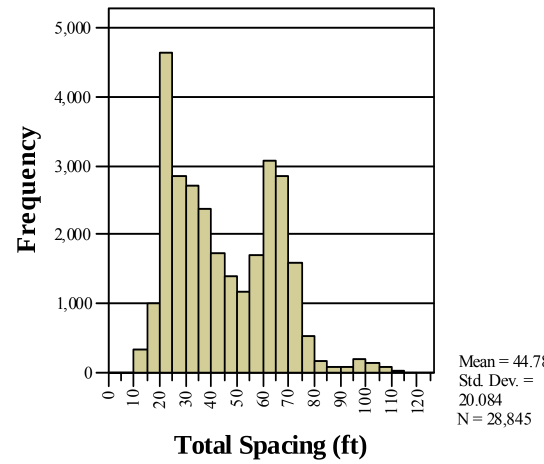


(d) Fourth Quarter

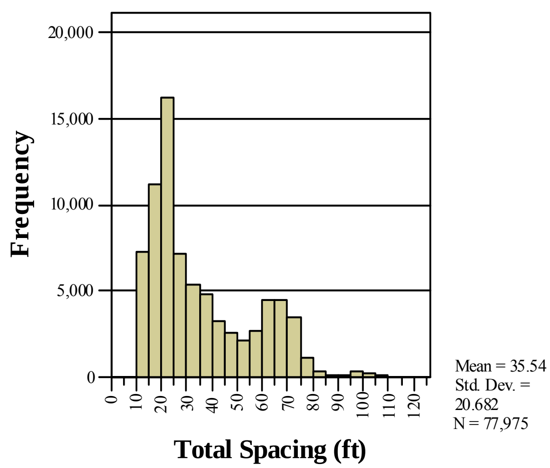
Figure A.8 I-15 5300 South quarterly truck class histograms.



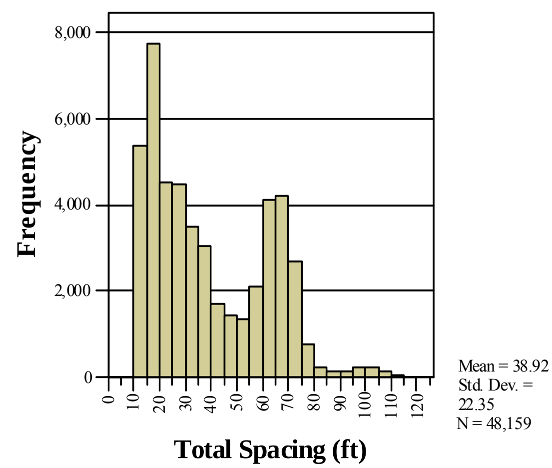
(a) First Quarter



(b) Second Quarter

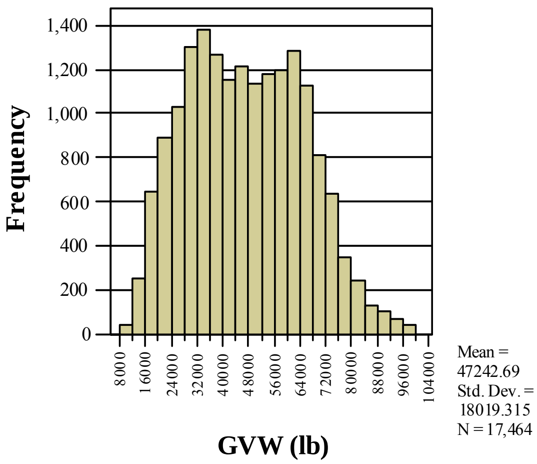


(c) Third Quarter

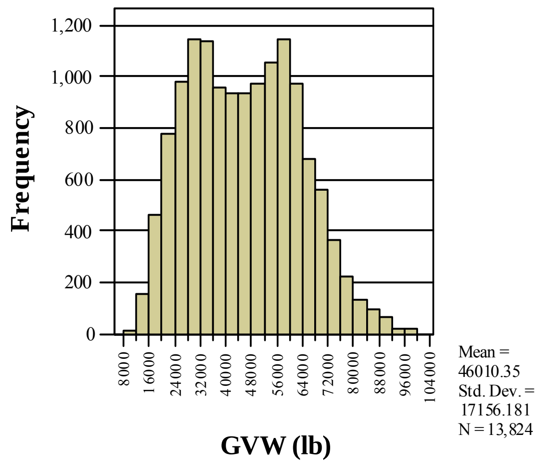


(d) Fourth Quarter

Figure A.9 I-15 5300 South quarterly total spacing histogram of all vehicle classes.



(a) First Quarter



(b) Second Quarter

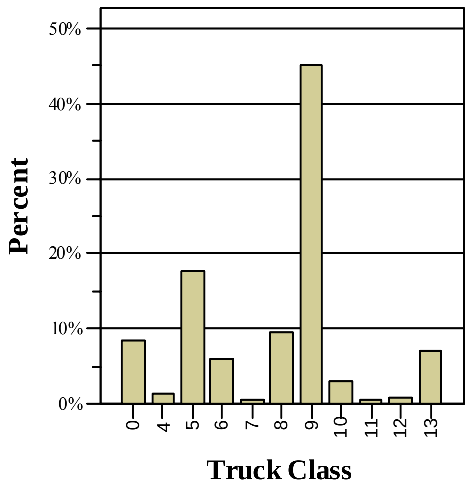
No Data

(c) Third Quarter

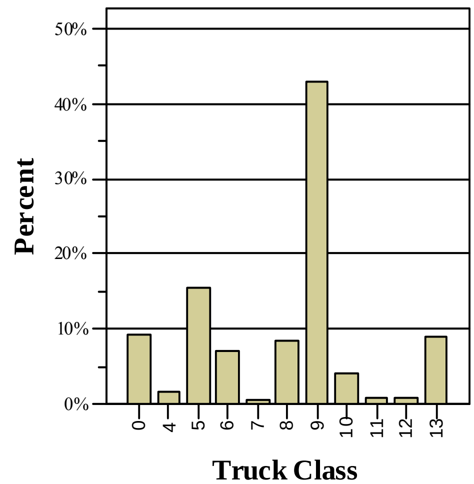
No Data

(d) Fourth Quarter

Figure A.10 I-15 10600 South quarterly GVW histograms of class 9 vehicles.



(a) First Quarter



(b) Second Quarter

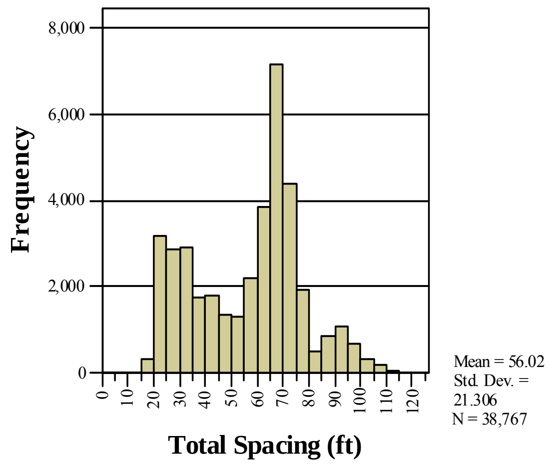
No Data

(c) Third Quarter

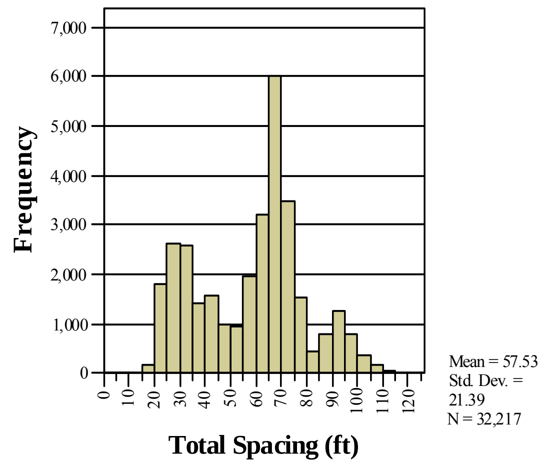
No Data

(d) Fourth Quarter

Figure A.11 I-15 10600 South quarterly truck class histograms.



(a) First Quarter



(b) Second Quarter

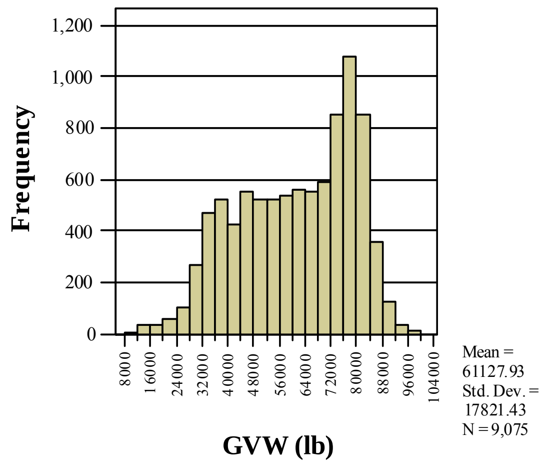
No Data

No Data

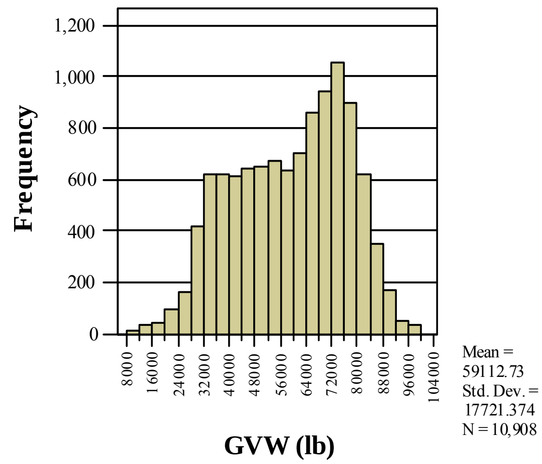
(c) Third Quarter

(d) Fourth Quarter

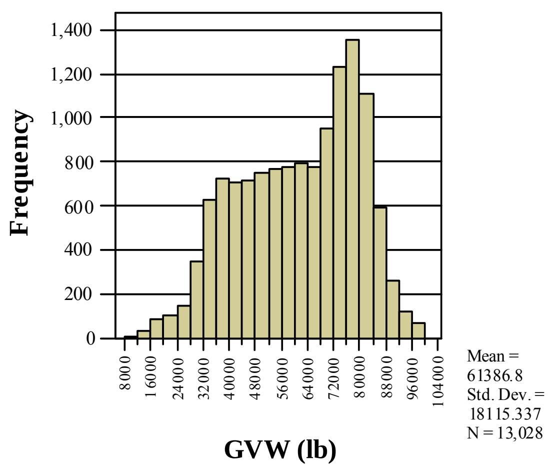
Figure A.12 I-15 10600 South quarterly total spacing histogram of all vehicle classes.



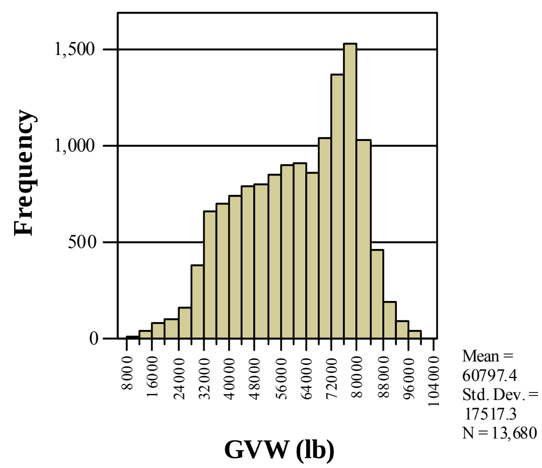
(a) First Quarter



(b) Second Quarter

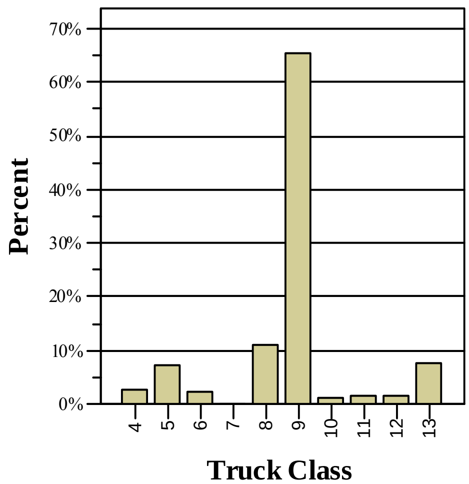


(c) Third Quarter

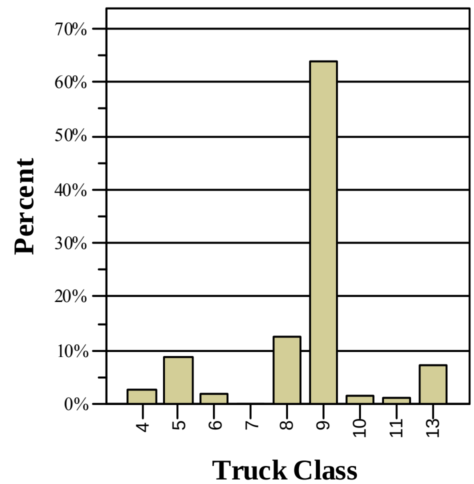


(d) Fourth Quarter

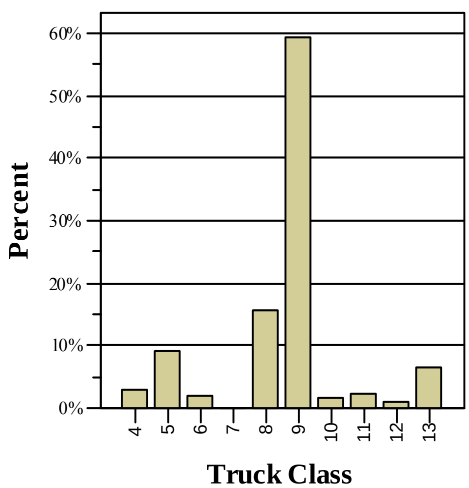
Figure A.13 I-15 Nephi quarterly GVW histograms of Class 9 vehicles.



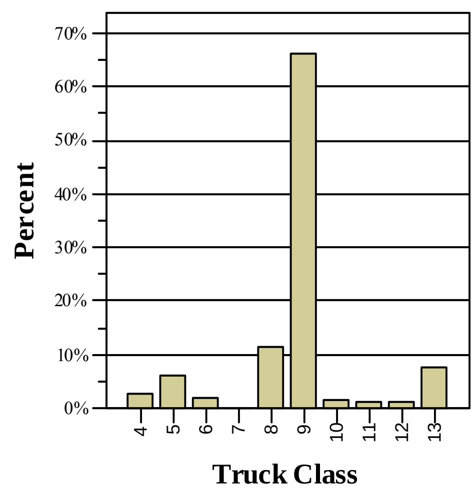
(a) First Quarter



(b) Second Quarter

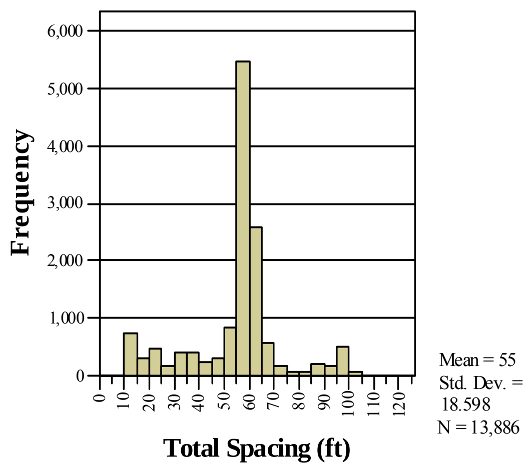


(c) Third Quarter

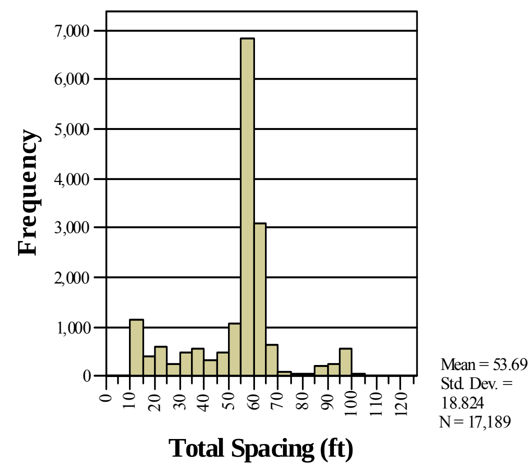


(d) Fourth Quarter

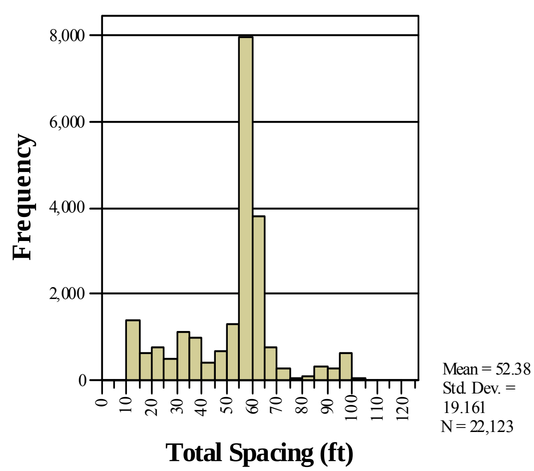
Figure A.14 I-15 Nephi quarterly truck class histograms.



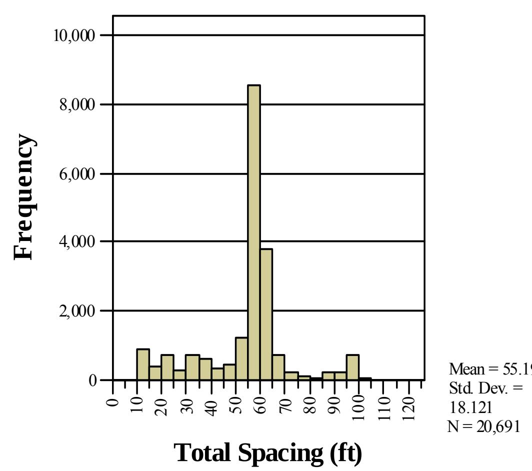
(a) First Quarter



(b) Second Quarter

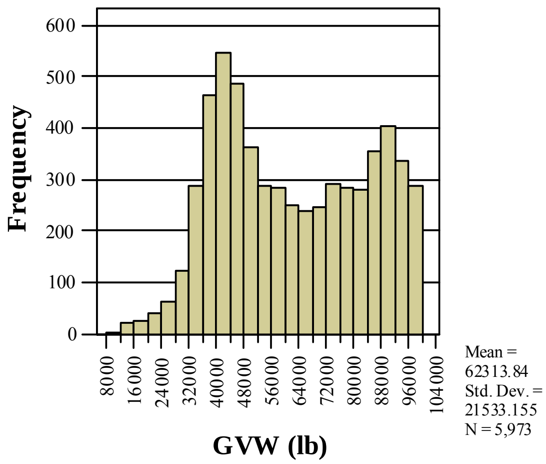


(c) Third Quarter

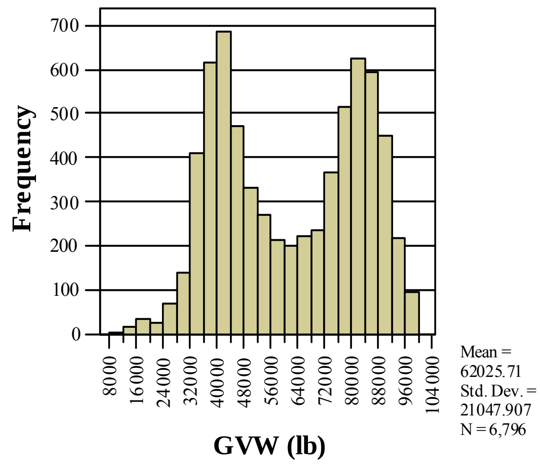


(d) Fourth Quarter

Figure A.15 I-15 Nephi quarterly total spacing histogram of all vehicle classes.



(a) First Quarter



(b) Second Quarter

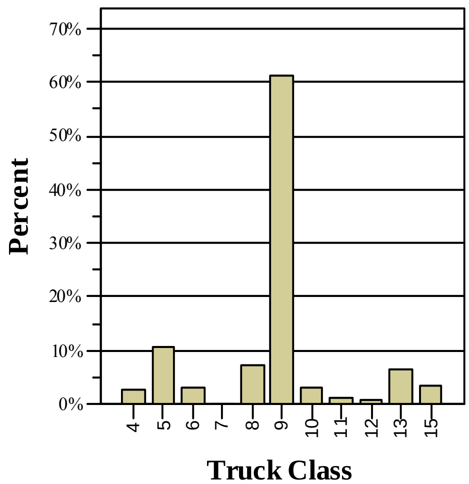
No Data

No Data

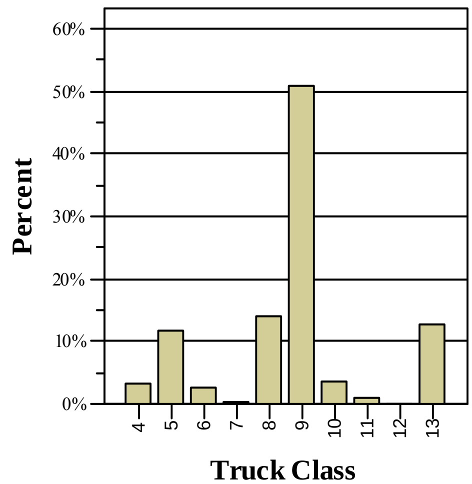
(c) Third Quarter

(d) Fourth Quarter

Figure A.16 I-15 Plymouth quarterly GVW histograms of Class 9 vehicles.



(a) First Quarter



(b) Second Quarter

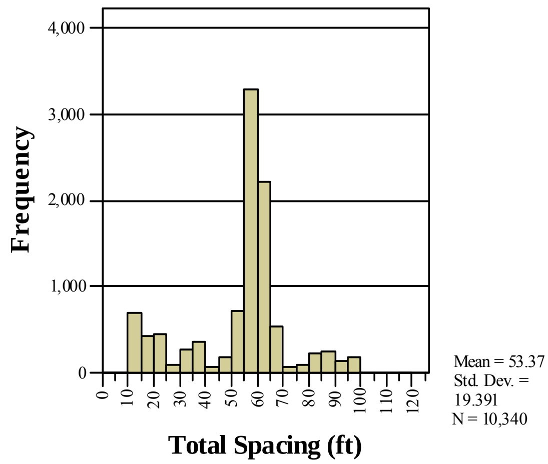
No Data

(c) Third Quarter

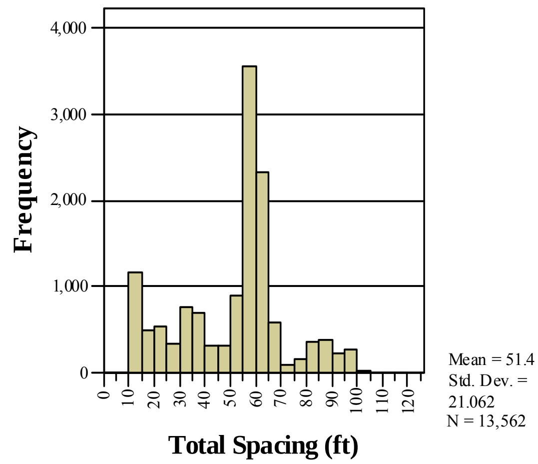
No Data

(d) Fourth Quarter

Figure A.17 I-15 Plymouth quarterly truck class histograms.



(a) First Quarter



(b) Second Quarter

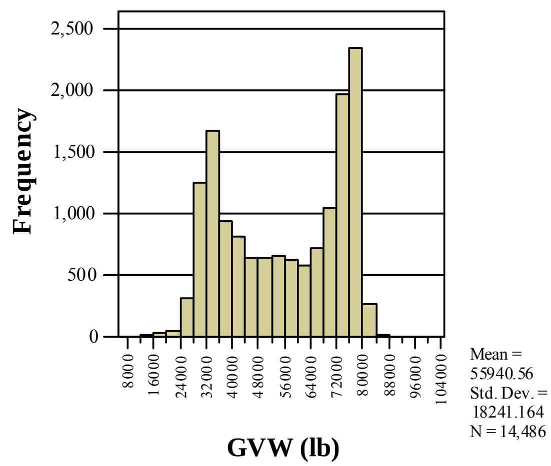
No Data

No Data

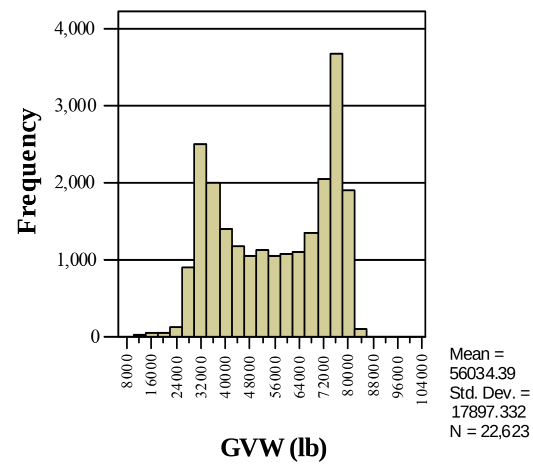
(c) Third Quarter

(d) Fourth Quarter

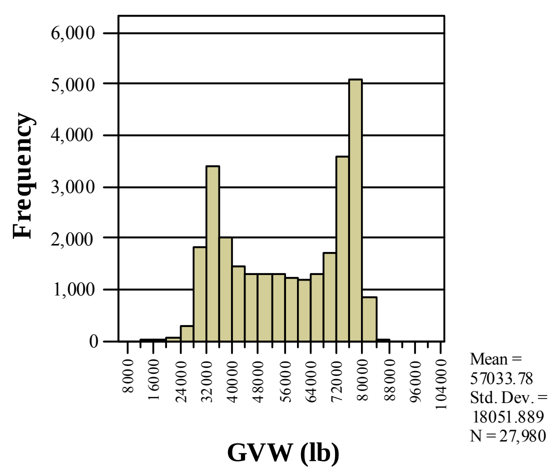
Figure A.18 I-15 Plymouth quarterly total spacing histogram of all vehicle classes.



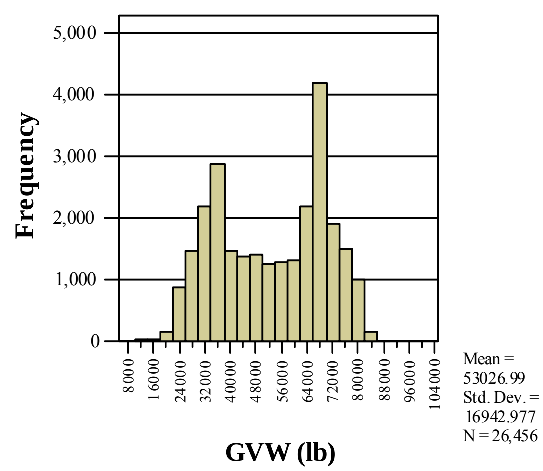
(a) First Quarter



(b) Second Quarter

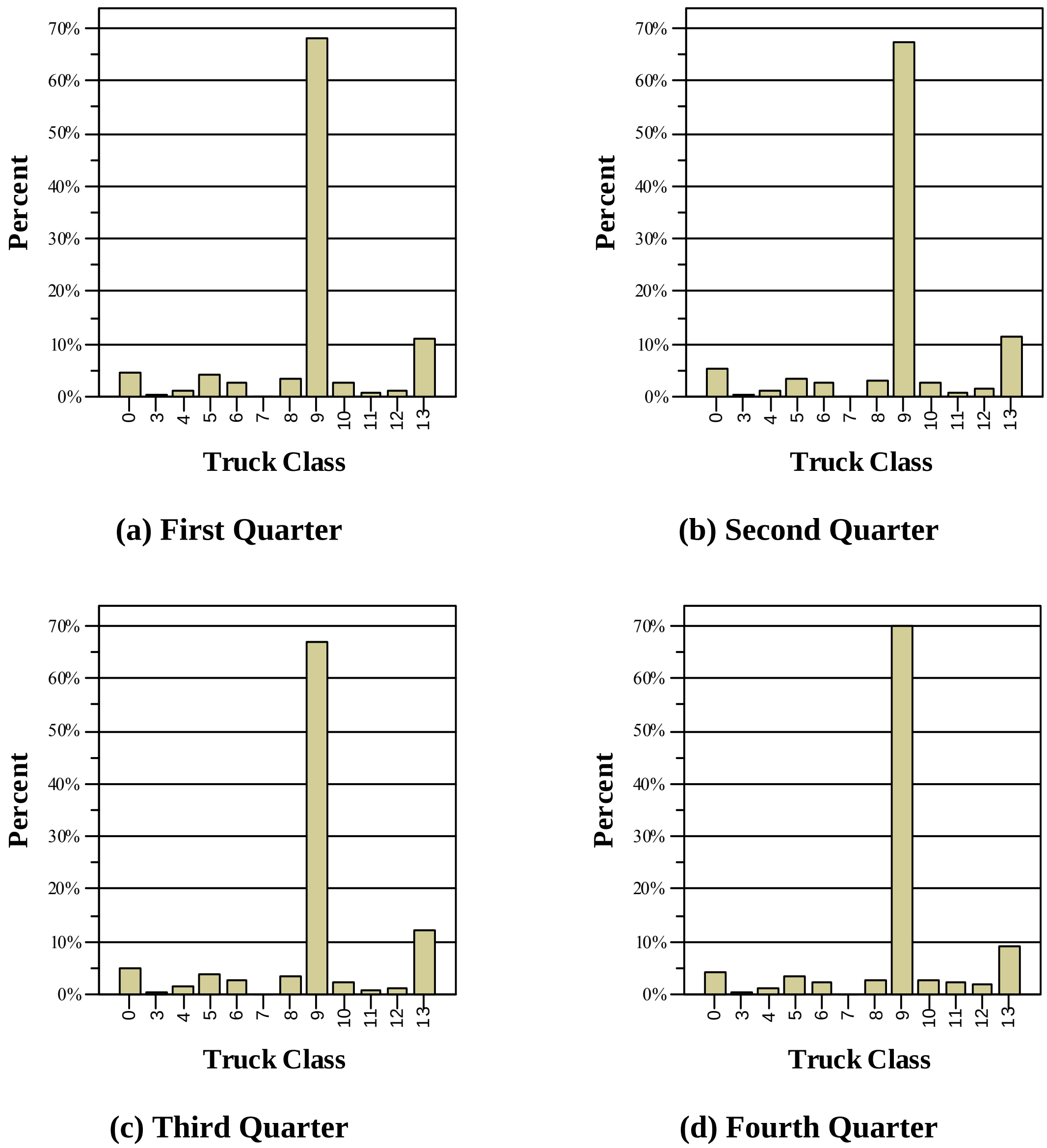


(c) Third Quarter



(d) Fourth Quarter

Figure A.19 I-15 Perry quarterly GVW histograms of Class 9 vehicles.



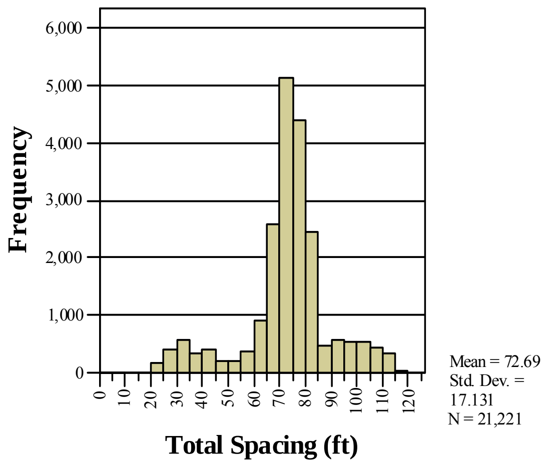
(a) First Quarter

(b) Second Quarter

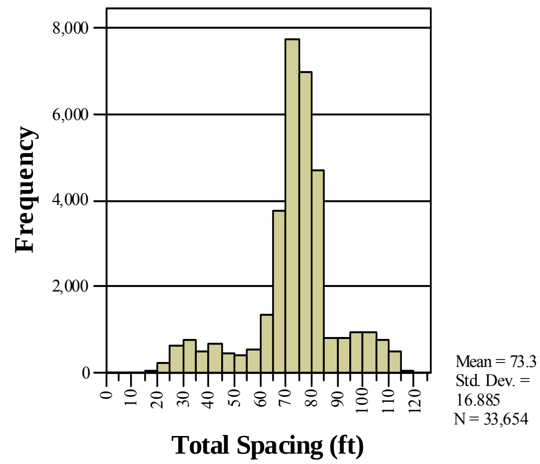
(c) Third Quarter

(d) Fourth Quarter

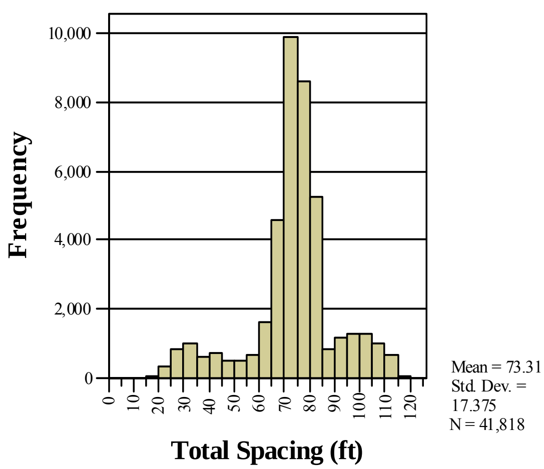
Figure A.20 I-15 Perry quarterly truck class histograms.



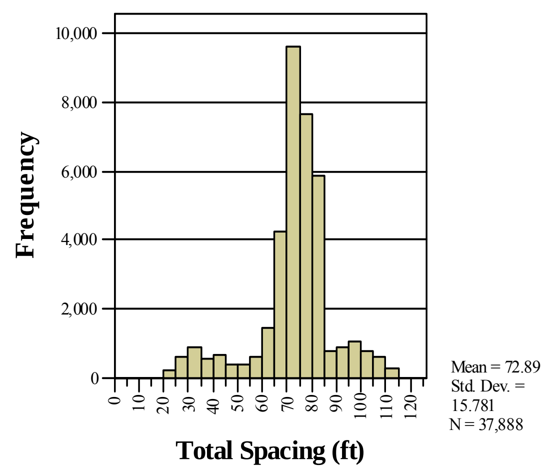
(a) First Quarter



(b) Second Quarter

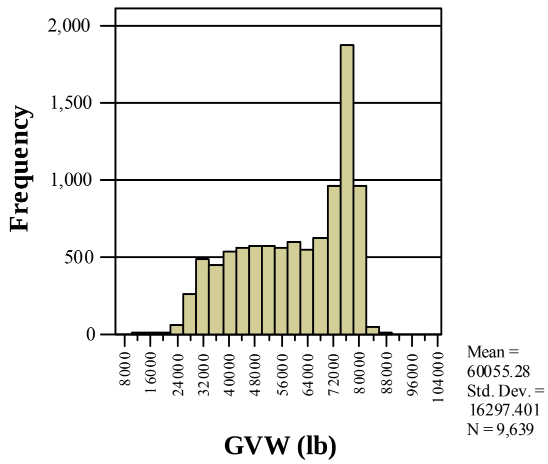


(c) Third Quarter

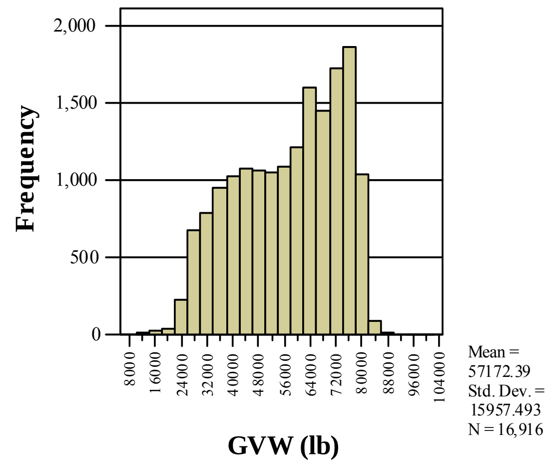


(d) Fourth Quarter

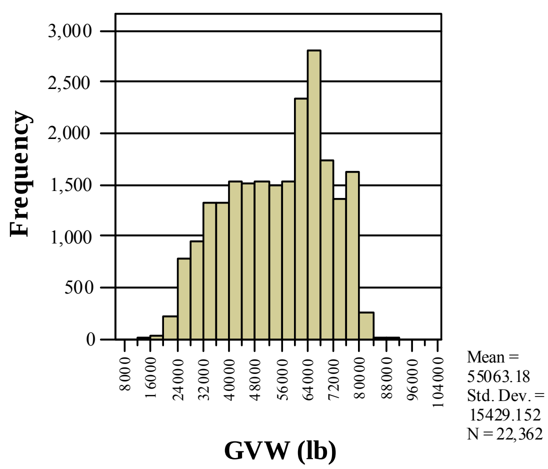
Figure A.21 I-15 Perry quarterly total spacing histogram of all vehicle classes.



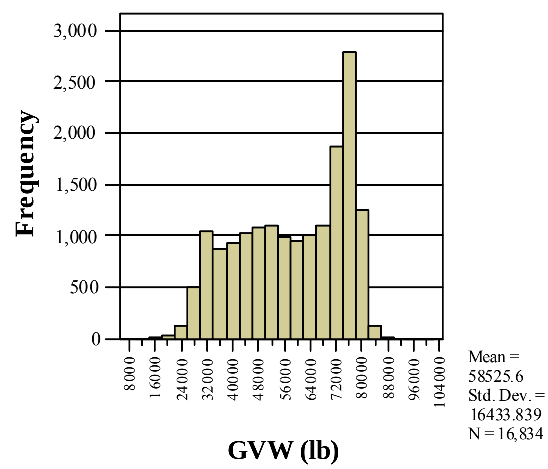
(a) First Quarter



(b) Second Quarter



(c) Third Quarter



(d) Fourth Quarter

Figure A.22 I-15 St. George quarterly GVW histograms of Class 9 vehicles.

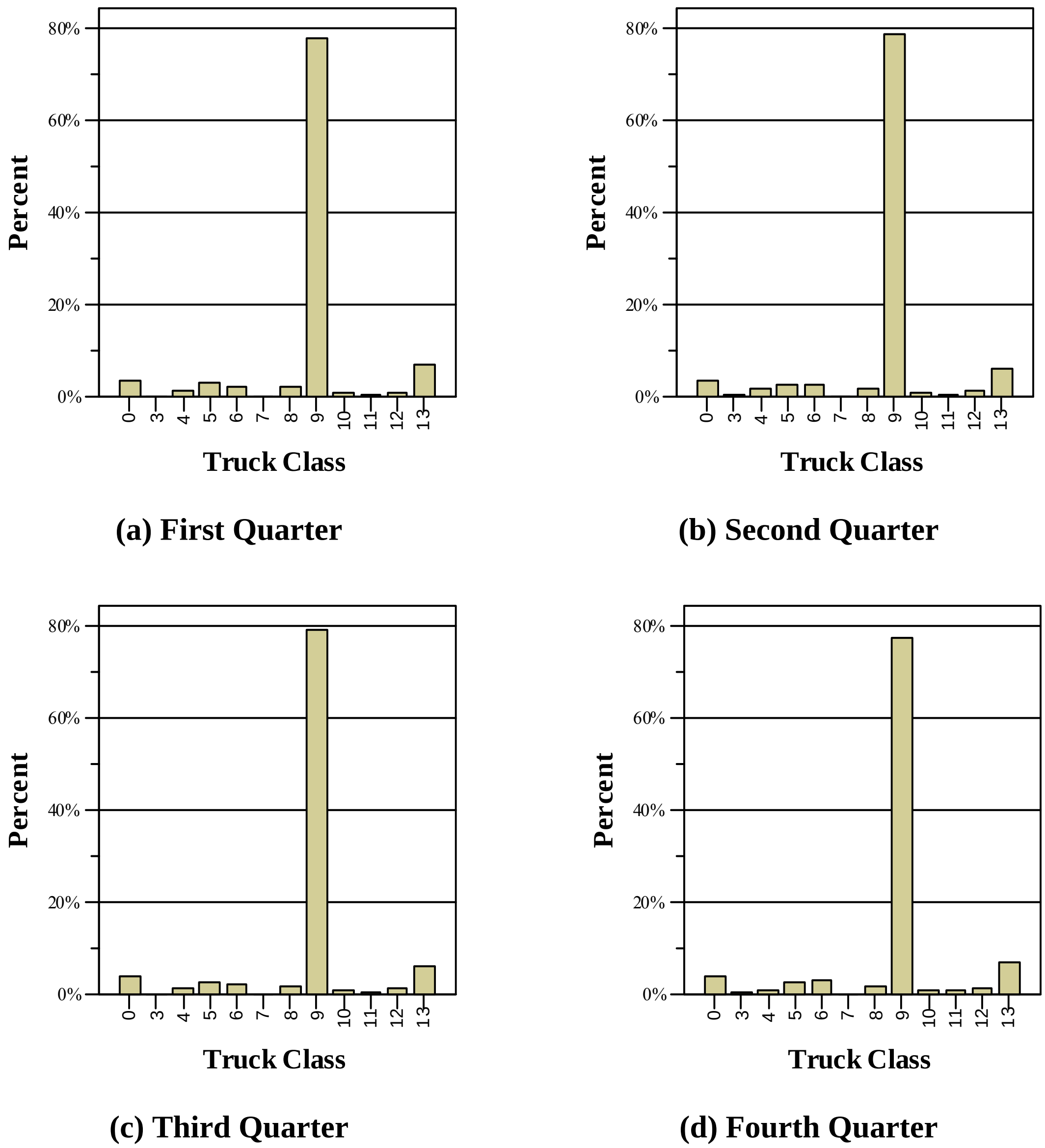
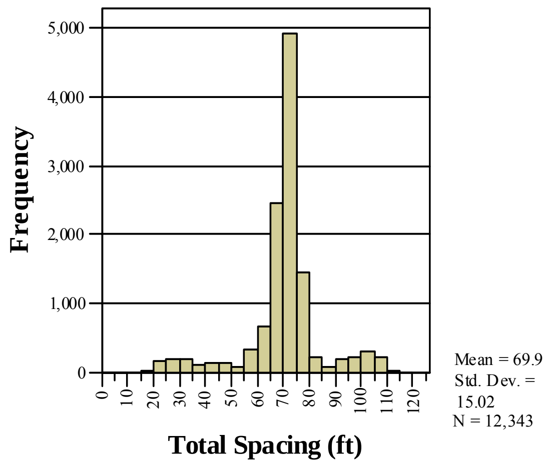
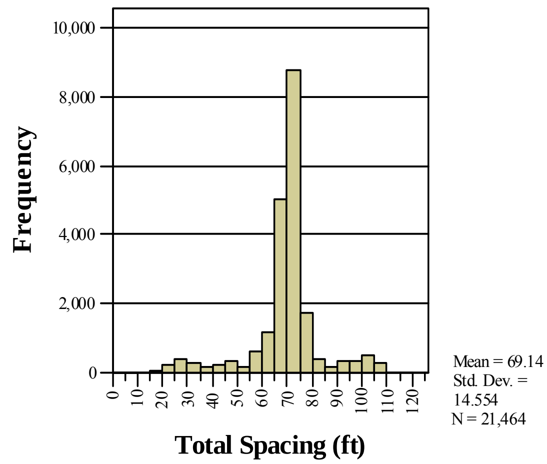


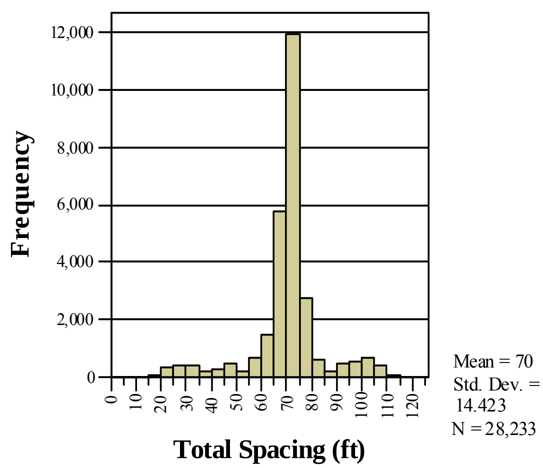
Figure A.23 I-15 St. George quarterly truck class histograms.



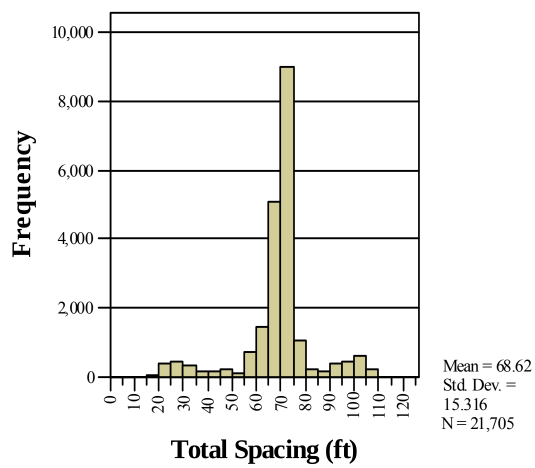
(a) First Quarter



(b) Second Quarter

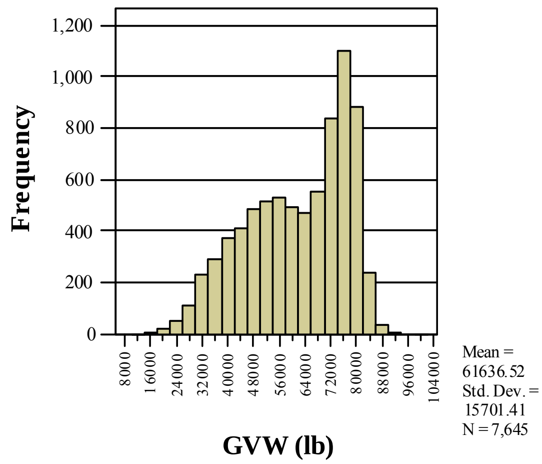


(c) Third Quarter

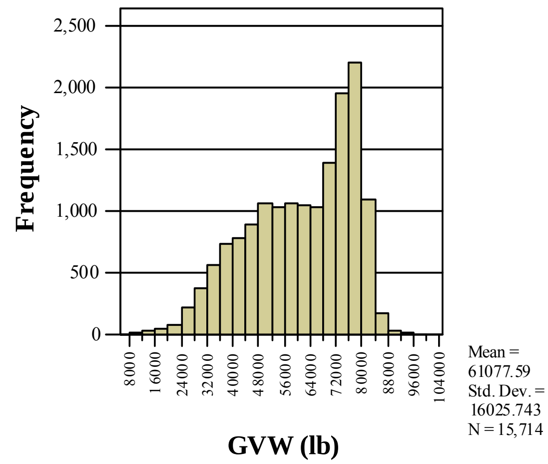


(d) Fourth Quarter

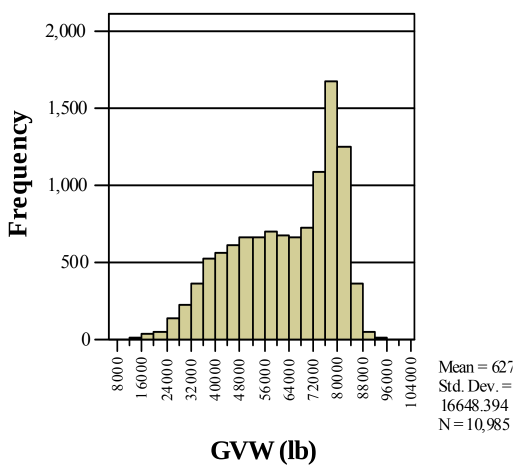
Figure A.24 I-15 St. George quarterly total spacing histogram of all vehicle classes.



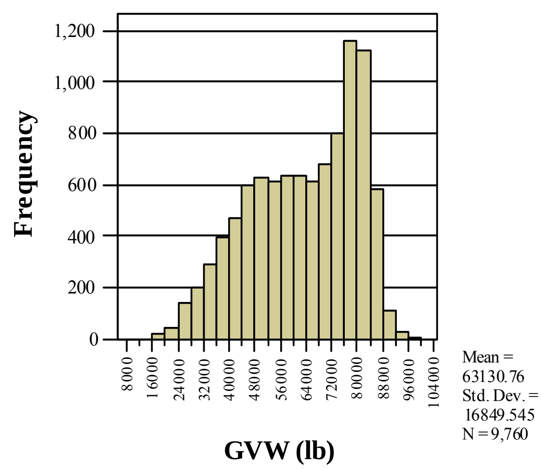
(a) First Quarter



(b) Second Quarter

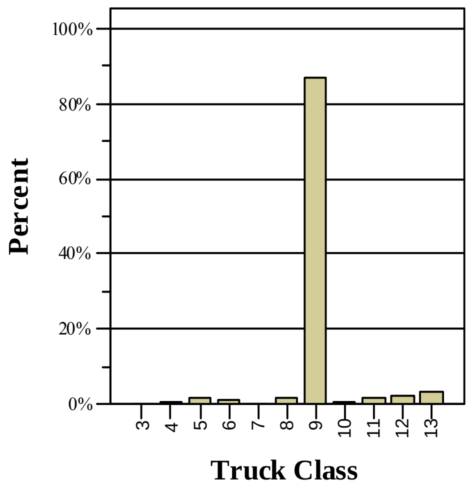


(c) Third Quarter

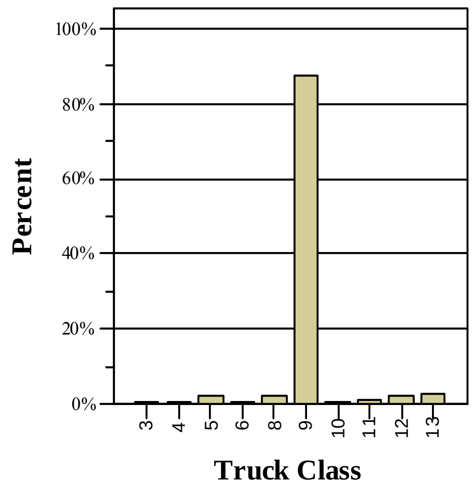


(d) Fourth Quarter

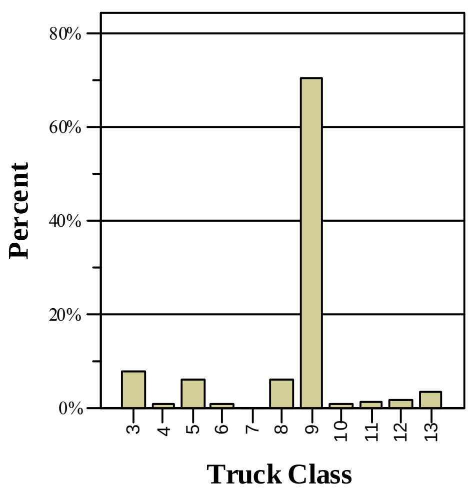
Figure A.25 I-80 Echo quarterly GVW histograms of Class 9 vehicles.



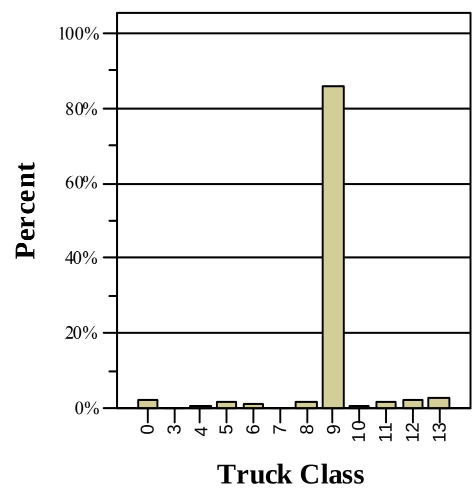
(a) First Quarter



(b) Second Quarter



(c) Third Quarter



(d) Fourth Quarter

Figure A.26 I-80 Echo quarterly truck class histograms.

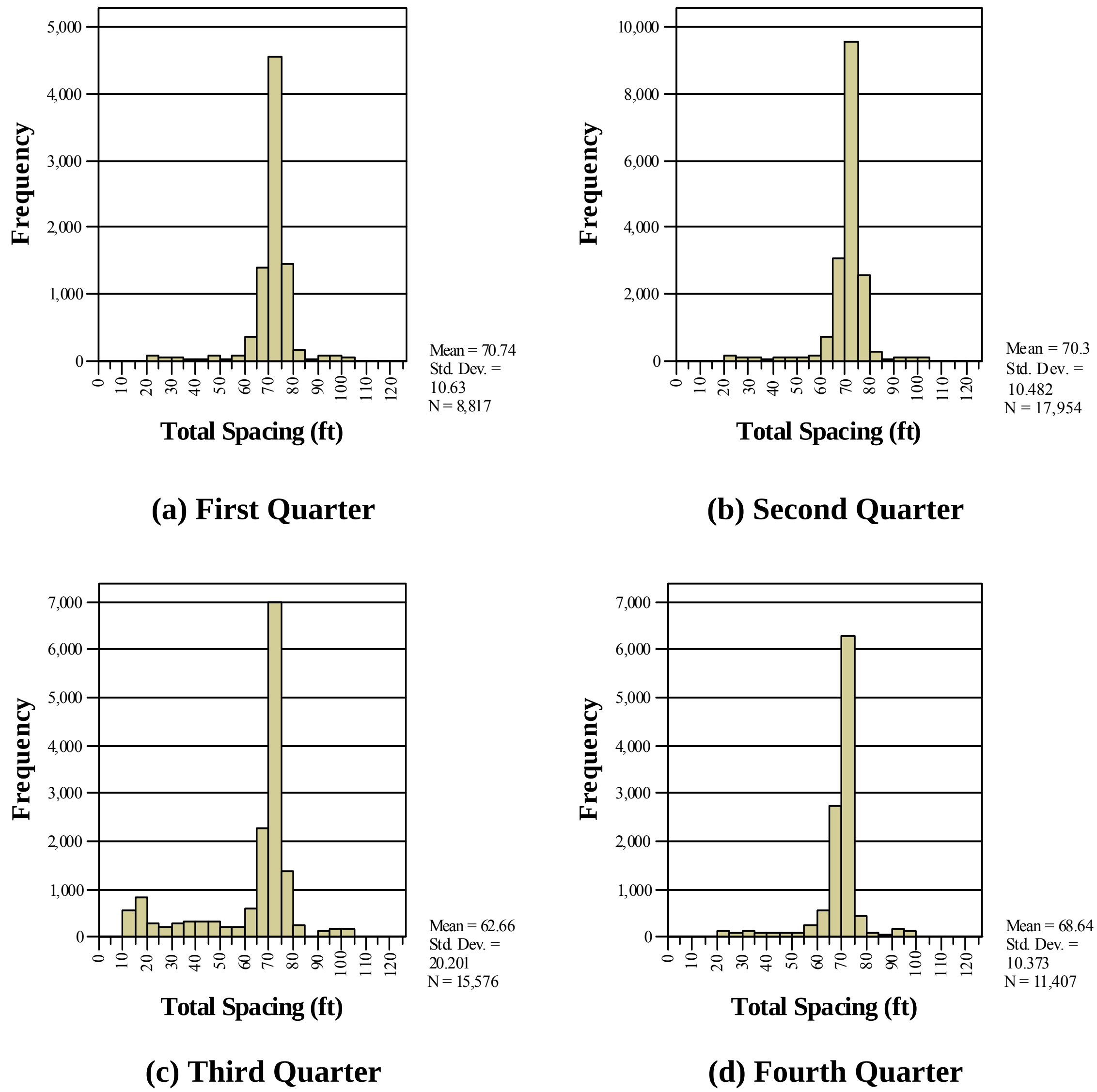
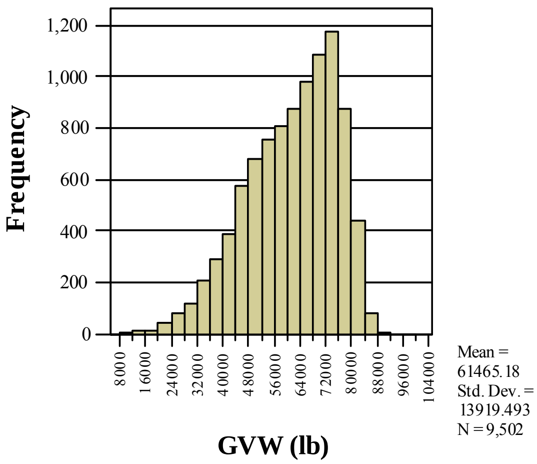
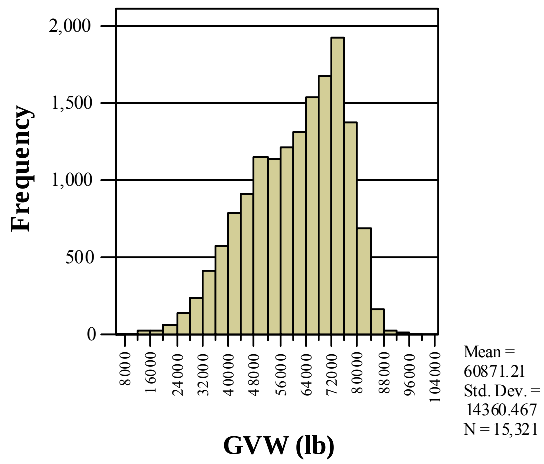


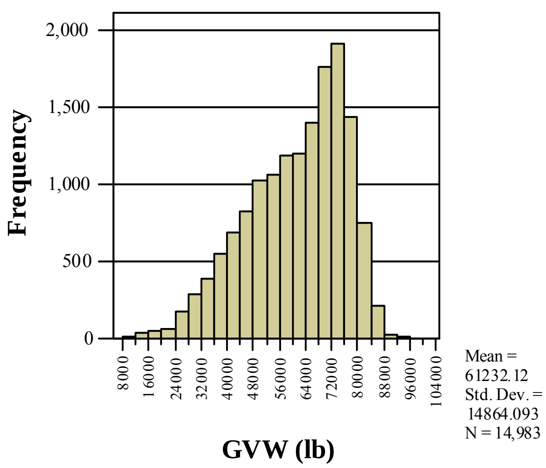
Figure A.27 I-80 Echo quarterly total spacing histogram of all vehicle classes.



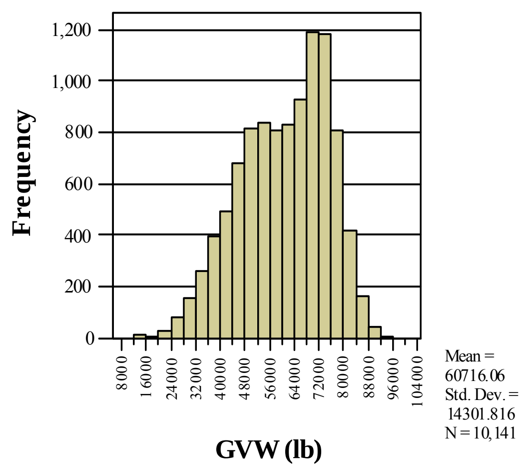
(a) First Quarter



(b) Second Quarter

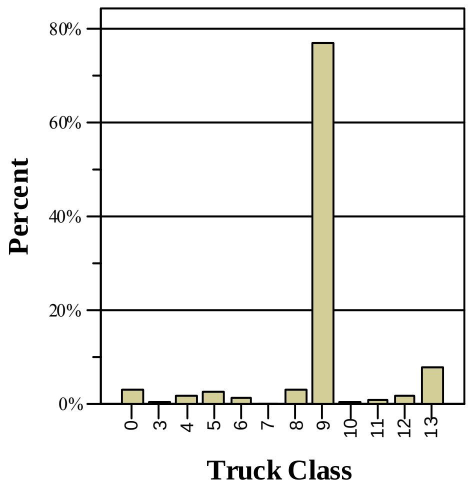


(c) Third Quarter

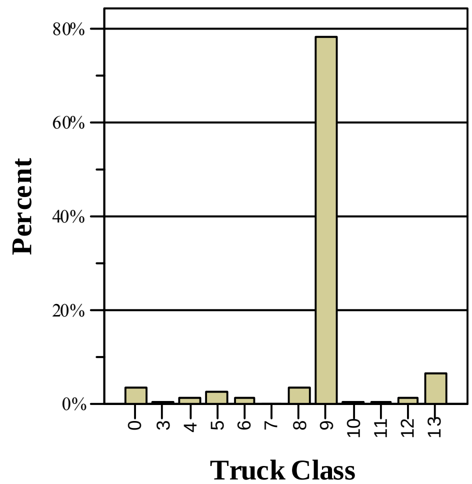


(d) Fourth Quarter

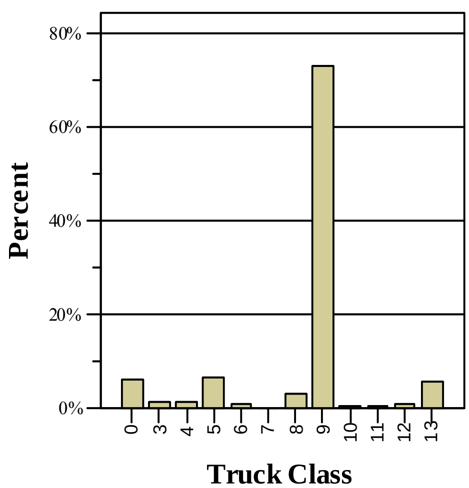
Figure A.28 I-80 Wendover quarterly GVW histograms of Class 9 vehicles.



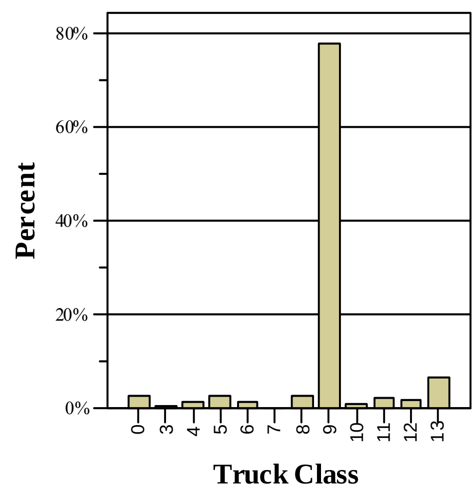
(a) First Quarter



(b) Second Quarter

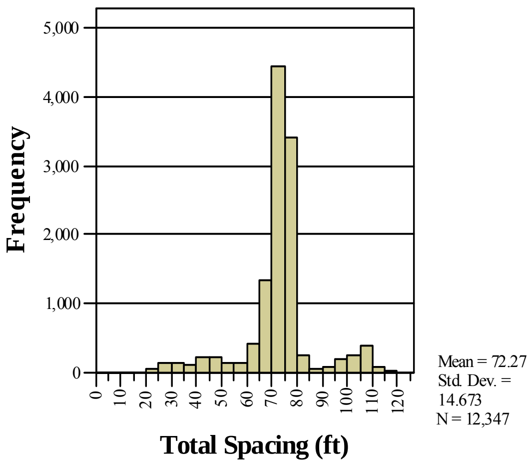


(c) Third Quarter

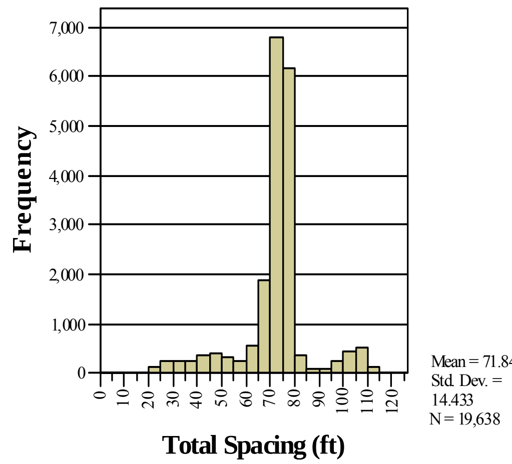


(d) Fourth Quarter

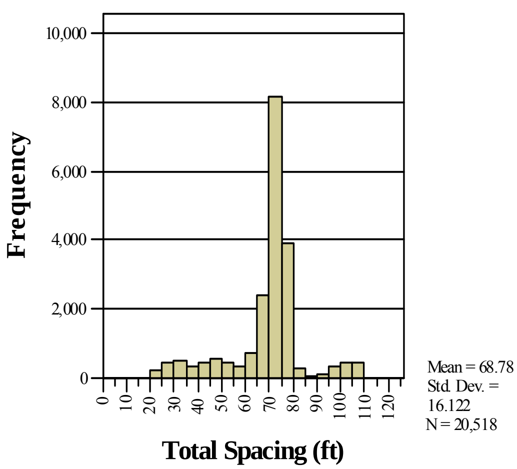
Figure A.29 I-80 Wendover quarterly truck class histograms.



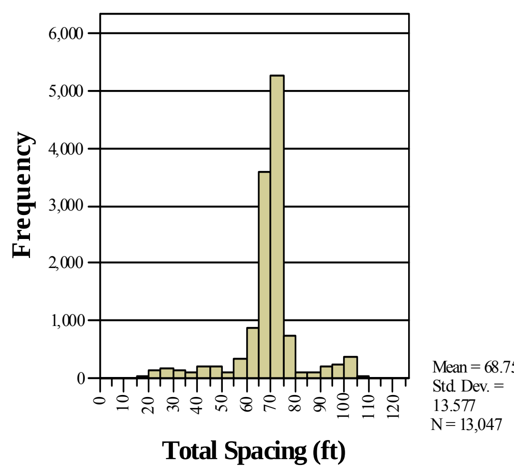
(a) First Quarter



(b) Second Quarter



(c) Third Quarter



(d) Fourth Quarter

Figure A.30 I-80 Wendover quarterly total spacing histogram of all vehicle classes.

Appendix B Lane Distribution Results

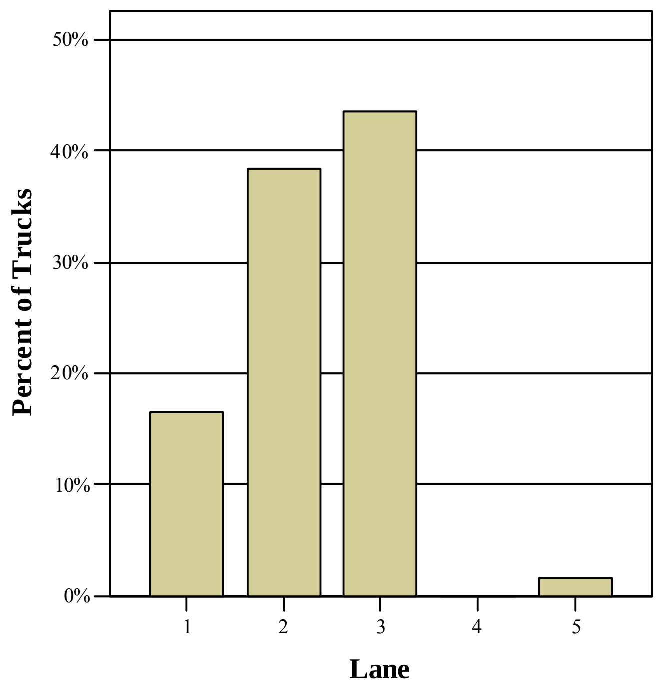


Figure B.1 I-15 400 North northbound percent of trucks in lane.

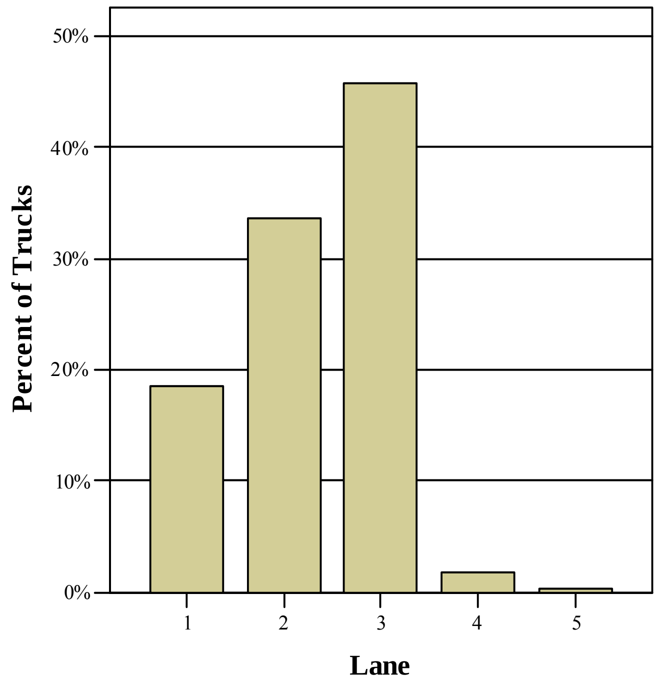


Figure B.2 I-15 400 North southbound percent of trucks in lane.

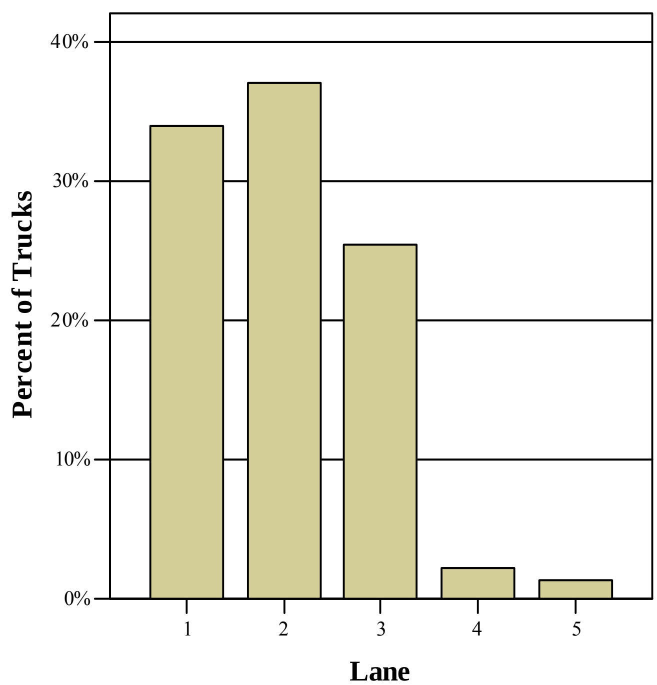


Figure B.3 I-15 1300 South northbound percent of trucks in lane.

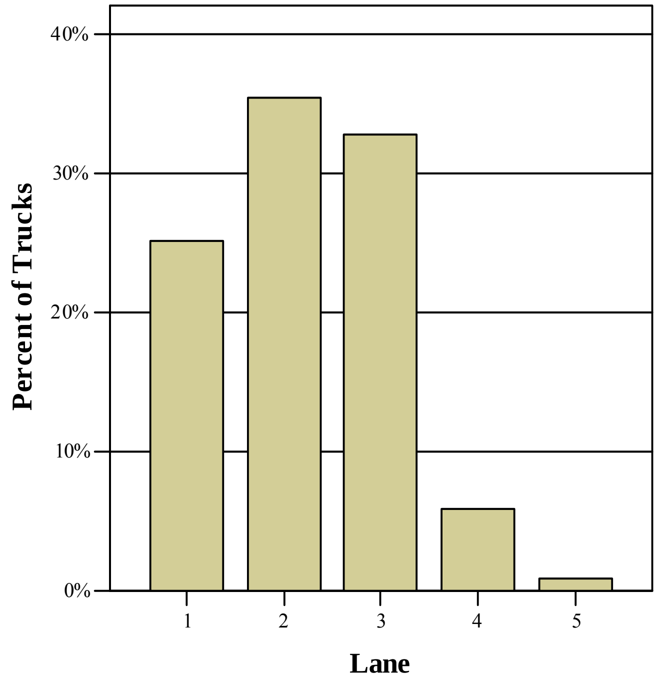


Figure B.4 I-15 1300 South southbound percent of trucks in lane.

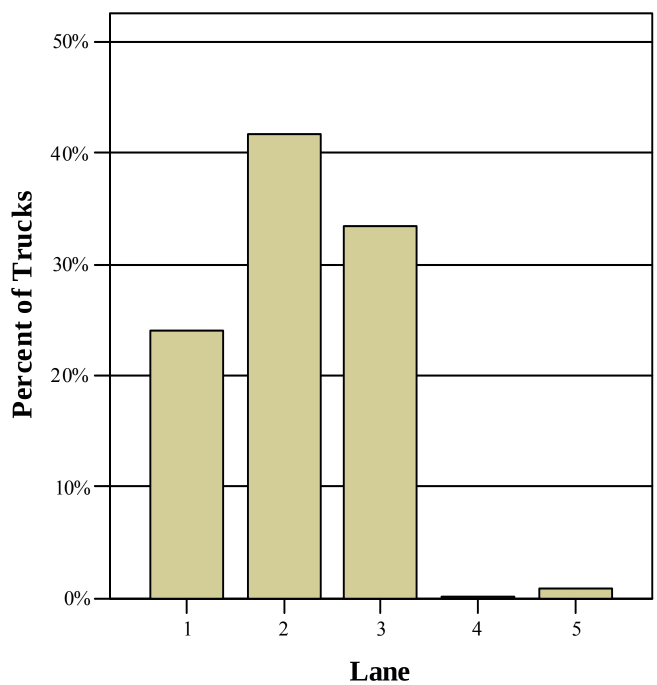


Figure B.5 I-15 5300 South northbound percent of trucks in lane.

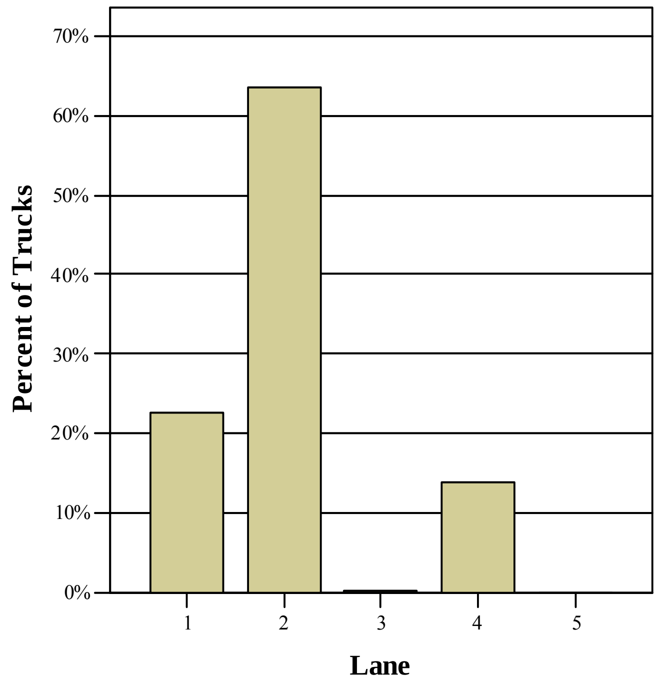


Figure B.6 I-15 5300 South southbound percent of trucks in lane.

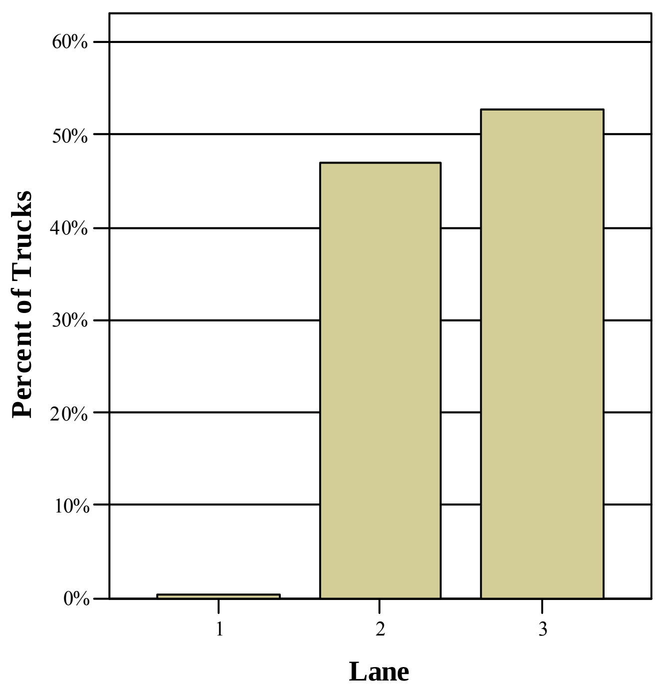


Figure B.7 I-15 10600 South northbound percent of trucks in lane.

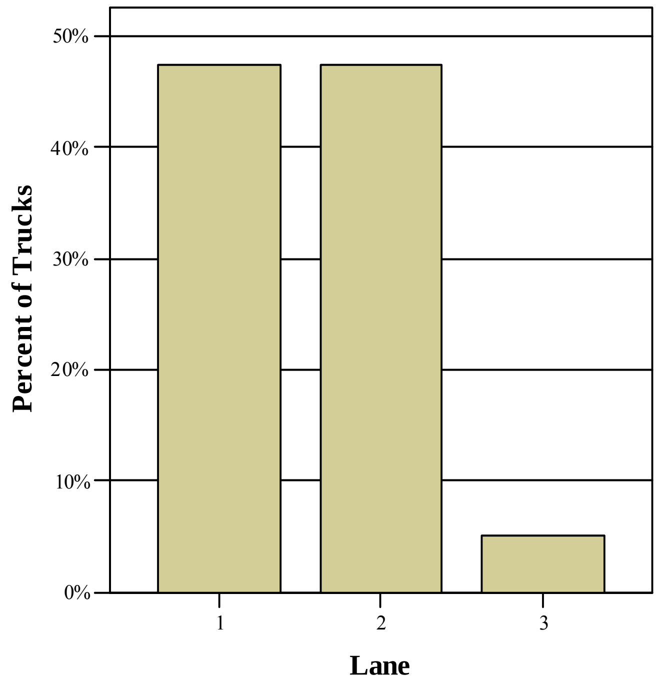


Figure B.8 I-15 10600 South southbound percent of trucks in lane.

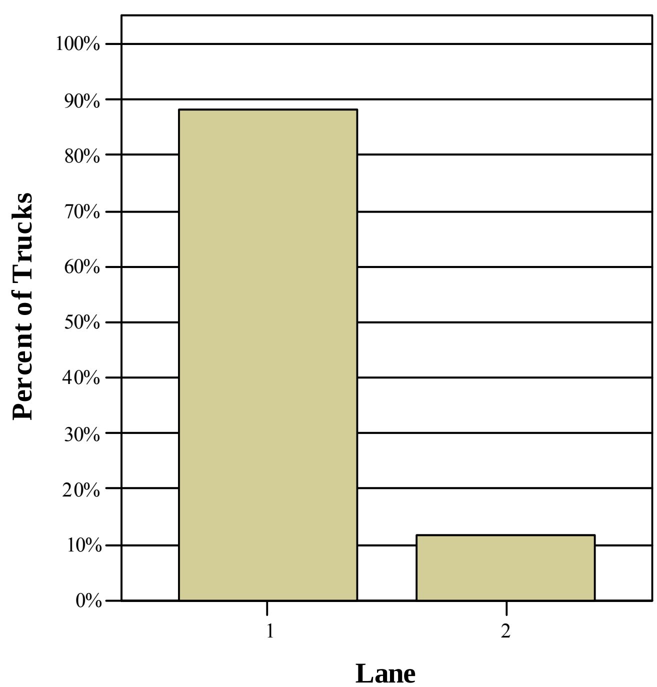


Figure B.9 I-15 Nephi northbound percent of trucks in lane.

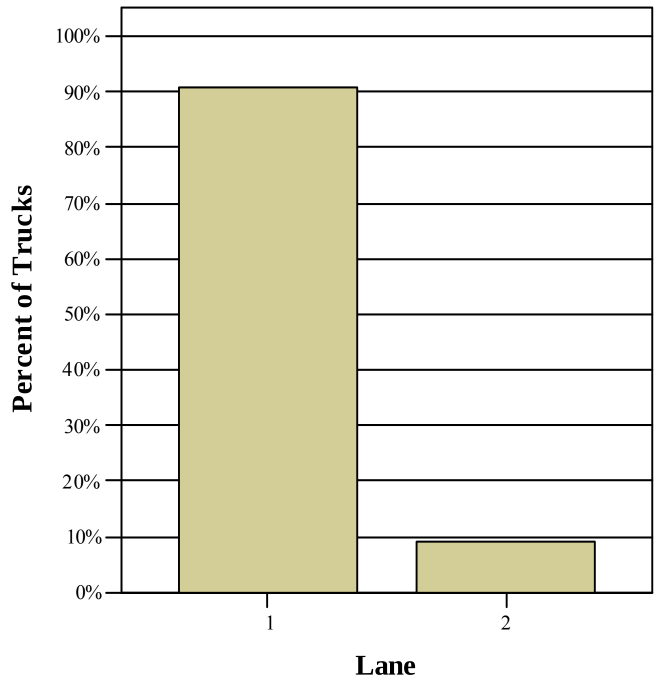


Figure B.10 I-15 Nephi southbound percent of trucks in lane.

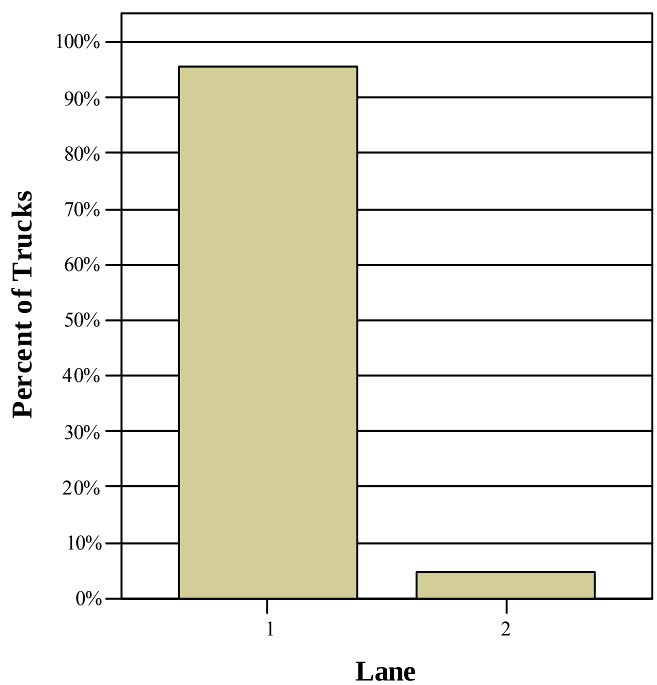


Figure B.11 I-15 Plymouth northbound percent of trucks in lane.

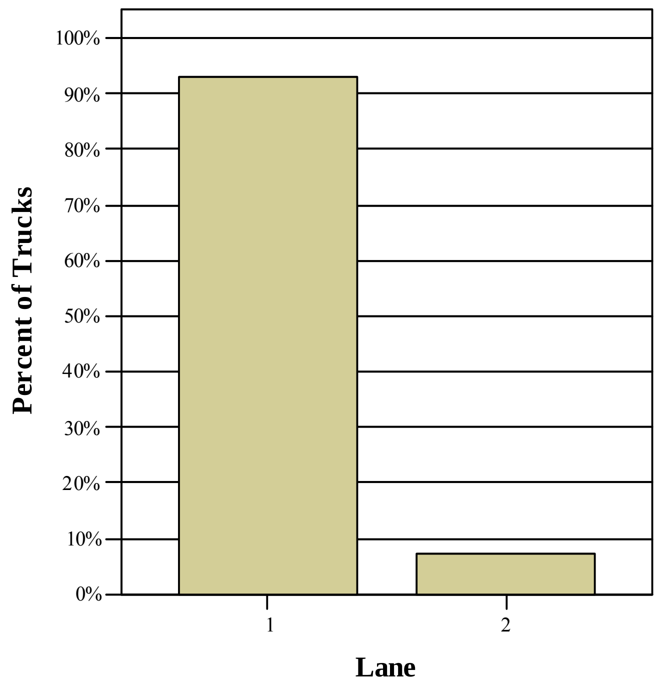


Figure B.12 I-15 Plymouth southbound percent of trucks in lane.

Appendix C Daily Average Steering-axle Weight Analysis

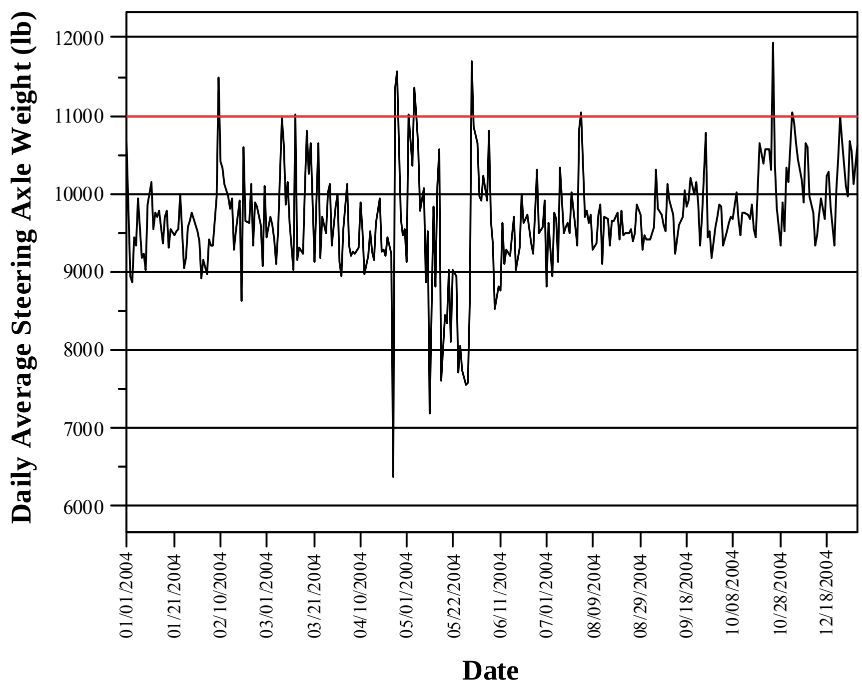


Figure C.1 I-15 400 North daily average steering-axle weight.

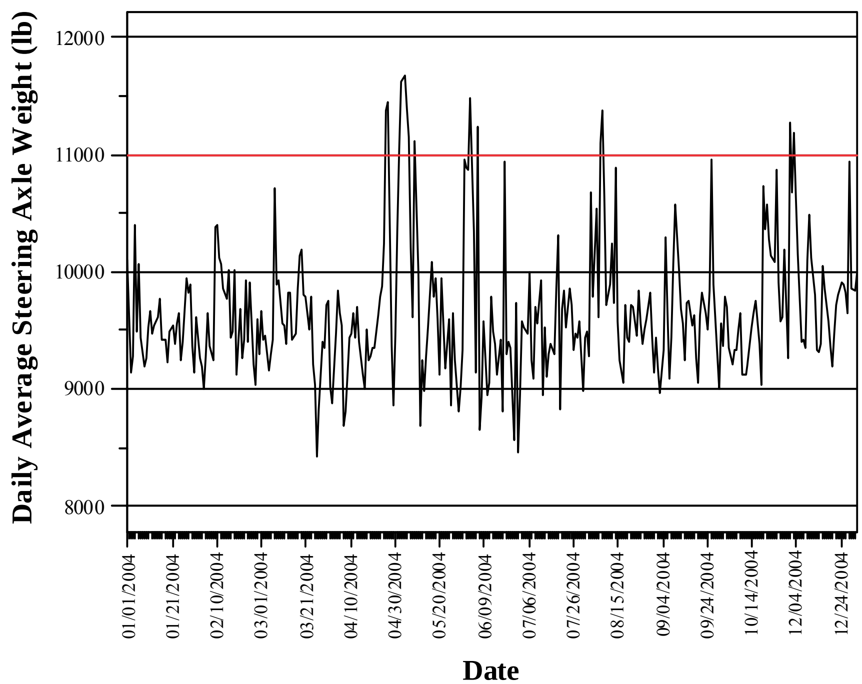


Figure C.2 I-15 1300 South daily average steering-axle weight.

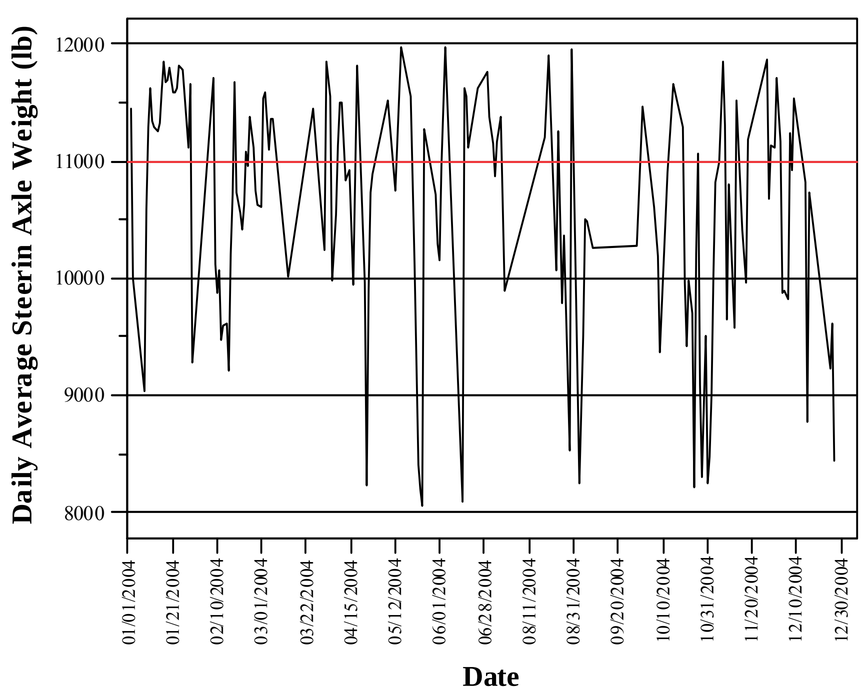


Figure C.3 I-15 5300 South daily average steering-axle weight.

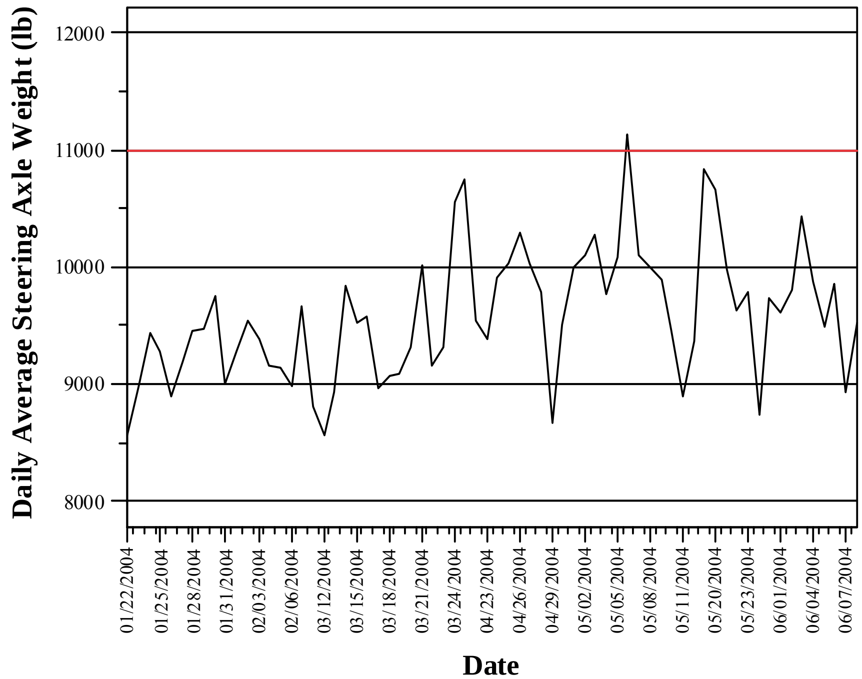


Figure C.4 I-15 10600 South daily average steering-axle weight.

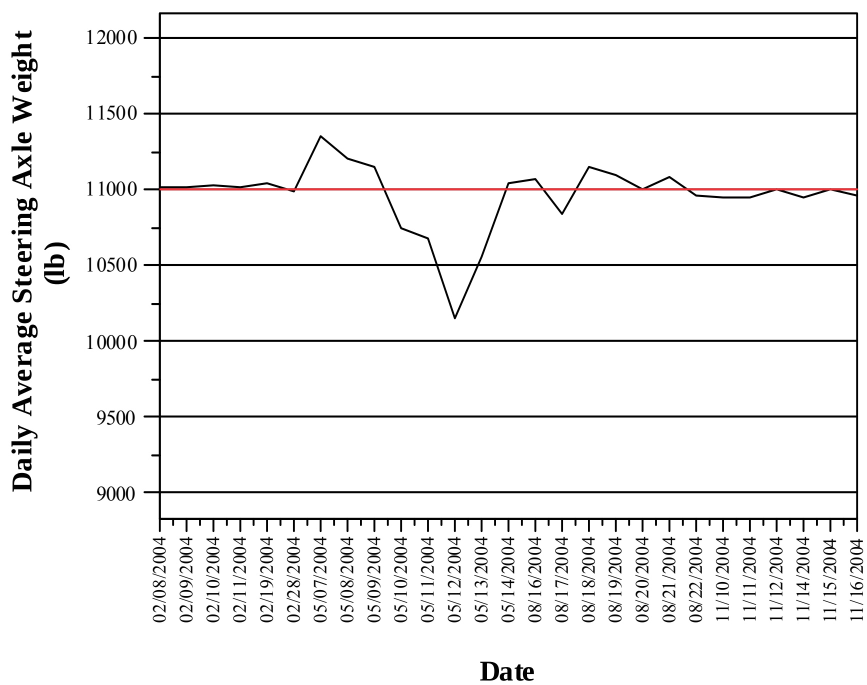


Figure C.5 I-15 Nephi daily average steering-axle weight.

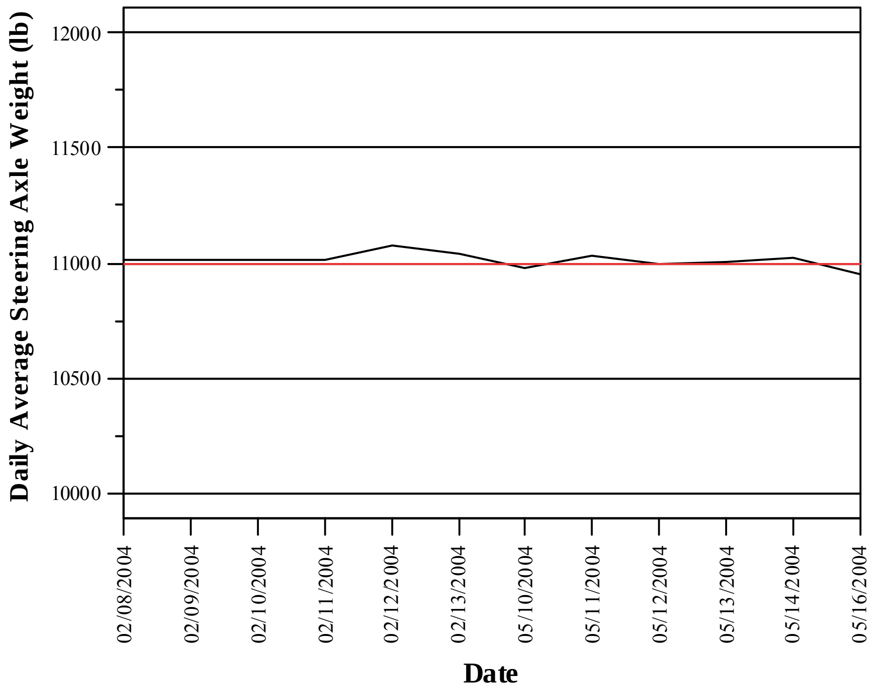


Figure C.6 I-15 Plymouth daily average steering-axle weight.

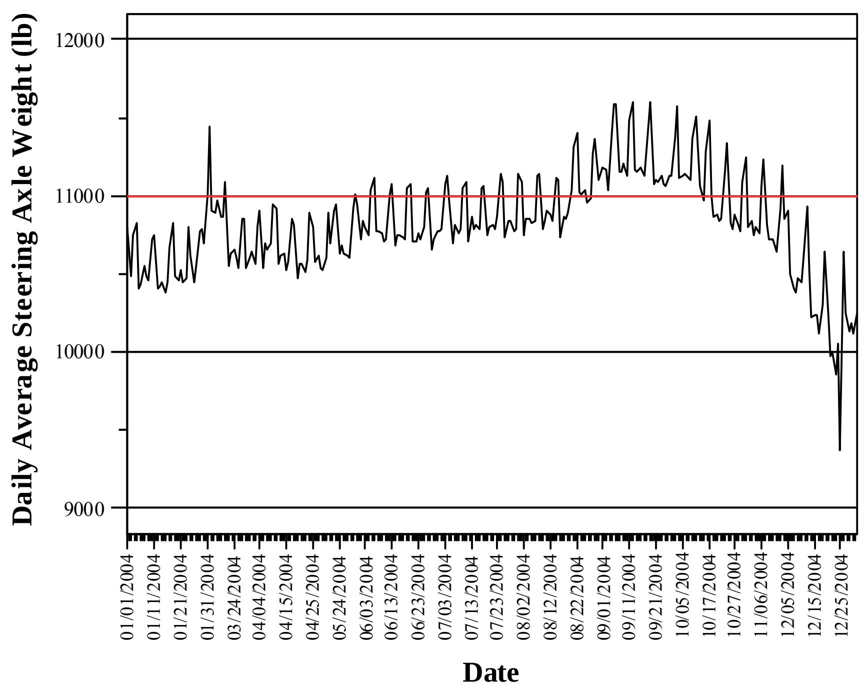


Figure C.7 I-15 Perry daily average steering-axle weight.

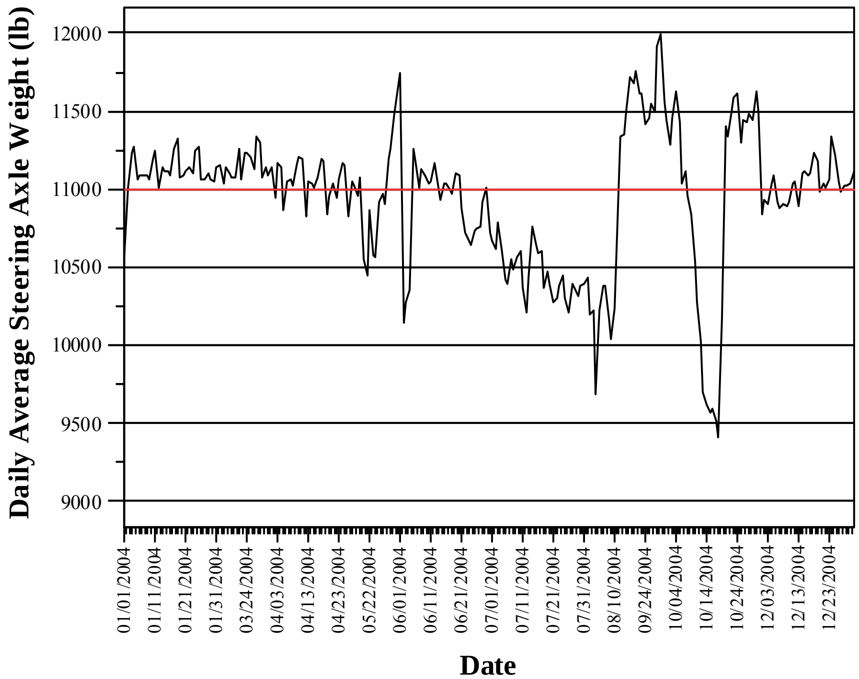


Figure C.8 I-15 St. George daily average steering-axle weight.

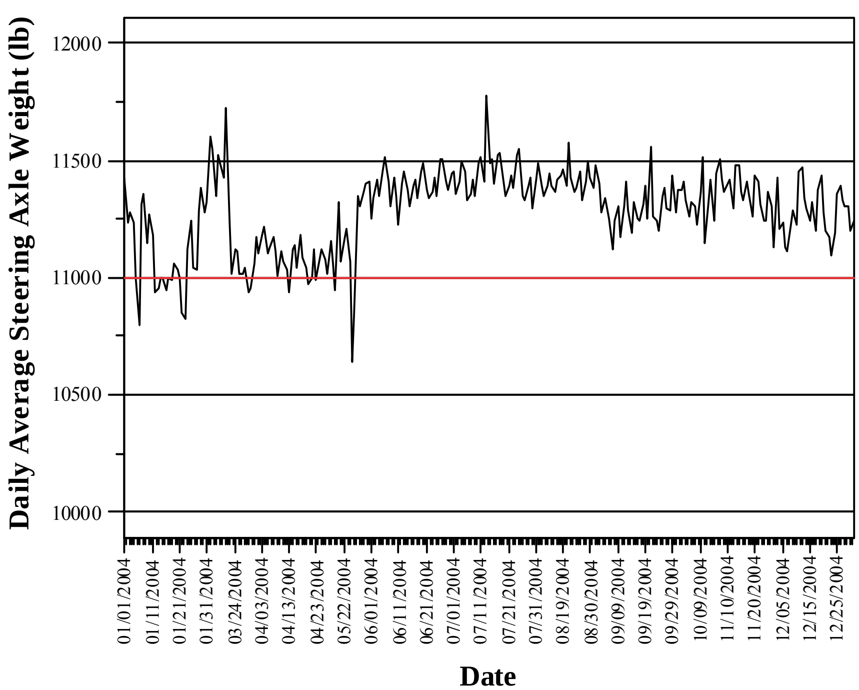


Figure C.9 I-80 Echo daily average steering-axle weight.

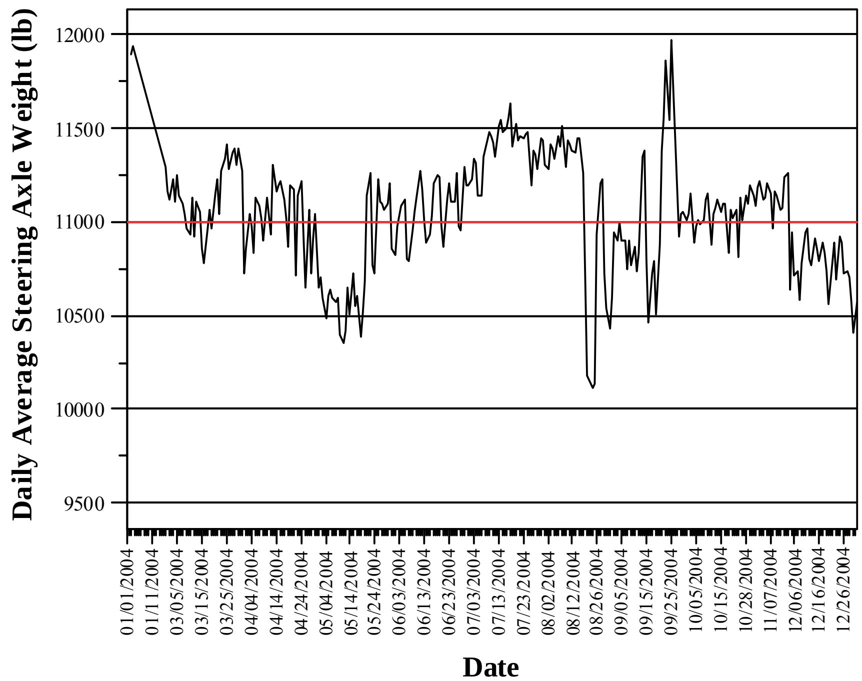


Figure C.10 I-80 Wendover daily average steering-axle weight.

Appendix D Temperature and Precipitation Data

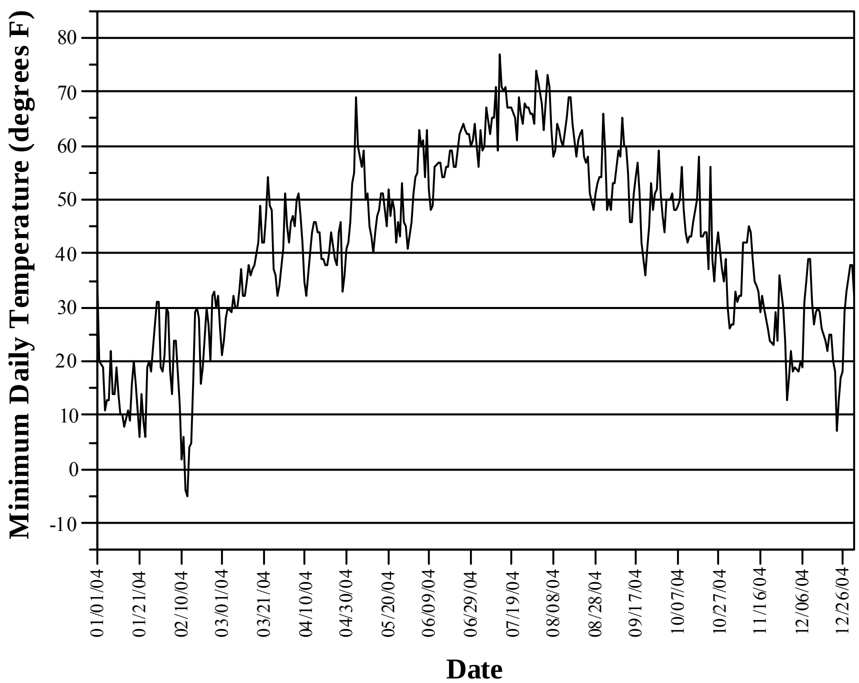


Figure D.1 Salt Lake City International Airport minimum daily temperature.

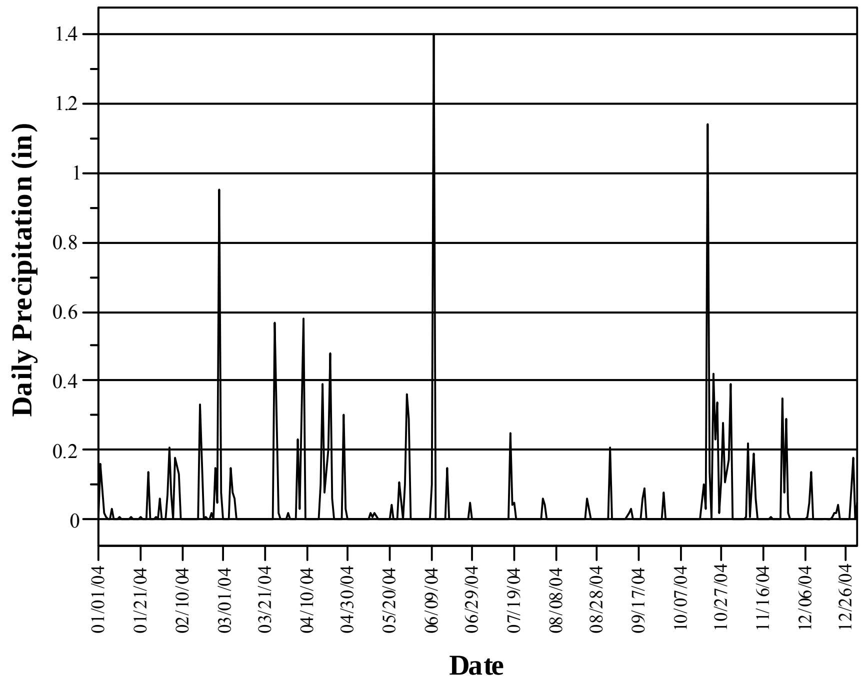


Figure D.2 Salt Lake City International Airport daily precipitation.

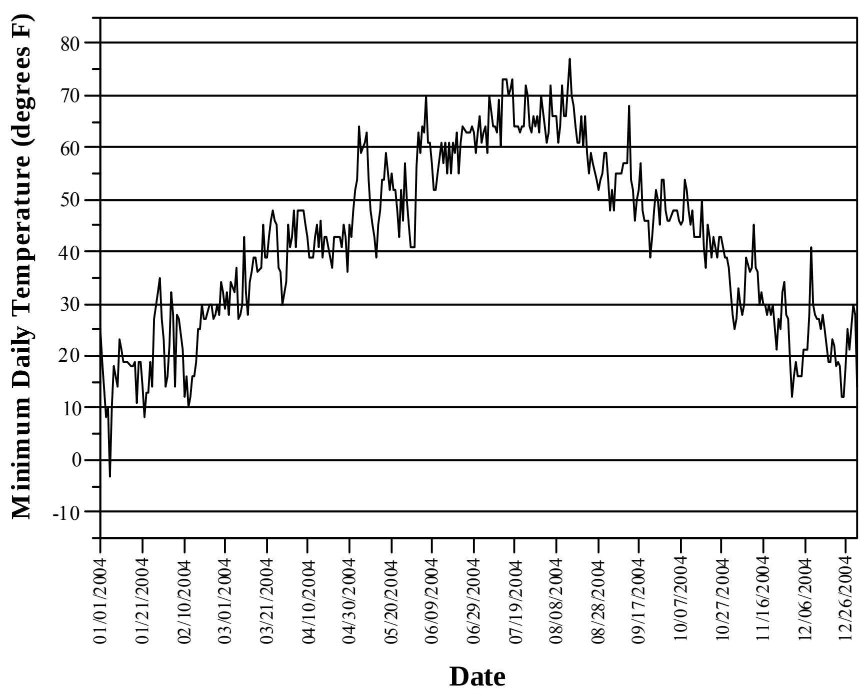


Figure D.3 Wendover minimum daily temperature.

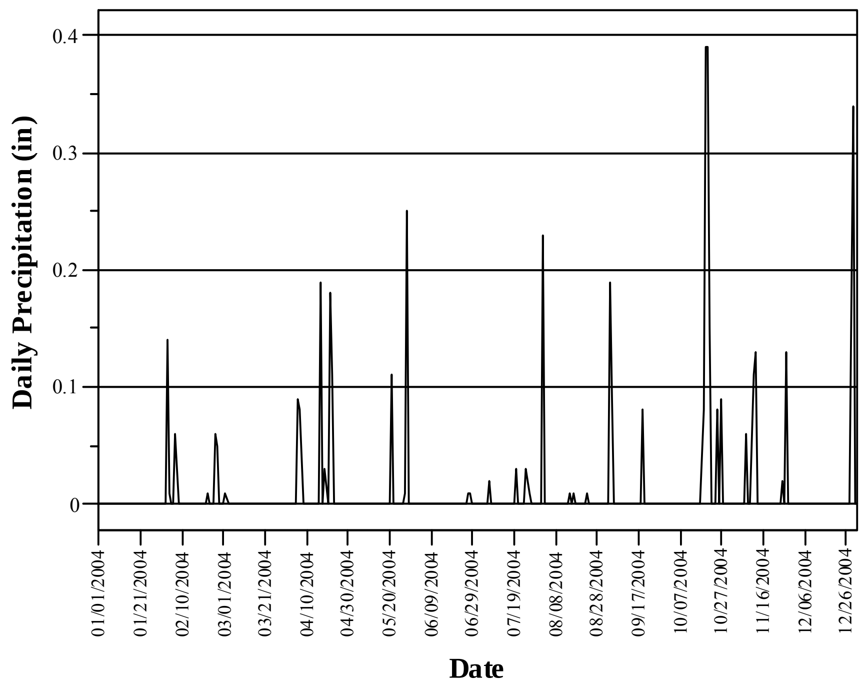


Figure D.4 Wendover daily precipitation.

Appendix E Daily Average Drive Tandem Spacing Analysis

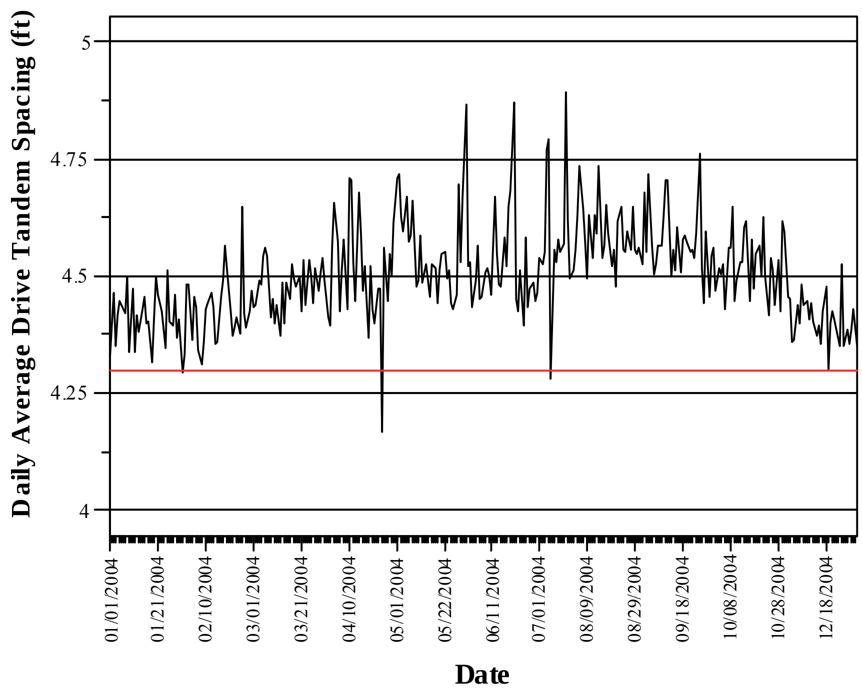


Figure E.1 I-15 400 North daily average drive tandem spacing.

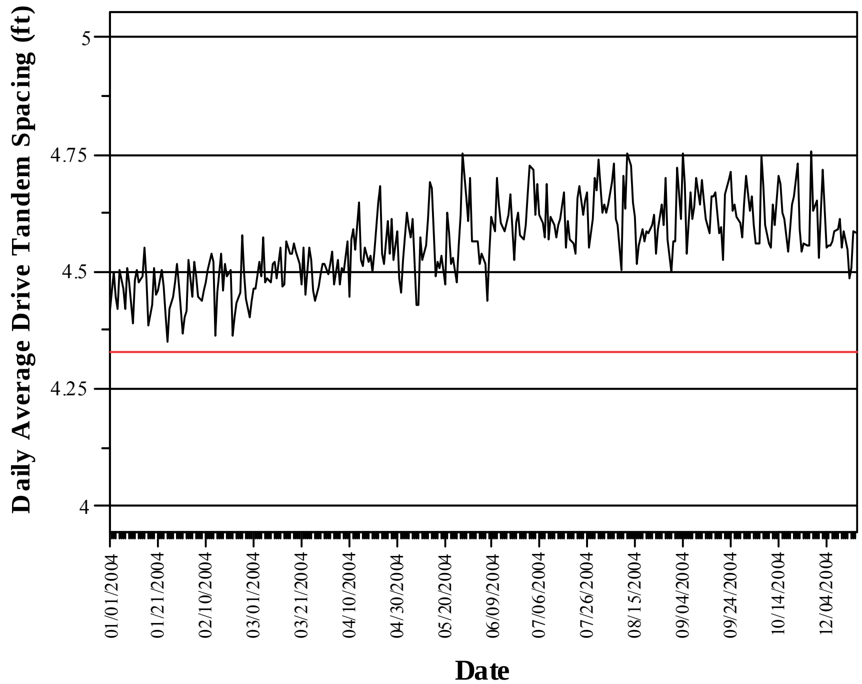


Figure E.2 I-15 1300 South daily average drive tandem spacing.

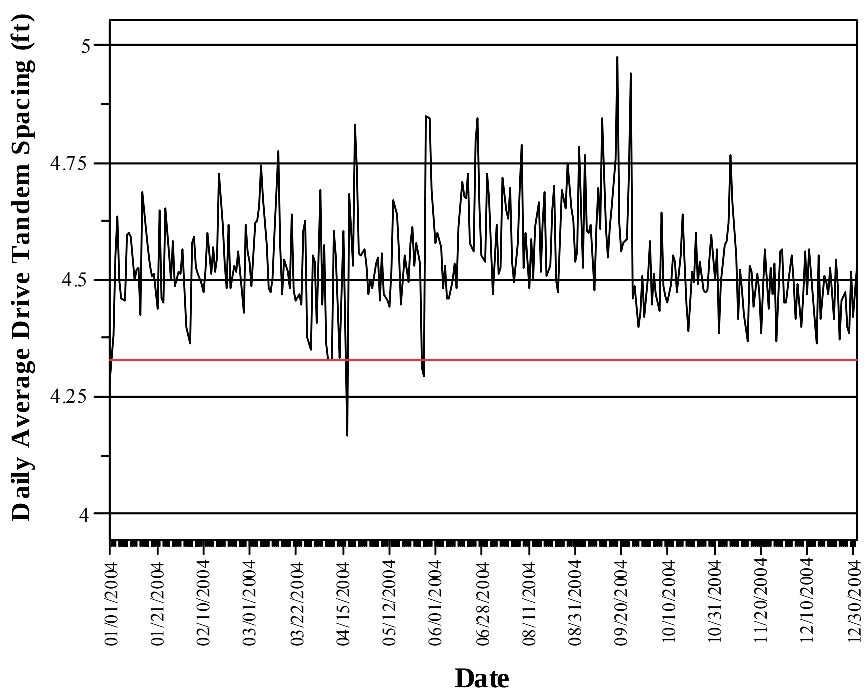


Figure E.3 I-15 5300 South daily average drive tandem spacing.

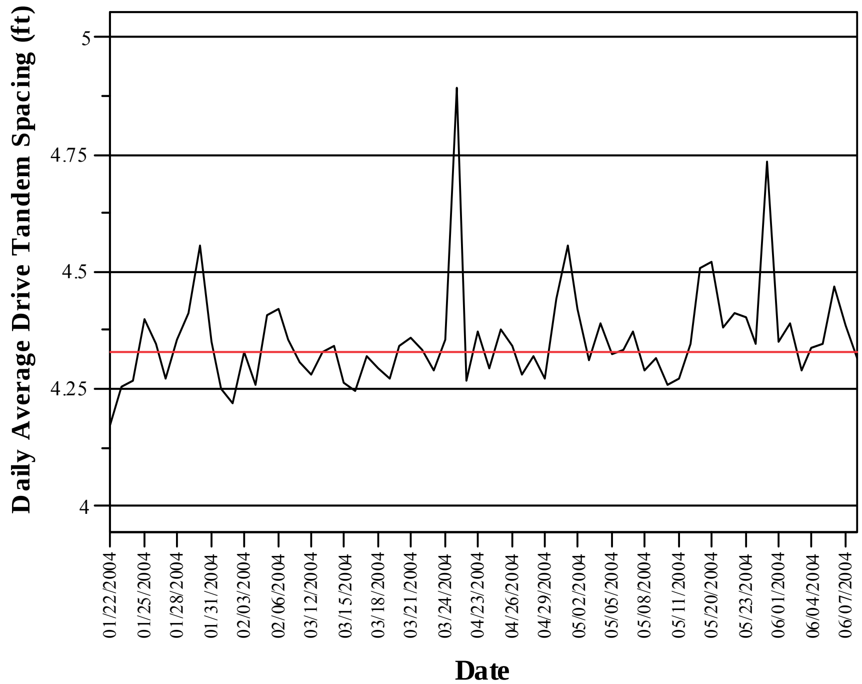


Figure E.4 I-15 10600 South daily average drive tandem spacing.

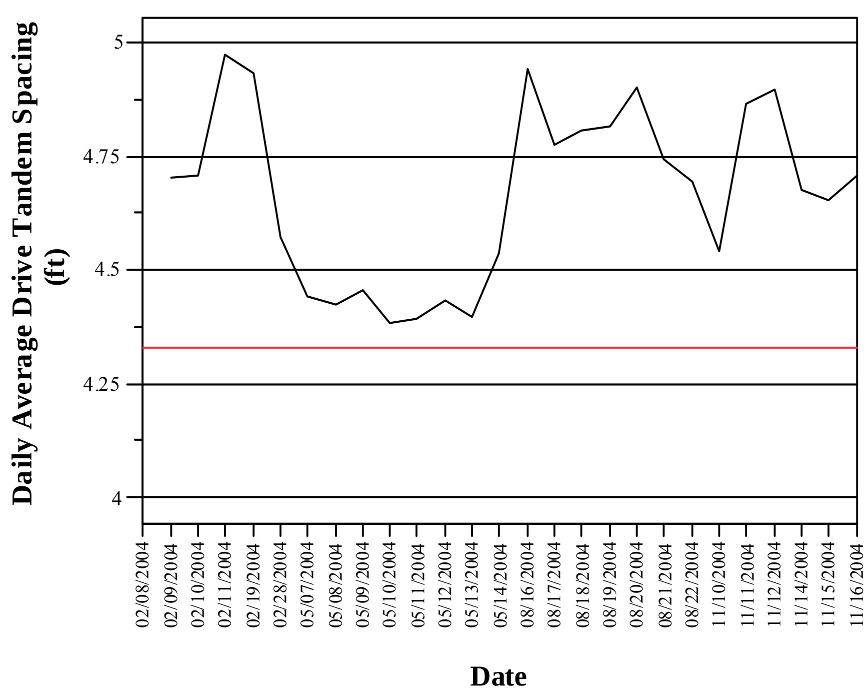


Figure E.5 I-15 Nephi daily average drive tandem spacing.

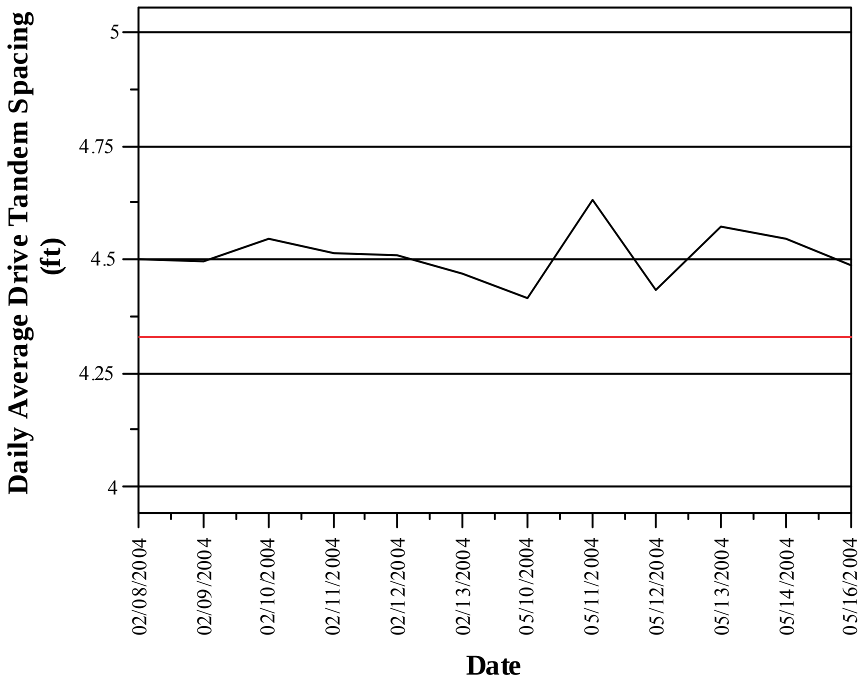


Figure E.6 I-15 Plymouth daily average drive tandem spacing.

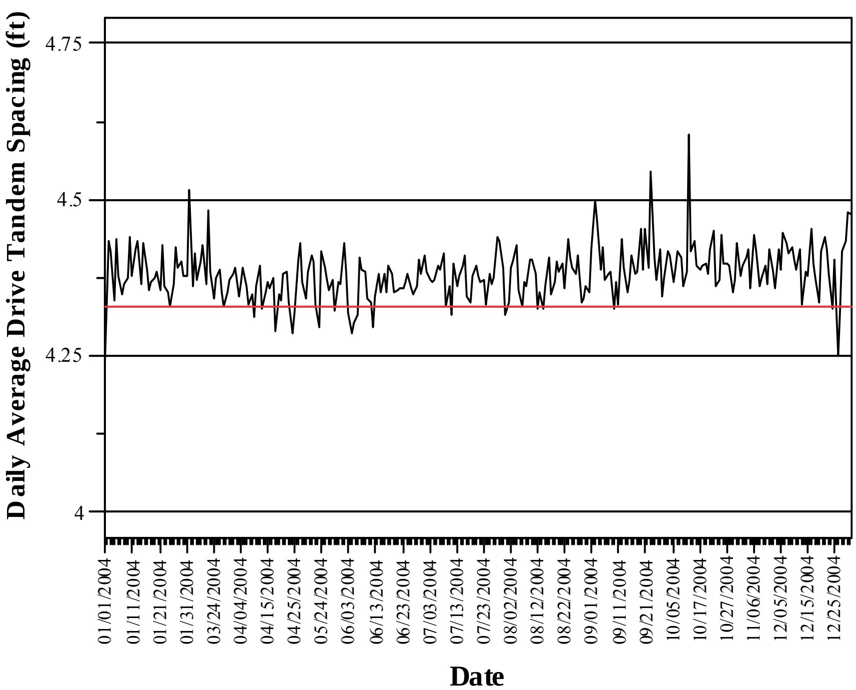


Figure E.7 I-15 Perry daily average drive tandem spacing.

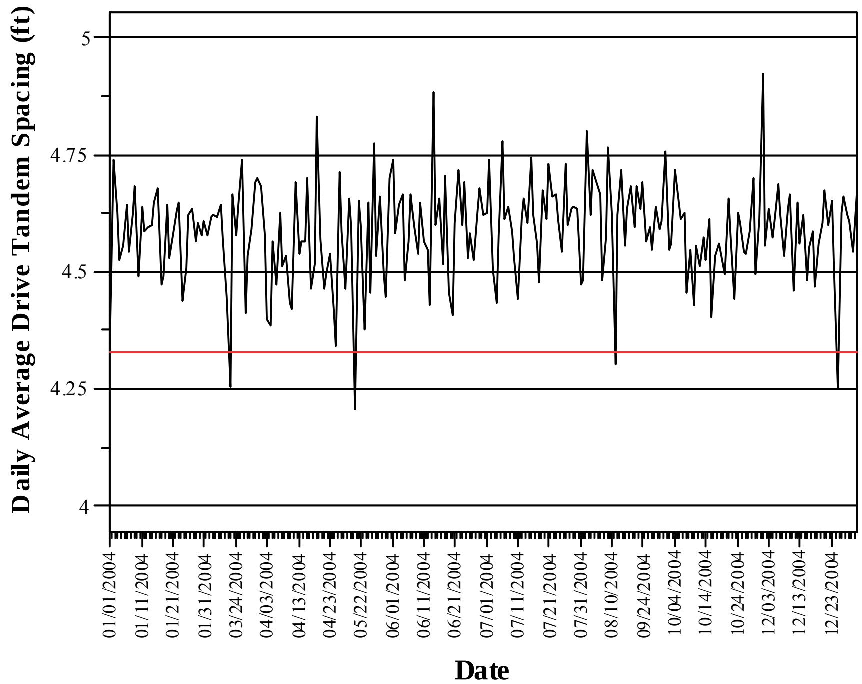


Figure E.8 I-15 St. George daily average drive tandem spacing.

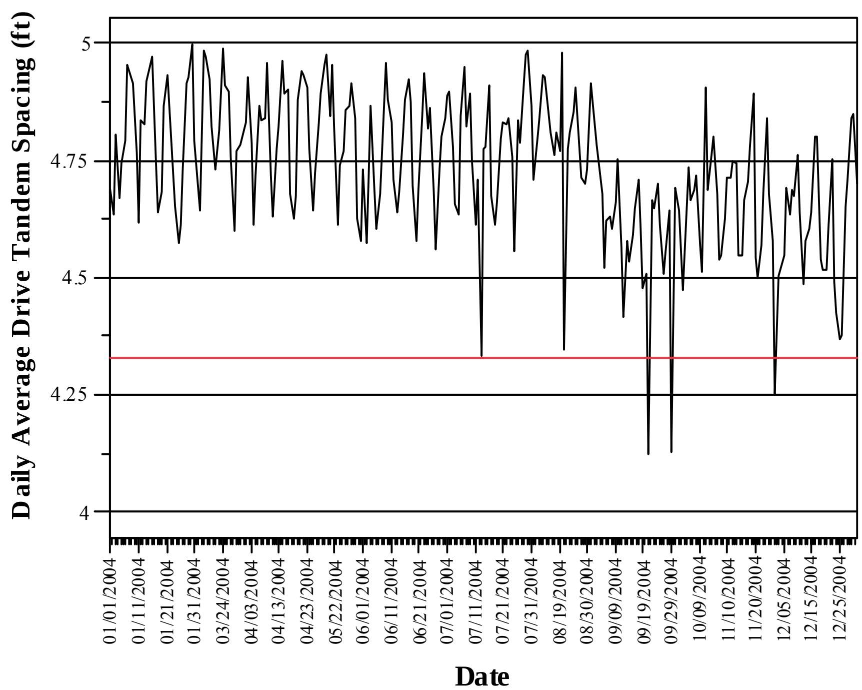


Figure E.9 I-80 Echo daily average drive tandem spacing.

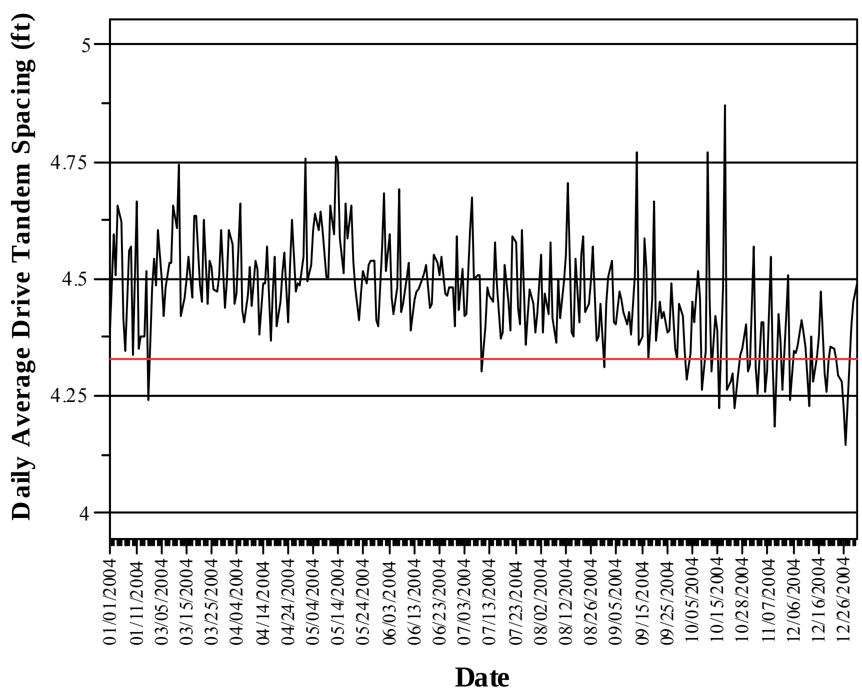


Figure E.10 I-80 Wendover daily average drive tandem spacing.