Options for Providing Quality Axle Load Data for Pavement Design

By

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ABSTRACT

This research evaluates four options to produce quality axle load data for pavement design: piezoelectric WIM sites (corrected and uncorrected data), static weigh scales, and a piezo-quartz WIM site. The evaluation applies four data quality principles: data validity, spatial coverage, temporal coverage, and data availability. While all principles are considered, the research contributes in the development and application of an integrated and sequential approach to assess data validity of the options by performing analyses to determine the precision and accuracy of axle load measurements. Within the context of Manitoba, the evaluation reveals that data produced by piezo-quartz and static weigh scales have superior validity, with piezo-quartz data offering better temporal coverage, data availability, and future geographic coverage. Ultimately, the selection of the best option for providing quality axle load data depends on the relative importance of data quality principles for producing data supporting sound pavement designs and infrastructure management decisions.

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1 INTRODUCTION

1.1 PURPOSE

This research evaluates options for providing quality axle load data for pavement design. In evaluating these options, the research develops and applies principles based on characteristics which help an axle load data monitoring program produce the quality data needed for sound infrastructure planning decisions. Three data sources are analyzed in this research: (1) static weigh scales, (2) Weigh-in-Motion (WIM) sites equipped with piezoelectric sensors, and (3) WIM sites equipped with piezo-quartz sensors. The results of this research provide insights into current axle load monitoring practices and future opportunities with axle load data.

1.2 BACKGROUND AND NEED

A common application of axle load data is to support design and management decisions regarding highway infrastructure. There are numerous potential sources of axle load data in North America, including WIM sites equipped with various types of technologies (e.g., piezoelectric, piezo-quartz, bending plates, load cells) and permanent weigh scales operated principally for enforcement purposes. Emerging axle load data sources such as bridge-WIM (BWIM) and on-board weighing equipment have the potential to provide axle load data in the future but currently are not prominent in North America. Each of these data sources has unique characteristics in terms of data quality and the ability to adequately represent the spatial and temporal variability of axle loads. There is a need to evaluate the quality of axle load data as jurisdictions seek to utilize available data to support improved highway infrastructure and design decisions (Lu and Harvey, 2006; Swan et al., 2008; Ishak et al., 2010; Jablonski et al., 2010; Sayyady et al., 2010; Smith and Diefenderfer, 2010; Haider et al., 2011; Wang et al., 2011; Mallela et al., 2013; Nassiri et al., 2013).

The need for quality data to design and manage highway infrastructure has long been a focus of jurisdictions in North America. Three landmark initiatives within the last 30 years highlight this need:

- The Long Term Pavement Performance (LTPP) program, launched in the late 1980's and operating as part of the Federal Highway Administration (FHWA), is a primary organization concerned with improving the service life of pavements (FHWA, 2010; Walker and Cebon, 2011; FHWA, 2017). Determining the effects of axle loads on pavement performance has been a key objective of the LTPP program.
- The pavement design methods set out by the American Association of State Highway and Transportation Officials (AASHTO) in 1993 require the calculation of the expected number of equivalent single axle loads (ESALs) as a key design parameter. An ESAL is a standard unit of pavement damage that depends on load, axle group, and other factors. (AASHTO, 1993).
- The pavement design method set out by the Mechanistic Empirical Pavement Design Guide (MEPDG) features significant changes over the AASHTO design method, including the requirement of detailed axle load distributions, referred to as Axle Load Spectra (ALS) (AASHTO, 2015). Specified axle load conditions have shown to have a significant impact on the final design and performance of pavement structures (Prozzi et al., 2008; Haider et al., 2010; Smith and Diefenderfer, 2010; Ahammed et al., 2011; Nassiri et al., 2013, Tarefder and Rodriguez-Ruiz, 2013; Selezneva et al., 2016).

Currently, many North American jurisdictions are making advances to axle load data monitoring programs to enable the production of ALS to support implementation of mechanistic-empirical (ME) pavement design methods. In many cases, the axle load data available at WIM sites are essential to this process. However, there is concern about the quality of the data produced by these sites, the spatial and temporal representativeness of the data, and the long-term sustainability of the data source. Moreover, jurisdictions are interested in the possibility of leveraging the axle load data provided by static scales for pavement design purposes, even though this data is typically collected for truck weight enforcement purposes. This thesis aims to address these issues.

1.3 OBJECTIVES AND SCOPE

The objectives of this research follow:

1. Develop an inventory of potential axle load data sources and review the importance of axle load data for evolving pavement design methods.
2. Establish relevant data quality principles related to axle load data monitoring programs and develop a method to evaluate the sources of axle load data against these principles.
3. Analyze the quality of data produced from: (1) static weigh scales, (2) WIM sites equipped with piezoelectric sensors, and (3) WIM sites equipped with piezo-quartz sensors.
4. Discuss options for providing quality axle load data within an axle load data monitoring program.

The scope of this research is constrained to the following:

- This research only considers data produced by traffic monitoring equipment located within the Province of Manitoba. However, results and lessons from this research are transferrable to other jurisdictions facing similar challenges.
- This research does not attempt to determine the sensitivity of pavement designs or performance to the quality of axle load distributions; rather, it focuses on the assessing axle load data quality unto itself.
- This research does not consider the effects of axle load data quality on vehicle weight enforcement programs, nor does it evaluate the effectiveness of Motor Carrier Enforcement in Manitoba.
- This research is not intended to provide specific recommendations regarding current and future axle load data monitoring programs. The intent is rather to highlight the lessons learned from the analyses and evaluations which may assist a jurisdiction in developing or updating an axle load data monitoring program.

1.4 APPROACH

This research considers three options for providing axle load data in Manitoba: (1) three static weigh scales, (2) six piezoelectric WIM sites, and (3) a piezo-quartz WIM site. To evaluate the data provided by these options, the research establishes relevant data quality principles that take into consideration the validity of data, the geographic/temporal scope of data, and present/future data availability. While all principles are considered in the evaluation, particular attention is given to the principle of data validity.

The evaluation approach enables an integrated and sequential assessment of the validity of data available from these three data sources. As an initial step, the quality of data produced at static weigh scales equipped with load cell technology is evaluated by studying operational practices and investigating the precision of axle load measurements observed at the scales. Based on the quality of data produced at these static scales, the quality of axle load data from the piezo-quartz WIM site is evaluated by means of matching it to axle load data for the same group of vehicles as observed at the static weigh scale. Axle load data matches are made on a vehicle-by-vehicle basis and compared to relevant industry standards.

Data from the static scale is also studied to establish a “ground truth” of month-to-month precision of certain characteristic axle loads produced by specific truck configurations. Data quality from piezoelectric WIM equipment is evaluated based on the ability of the equipment to replicate these known precise axle load measurements. It is anticipated that data quality issues at these piezoelectric WIM sites are caused by external conditions such as pavement temperature. Therefore, the effects of temperature are investigated on a site-by-site basis and efforts are made to improve data quality by compensating for these effects. Finally, data produced by these sources undergo standard data quality checks to identify potentially uncharacteristic axle loads and identify potential issues with the data.

1.5 THESIS ORGANIZATION

This thesis is organized into five chapters:

Chapter 2 – Sources and Applications of Axle Load Data: This chapter introduces types of WIM equipment and discusses methods of data evaluation and historical validity of data. Next, the need for quality axle load data in the context of pavement design is discussed, as well as the historical sensitivity of pavement design to axle load data. Finally, the current state-of-practice of pavement design in North America is presented.

Chapter 3 – Research Methodology: This chapter provides an inventory and characteristics of available sources of axle load data in Manitoba. Next, the approach to evaluating these axle load data sources is discussed. Finally, the methodologies and analyses behind data evaluation are described.

Chapter 4 – Analysis: This chapter presents the results of the data analyses, and evaluates the axle load data sources against relevant data quality principles.

Chapter 5 – Conclusions: This chapter outlines the conclusions drawn from this research, and discusses implications to the design and management of highway infrastructure as well as opportunities to enhance axle load data monitoring programs.

1.6 TERMINOLOGY

The following are terms used throughout this research:

Accuracy – The closeness or degree of agreement between a measured value and an accepted reference value.

Annual Average Daily Truck Traffic (AADTT) – The number of trucks passing a point on a stretch of road on an average day of the year.

Automatic Vehicle Classifier (AVC) – Equipment collecting vehicle speed, count, classification, and axle spacing data.

Axle Group – A defined group of adjacent axles. Includes steering axles, single axles, tandem axles, and tridem axles.

Axle Load – The sum of all tire loads of the wheels on an axle; a portion of the gross vehicle weight.

Axle Load Data Monitoring Program – A system of axle load data sources installed, operated and maintained on a highway network.

Calibration – The adjustment of WIM system settings to produce valid loads, based on trial load measurements of test vehicles of known axle loads, axle group loads, and gross vehicle weight.

Data Quality – The ability for data to represent actual conditions and be reasonably attained and developed. This includes validity, and the ability to represent good geographic/temporal coverage.

Equivalent Single Axle Load (ESAL) – A standard reference unit describing the degree of pavement damage caused by a single axle of 80 kN, with tires inflated to 586 kPa.

Gross Vehicle Weight (GVW) – The combined loads of all tires on all axles of a vehicle.

Mechanistic-Empirical (ME) – A pavement design approach involving aspects of calculating pavement responses, such as stresses, strains and deflections (mechanistic component), and computing incremental damage over time (empirical component).

Precision – The ability to produce stable and consistent results.

Steering Axle – The articulated axle or axle group of a vehicle that is controlled by the driver in managing the direction travelled by the vehicle, or an articulated axle on a trailer or semi-trailer where the direction of travel of the trailer is controlled by the towing unit (Manitoba Infrastructure, 2017a).

Single Axle – One axle or two consecutive axles having a spread of less than 1.0 m (Manitoba Infrastructure, 2017a).

Tandem Axle – Two or more equally spaced consecutive axles having an axle spread of not less than 1.0 m nor more than 1.85 m that are designated to automatically distribute the load so that gross axle weight on each single axle does not exceed the maximum prescribed for a single axle (Manitoba Infrastructure, 2017a)

Tridem Axle – Three equally spaced consecutive axles, having an axle spread of not less than 2.4 m nor more than 3.7 m and which are designed to automatically distribute the load so that the gross axle weight on each single axle does not exceed the maximum prescribed for a single axle and so that the gross axle weight on any two adjacent single axles does not exceed the maximum prescribed for a tandem axle (Manitoba Infrastructure, 2017a).

Validity – The ability of measuring a value that is intended to be measured. Validity includes elements of both accuracy and precision.

Verification – The evaluation of WIM system performance based on trial load measurements of test vehicles of known axle loads, axle group loads, and gross vehicle weight.

Weigh in Motion (WIM) – The process of estimating a vehicle's gross vehicle weight and the weights of individual axles or axle groups by measurement and analysis of dynamic tire forces.

2 SOURCES AND APPLICATIONS OF AXLE LOAD DATA

This chapter introduces types of WIM equipment and discusses methods of data evaluation and historical validity of data. Next, the need for quality axle load data in the context of pavement design is discussed, as well as the historical sensitivity of pavement design to axle load data. Finally, the current state-of-practice of pavement design in North America is presented.

2.1 TYPES OF WEIGH IN MOTION

The American Society of Testing and Materials (ASTM) defines WIM as the process of estimating a vehicle's gross vehicle weight (GVW) and the weights of individual axles or axle groups by measurement and analysis of dynamic vehicle tire forces (ASTM, 2009). A typical WIM system consists of three broad components (FHWA, 2009):

- A scale or series of sensors installed either on the main highway or a side ramp which measure the loads created by passing vehicles/axles.
- A roadside processing cabinet which converts the load measurements into axle weights and GVWs.
- A communication system which transmits weight data to enforcement agencies or to WIM databases where the data can be further processed and analysed.

ASTM further classifies WIM systems into four different types: *type I*, *type II*, *type III*, and *type IV*:

- ASTM defines a *type I* system as an installation in one or more lanes of traffic, capable of accommodating highway vehicles operating at speeds from 15 to 130 km/h. Typical data items produced by a *type I* WIM system include: wheel loads, axle loads, axle-group loads, GVW, speed, axle spacing, vehicle classification, lane/direction of travel, date/time of passage, wheelbase, equivalent single axle loads (ESALs), and other codes/vehicle record numbers.

- ASTM defines a *type II* WIM system as an installation in one or more lanes of traffic capable of accommodating highway vehicles operating at speeds from 25 to 130 km/h. *Type II* WIM systems produce the same data items as *type I* WIM systems, with the exception of individual wheel loads.
- *Type III* WIM systems are installed in one or more lanes of traffic or in one or more lanes off the highway at weigh enforcement stations. These systems weigh vehicles operating at speeds from 15 to 130 km/h, which are suspected of weight-limit violations. *Type III* WIM systems produce the same data as *type I* WIM systems, with the exception of vehicle classification, wheelbase, and ESALs.
- *Type IV* WIM systems are used at weight enforcement stations to detect weight limit violations. These systems weigh vehicles operating at speeds from 3 to 15 km/h, and use tire-force sensors that support the entire tire-contact areas of all tires on a wheel assembly simultaneously. *Type IV* WIM systems produce the same data as *type I* WIM systems, with the exception of vehicle classification, lane/direction of travel, wheelbase, and ESALs.

FHWA identifies four main types of WIM technologies (FHWA, 2015): piezoelectric sensors, piezo-quartz sensors, bending plate, and load cell. BWIM is a fifth technology identified. Piezoelectric sensors consist of a copper strand surrounded by piezoelectric material, covered by a copper sheath. When the sensor is compressed, an electrical charge is produced from which the weight of passing axles can be determined. The sensor is embedded in the pavement, and therefore pavement characteristics, including temperature, will affect the electrical charge and weight measurement.

Piezo-quartz sensors consist of a metal surface under which quartz disks are installed. When load is applied to the sensor, the disks yield an electrical charge proportional to the load applied. This charge is converted to a voltage, from which the weight of passing axles can be determined.

Bending plate WIM systems consist of steel platforms, spanning the width of a traffic lane, under which strain gauges are mounted. The strain gauges are located at critical points under the bending plate to determine the pressure in the plate as an axle passes over. The strain measured is used to determine the weights of the axles passing over the bending plate.

Load cell systems consist of steel platforms installed over a concrete vault or pit. Hydraulic load cells are installed under the platforms in various configurations to measure the forces applied by axles to the scales.

BWIM systems are another common type of WIM technology recognized by FHWA. With these systems, multiple strain gauges are installed on the bottom of a bridge slab, eliminating the need to disrupt traffic during installation. With this technology, GVWs can be measured accurately enough for enforcement screening purposes, but this is only possible if the technology is correctly installed.

2.2 VALIDITY OF AXLE LOAD DATA

According to Davies and Sommerville, (1987) WIM errors are typically expressed as the percent difference between a given axle load as measured by a WIM and the load of the same axle as measured statically (see Equation 1). Using this equation, WIM error is typically evaluated over a large sample size.

$$\varepsilon = 100 * \left(\frac{W_{WIM} - W_{Static}}{W_{Static}}\right) \quad (1)$$

Where: ε *is the WIM measurement error, expressed as a percent,* W_{WIM} *is the axle load weight as measured by the WIM, and* W_{Static} *is the axle load weight measured while the vehicle is at rest (i.e., static load).*

Accuracy is a critical consideration associated with all types of WIM systems. Inherently, WIM systems are inferring static loads from dynamic measurements, and thus, errors will inevitably be incorporated into the measurements (Davies and Sommerville, 1987). Additionally, sensors are exposed to elements such as weather conditions, and general wear and tear.

Generally speaking, the nature of WIM inaccuracy includes two different components: (1) random inaccuracy, and (2) systematic inaccuracy (Prozzi et al., 2008). Random inaccuracy consists of statistical fluctuations of a measurement from the truth. Systematic inaccuracies, on the other hand, occur in one direction due to inadequate calibration or faulty design. Normally, random inaccuracy is reflected in the standard deviation or spread of WIM errors, while systematic inaccuracy is reflected in the mean of the WIM errors (Davies and Sommerville, 1987).

WIM inaccuracy is caused by a number of different factors, including roadway profile, speed, acceleration and tire/suspension conditions of the vehicle, and environmental factors including wind, water, and temperature (Lee, 1988). Specifically, Papagiannakis and Masad (2008) characterize the nature in which increasing speed and pavement roughess will yield an increase in the variations (i.e., random inaccuracies) of loads measured by WIM systems.

A properly functioning WIM will minimize these two types of inaccuracies thus producing measurement results which are both precise and accurate. Hence, errors from a properly functioning WIM will rarely be outside of reasonable tolerances. In this research, the term “validity” is used as an overarching characteristic, which describes the ability of a system (WIM site) to measure what is intended to be measured (axle loads), and encompasses the terms “accuracy” and “precision”.

Efforts to produce valid WIM data include calibration and verification. ASTM specifies a typical calibration procedure, which must be applied after initial installation of a *type I*, *type II*, or *type III* WIM system. The calibration procedure should be applied again in the following situations (ASTM, 2009):

- After WIM system re-installation.
- After any significant change in WIM system components.
- When a full year has elapsed since the previous calibration.

As per ASTM (2009) standards, site calibration involves running test vehicles of known (statically pre-weighed) axle and GVW over the site to provide a reference for adjusting WIM system parameters. The test vehicles shall consist of two FHWA Class 9 trucks, each loaded to at least 90 % of the registered maximum GVW, with a non-shifting, symmetric load. The test vehicles shall be in excellent mechanical condition, and be equipped with tires in excellent condition and a suspension system which represents local traffic conditions. Additionally, site conditions such as pavement condition and temperature shall be quantitatively measured and logged.

With appropriate test vehicles and test conditions logged, the calibration procedure outlined by ASTM (2009) includes the following steps:

1. Adjust WIM settings to vendor's recommendations, or to settings based on previous experience.
2. Provide a means for calculating the speed of test vehicles during trial runs.
3. Have each test vehicle make a series of trial runs over the WIM sensor, with the vehicle centered in the lane. For each test vehicle, at least three runs should be made at each of the following speeds: (1) below the average operating speed, (2) above the average operating speed, and (3) at an intermediate speed.
4. For each wheel load, axle load, axle-group load, and GVW recorded during test runs, calculate the percent difference between measured and reference (actual) loads. For each type of load, calculate the mean percent difference.
5. Determine the WIM system settings required to adjust the respective mean differences to be approximately zero.
6. Program the required settings to the WIM system. Have each test vehicle make two more runs over the WIM system each; one at the higher end of test speeds and one at the lower end of test speeds. If the WIM system performance is outside the required tolerances (see Table 1), continue the cycle of updating system settings and running test vehicles until performance is within the required tolerance.

In addition, ASTM specifies a procedure for verification of a WIM site. Verification involves testing system performance at a desired point in time to ensure WIM performance is within specifications. Verification may follow-up WIM system calibration to check that the system maintains performance standards after the calibration procedure. WIM site verification uses two test vehicles, satisfying the same requirements as test vehicles used during the calibration process. These verification steps are as follows (ASTM, 2009):

1. Have each test vehicle make a series of five trial runs at each of the following speeds: (1) below the average operating speed, and (2) above the average operating speed. Lane positioning should include a mixture of centre-of-lane, left-of-centre, and right-of-centre trial runs.
2. For each wheel load, axle load, axle-group load, GVW, speed, axle spacing, and wheelbase recorded during test runs, calculate the percent difference between measured and reference (actual) loads.
3. Compare percent differences to required system tolerances (see Table 1). Report whether the system was within these required tolerances or not. Failure of the system to perform within required tolerances should result in further investigation into issues causing failure of verification test.

Studies have been conducted to determine the data validity of WIM sensors in various jurisdictions including Nevada/California, Texas, Louisiana, and New Mexico (Alavi et al., 2001; White et al., 2006; Ishak et al., 2010; Tarefder and Rodriguez-Ruiz, 2013). Additional studies have been conducted in Manitoba and Alberta (Zhi et al., 1999; Farkhideh et al., 2014), as follows:

Zhi et al. (1999) evaluated the accuracy of a piezoelectric WIM station installed on a major rural highway east of Winnipeg by comparing weights measured by the WIM to certified weights taken at a nearby static weigh scale. Trucks were matched through detailed characteristics (i.e., axle configurations, body type, etc.) and time travelled from static scale to WIM. For approximately 350 trucks, percent differences between WIM and static weigh scale weights were calculated. Results were compared against ASTM standards and are summarized as follows:

- Approximately 70 percent of steering axle weights were within ± 20 percent of certified weights.
- Approximately 50 percent of drive tandem axle weights were within ± 15 percent of certified weights.
- Less than 50 percent of trailer tandem weights were within ± 15 percent of certified weights.
- Less than 50 percent of GVWs were within ± 10 percent of certified weights.

Farkhideh et al. (2014) tested the accuracy of WIM data at WIM sites in Alberta equipped with piezoelectric sensors. In these evaluations, test trucks with known validated weights were run over WIM sensor lanes. In total, approximately 10,000 trial runs were made at six WIM sites, with weights measured at the WIM sites being compared to the corresponding verified weights. Results for each WIM site were compared against ASTM standards, and are summarized as follows:

- 53 to 90 percent (depending on site) of steering axle weights were within ± 20 percent of verified weights.
- 61 to 83 percent (depending on site) of drive tandem axle weights were within ± 15 percent of verified weights.
- 60 to 84 percent (depending on site) of trailer tandem weights were within ± 15 percent of verified weights.
- 44 to 70 percent (depending on site) of GVWs were within ± 10 percent of verified weights.

It is well-established that piezoelectric sensors are sensitive to temperature. Alavi et al. (2001) studied the effects of temperature on piezoelectric WIM installations during controlled field tests in Nevada.

Gajda et al. (2013) reveal that the relationship between measured weights and temperature is influenced by the type of WIM equipment and the type of pavement, and stress the use of caution when interpreting results from such WIM systems which have not been corrected for temperature. This relationship was tested by weighing a reference vehicle at a WIM site installed in a flexible pavement at different asphalt temperatures. Results showed that a pavement temperature change of -20 degrees Celsius and +20 degree Celsius could be accompanied by relative measurement errors of approximately -20 percent and +30 percent, respectively.

Due to the effects of temperature on axle loads measured by piezoelectric WIM sites, International Road Dynamics (IRD) has incorporated temperature correction factors into standard software processing features. The general process for manipulating raw data signals from the WIM sensors is given by Equation 2 (Roy Czinku, personal communication, January 3, 2017):

$$W = Output * F_{Calibration} * F_{Correction} \tag{2}$$

Where: *W is the weight reported by the WIM system, $Output$ is the output signal from the sensor, $F_{Calibration}$ is a constant calibration factor to be set during site calibration, and $F_{Correction}$ is a correction factor, which is a function of pavement temperature.*

While $F_{Calibration}$ is intended to account for long-term changes in WIM site conditions, WIM electronic system settings allow for correction factors ($F_{Correction}$) to be applied to the output signal, as per Equation 2, depending on the pavement temperature as measured by equipment as part of the WIM installation. Default factors from system vendors can be used, but the development of more specific and appropriate factors occurs at the discretion of a jurisdiction. Enabling the auto-calibration feature also allows the system to continuously review and update correction factors, based on characteristic axle loads.

However, starting with a specific representative set of correction factors is ideal (Roy Czinku, personal communication, January 3, 2017).

To encourage site-specific development of temperature correction factors, standard recommended procedures exist to aid with the development of the factors. One such recommended procedure follows (Roy Czinku, personal communication, May 3, 2016):

- Calibrate the system (by adjusting $F_{Calibration}$), and collect at least one-week worth of data, using no correction factors (i.e., $F_{Correction}$ equals 1.0 for all temperatures, hence data represents output signal from Equation 2).
- Filter out WIM output signal for steering axles for FHWA Class 9 trucks.
- Select a “target weight” for these steering axle outputs, based on the expected value in the region (i.e., approximately 5200 to 5300 kg).
- Plot temperature versus WIM output signal for Class 9 steering axle outputs and generate a regression line illustrating the sensitivity of output as a function of temperature.
- Based on this sensitivity, develop a set of correction factors. For each temperature (use a resolution of approximately 2 degrees Celsius), find the typical output by reading the output at the given temperature from the regression line from the previous step. Divide the target weight by this output to obtain the correction factor for that particular temperature.
- Enter the correction factors into the WIM system electronics.

In this procedure, it is assumed that loads of steering axles from FHWA Class 9 trucks do not fluctuate in reality. Therefore, observed fluctuations in output signal for these axles indicate the influence of external variables, and this procedure assumes that temperature accounts for a significant portion of these output signal fluctuations.

2.3 THE NEED FOR AXLE LOAD DATA FOR PAVEMENT DESIGN

2.3.1 Pavement Design Approaches

The need to collect information concerning pavement performance began in the early 1980's, when concerns were raised about the deterioration of aging highways. The LTPP was first launched in 1987, as part of the first ever Strategic Highway Research Program (SHRP) (Walker and Cebon, 2011), and strives to extend the life of pavements through various initiatives, including (FHWA, 2010):

- Evaluating pavement design methods.
- Improving pavement rehabilitation strategies.
- Improving pavement design models.
- Determining the effects of weather/traffic exposure and design features on pavement performance.

As part of these initiatives, LTPP monitors data on over 2500 asphalt and Portland cement concrete test sections, with traffic data being a core component of the measured data (FHWA, 2017). These 2500 sections are evenly dispersed throughout the U.S. and southern Canada, with sites also in Alaska and Hawaii (FHWA, 2010).

Representative axle load distributions are key inputs when practicing pavement design for a given section of highway. The pavement design method set out by AASHTO in 1993, which has long been relied-upon until the introduction of more modern practices, allows for the calculation of required pavement structure thicknesses, based on assumed structural parameters, performance requirements, and loading conditions. This method requires the calculation of the expected number of ESALs to be applied over the pavement service life as an input during the design of a flexible or rigid pavement structure. An ESAL is referred to as a standard unit of pavement damage caused by a single axle of 80 kN with tires inflated to 586 kPa, and the pavement structure must withstand an expected quantity of ESALs throughout its service life. The basic formula for computing the ESAL value for a set of axle groups of a certain load is given in Equation 3 (AASHTO, 1993).

$$ESAL = LEF * N \tag{3}$$

Where: $ESAL$ *is the equivalent single axle load,* LEF *is the load equivalency factor designating the number of ESALs produced by a given axle group, and* N *is the number of axle groups.*

Note that in Equation 3, LEF is a function of load, axle group (i.e., single, tandem, tridem), and other factors related to the pavement. A common practice when using the AASHTO 1993 method is to sum up the ESALs for all types of axle groups and all load ranges for a representative sample of a given vehicle configuration. Dividing the resulting sum of ESALs by the number of vehicles in the sample yields what is referred to as a truck load factor. The truck load factor represents the number of ESALs produced by a typical truck of a certain configuration (AASHTO, 1993).

Next, the truck load factor is multiplied by the number of vehicles of the given configuration which are expected to pass over the design lane over the service life of the pavement, yielding the design ESAL value for the given vehicle configuration. Finally, the design ESAL values are summed for all vehicle configurations, yielding the total design ESAL value to be used in the AASHTO 1993 pavement design method (AASHTO, 1993).

Representative axle load distributions are also instrumental to the pavement design process when using the more modern method set out by the MEPDG, referred to as the "ME design method". This method differs from the AASHTO 1993 method, in that a trial design is first selected, and then performance of that design is tested and evaluated using accompanying software, assuming very specific structural parameters and environmental/loading conditions. The design is then modified based on the results until a suitable pavement structure design is produced (AASHTO, 2015). Released in 2004, the MEPDG provides improvements over the AASHTO 1993 method, including: More realistic pavement characterization; a better representation of the interactions between traffic, climate, and the pavement; more detailed pavement performance outputs; and a measure of design variability and reliability (ARA, 2004).

With the ME design method, when designs are tested using software, specific axle loading conditions must be entered as inputs. ALS, which are distributions of the percent of axle groups within a series of load ranges, must be calculated for the different types of axle groups within a truck configuration (i.e., single, tandem, tridem). In the accompanying software, these ALS must be computed for each FHWA vehicle class, for each month of the year. The software uses these ALS in conjunction with truck traffic-related data to evaluate the input designs. Other truck traffic-related data includes: Annual average daily truck traffic (AADTT), percent trucks in the design lane/design direction, truck traffic growth rates, distribution of FHWA vehicle classes, typical axle load spacings, and temporal truck traffic distributions (AASHTO, 2015).

The quality and regional relevance of this axle load data also has a significant impact on the design. The ME design method addresses this concern by offering different hierarchical input levels, representing different levels of data quality (AASHTO, 2015). The first input level – *Level 1* – involves the measurement of axle loads directly, on the specific project site.

The second input level – *Level 2* – involves using input axle loads which were calculated from sites away from of the specific project location. In this case, the recommended procedure from the Traffic Monitoring Guide (FHWA, 2001) involves the combining of data from WIM sites exhibiting similar axle loads, through objective statistical cluster analyses, as well as specific regional expertise.

The third input level – *Level 3* – involves estimating axle loads based on established default values. In this case, axle load distributions are averaged for a sample of WIM data which satisfies basic criteria related to temporal availability. In all, 134 WIM sites were used to develop the original MEPDG default ALS. The main limitations of the default ALS include the uncertainty of data quality from applicable sites, and the lack of applicability to sites with axle load patterns which differ significantly from those patterns at sites used to develop the defaults.

To help address the data quality issue, updated MEPDG loading defaults are being developed using 26 sites across the U.S. which have data of known high quality. These sites are part of the Specific Pavement Study (SPS) Transportation Pooled Fund (TPF) study. These WIM sites use reliable equipment with regular data quality checks, and satisfy strict data quality specifications set out by LTPP (Selezneva et al., 2016). Unfortunately, these updated defaults do not consider data from Canadian sites. Thus, it is up to Canadian jurisdictions to develop more appropriate defaults.

2.3.2 Sensitivity of Design Approaches to Axle Load Data

The potential for axle loads to affect designs has been widely recognized. Prozzi et al. (2008) simulated a series of biased axle load distributions and examined the effects of these biases on pavement life prediction. Results showed that under the rutting criterion, systematic axle load errors of approximately -20 percent and +20 percent led to approximately 60 percent overestimation and 40 percent underestimation in predicted pavement life, respectively. Similarly, under the fatigue cracking criterion, systematic axle load errors of approximately -20 percent and +20 percent also led to approximately 60 percent overestimation and 40 percent underestimation in predicted pavement life, respectively.

Haider et al. (2010) investigated the effects of overall positive or negative ALS bias on the prediction of key pavement performance metrics, including: cracking, rutting, and roughness for flexible pavements; and cracking, faulting, and rutting for rigid pavements. The base ALS were developed based on data from LTPP SPS-1 sites. It was found that for flexible pavements, a 10 percent positive bias in ALS resulted in significant overestimation of longitudinal and alligator cracking, and a 10 percent negative bias in ALS resulted in significant underestimation of longitudinal cracking, alligator cracking, and surface rutting. For rigid pavements, it was found that transverse cracking was significantly overestimated and underestimated with a positive 10 percent bias and negative 10 percent bias of ALS, respectively.

Smith and Diefenderfer (2010) compared flexible pavement distresses under varying ALS conditions. Pavement performance was tested under different site specific ALS conditions from eight separate WIM sits in Virginia from the years 2007 and 2008, as well as the MEPDG defaults. Results showed that varying the ALS between site-specific conditions versus MEPDG default conditions considerably increased the predicted time to pavement failure under the total rutting failure mode.

Ahammed et al. (2011) investigated the effects of varying between site-specific ALS data from a Manitoba WIM, and the U.S. default ALS when evaluating the performance of a flexible pavement design. Results from the two different load conditions were similar for the terminal International Roughness Index (IRI), surface down cracking, bottom up cracking, thermal fracture, and rutting of the top layer. However, predicted rutting decreased when using the site-specific data, and since this was the critical performance measure, predicted pavement life increased when using site-specific data.

Nassiri et al. (2013) tested the impacts of varying between site specific ALS from Alberta WIM sites, the Alberta provincial default ALS, and the MEPDG default ALS when evaluating pavement performance. They discovered that for rigid pavements, predicted transverse cracking was significantly reduced when using site specific data. They also discovered that for flexible pavements, predicted alligator cracking was significantly reduced when using site specific data.

Tarefder and Rodriguez-Ruiz (2013) simulated positive and negative axle load biases from three WIM sites in New Mexico to examine the impacts on pavement design. Results showed that a positive 30 percent bias in axle loads lead to approximately 30 percent, 350 percent, and 200 percent increases in predicted rutting, longitudinal cracking, and alligator cracking, respectively. A negative 30 percent bias in axle loads lead to approximately 30 percent, 50 percent, and 75 percent decreases in predicted rutting, longitudinal cracking, and alligator cracking, respectively. Additionally, positive and negative biases in axle loads had a significant impact on predicted IRI.

FHWA conducted analyses using methods from the MEPDG to determine the effects of changing input axle load conditions using WIM data from 26 LTPP SPS TPF sites (Selezneva et al., 2016). This study was designed to isolate the effects of changing the axle load conditions for each axle group (i.e., single, tandem, tridem) of each FHWA vehicle class (i.e., 1 to 13) separately. Therefore, for each axle group and class combination, a number of axle load cluster groups were developed and consisted of SPS

TPF sites exhibiting similar axle load patterns for the particular axle group and class. Pavement designs were evaluated by changing the axle load cluster group used for each axle group of each vehicle class in-turn.

Selezneva et al. (2016) determined that for the typical flexible pavement design selected, an altering of axle load patterns for specific axle types and vehicle classes produced a significant effect on predicted pavement life at failure. For the top-down cracking failure mode, altering Class 4, 6, 7, 8 and 9 tandem axles, and Class 7 and 13 tridem axles significantly affected predicted pavement life. For the bottom-up cracking failure mode, altering Class 8 and 11 single axles, Class 6, 7, 8, 9 and 13 tandem axles, and Class 13 tridem axles significantly affected predicted pavement life. For the rutting failure mode, altering Class 9 single, and Class 13 tridem axles significantly affected predicted pavement life. For the typical rigid pavement design selected, an altering of axle load patterns for specific axle types and vehicle classes also produced a significant effect on predicted pavement life at failure. For the slab cracking failure mode, altering Class 4, 6, 8, 9, and 13 tandem axles significantly altered predicted pavement life.

2.3.3 ME Design Practice in North America

The state-of-practice of collection and application of axle load data has significantly advanced over the last decade in North America. The introduction of more advanced pavement design practices and WIM technologies, and the need to maintain safe and reliable highway systems has motivated many jurisdictions to investigate more detailed, extensive, and accurate axle load data. A review of documents revealed several North American jurisdictions which have recently made efforts to develop axle load inputs to support pavement design efforts using the ME design method:

- Lu and Harvey (2006) in California.

- Swan et al. (2008) in Ontario.
- Ishak et al. (2010) in Louisiana.
- Jablonski et al. (2010) in Manitoba.
- Sayyady et al. (2010) in North Carolina.
- Smith and Diefenderfer (2010) in Virginia.
- Haider et al. (2011) in Michigan.
- Wang et al. (2011) in Arkansas.
- Mallela et al. (2013) in Colorado.
- Nassiri et al. (2013) in Alberta.

As discussed in Section 2.3.1, the MEPDG uses a more sophisticated pavement modelling approach, as compared to the AASHTO 1993 method. As a result, the subject of axle load data quality has become an important consideration related to infrastructure management, since there is opportunity to produce highly accurate pavement structure designs using the ME design method, given the appropriate data inputs.

3 RESEARCH METHODOLOGY

This chapter provides an inventory and characteristics of available sources of axle load data in Manitoba. Next, the approach to evaluating these axle load data sources is discussed. Finally, the methodologies and analyses behind data evaluation are described.

3.1 SOURCE DATA

In Manitoba, vehicle weights are measured using a variety of equipment and at several locations. Each location is unique in terms of the type of equipment installed, the reasoning behind equipment installation, and the traffic conditions at the site. The characteristics of Manitoba's highway system and the various freight industries served influence the types of traffic observed and weighed in Manitoba. A detailed description of pertinent characteristics of Manitoba's highway system can be found in Appendix B.

3.1.1 Static Weigh Scales

Three primary static weigh scales exist in Manitoba:

1. The Headingley weigh scale is located on PTH 1, approximately 6.6 km west of the junction of PTH 1 with Winnipeg's perimeter highway (PTH 100 & 101). This scale captures eastbound and westbound truck traffic, which is subject to Road Transportation Association of Canada (RTAC) weight limits.
2. The West Hawk weigh scale is located on PTH 1, approximately 1.1 km west of the Manitoba-Ontario border. This scale captures eastbound and westbound truck traffic, which is subject to RTAC weight limits and the Ontario bridge formula.
3. The Emerson weigh scale is located on PTH 75, approximately 1.8 km north of the Canada-U.S. border. This scale captures northbound truck traffic only, which is subject to RTAC weight limits and the various U.S. truck size and weight laws.

Figure 1 shows the locations of these weigh scales.

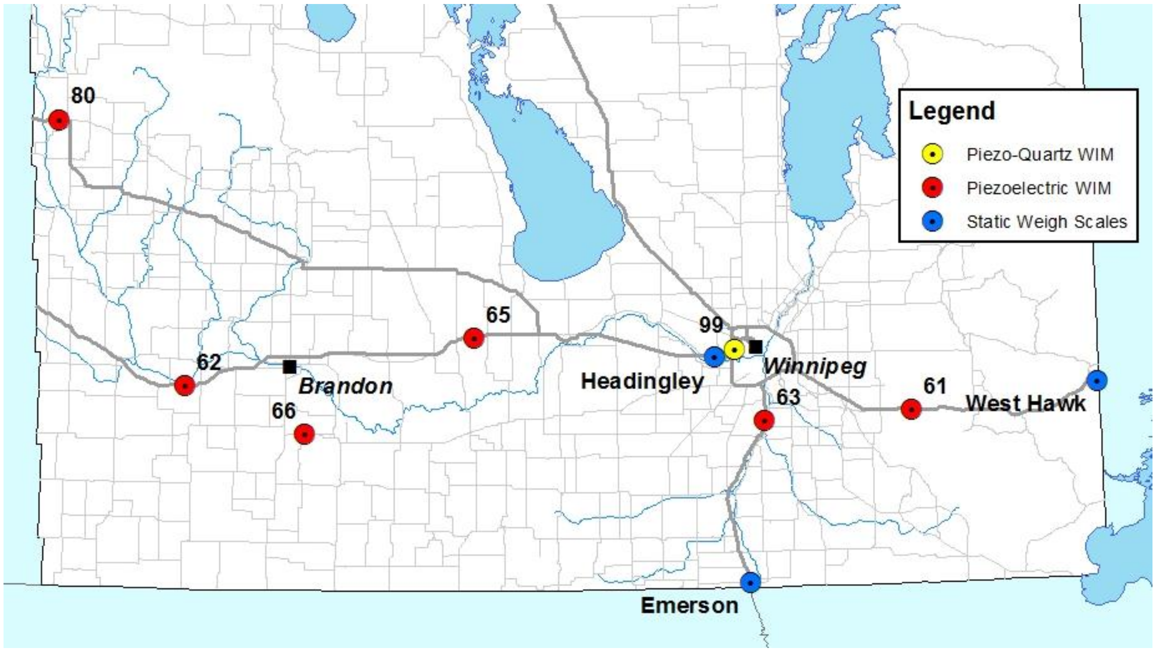


Figure 1: Weight data collection sites in Manitoba, 2016.

These weigh scales are operated by the Motor Carrier Division at Manitoba Infrastructure (MI). All three of these scales are located on RTAC routes, and they enforce vehicle weights and dimensions specific to these routes in Manitoba, as specified in the Highway Traffic Act, Regulation 575/88 (Manitoba Infrastructure, 2017a). However, vehicle weights may be influenced by nearby non-RTAC highways as well.

These scales all feature load cell weighing devices, manufactured by Weigh Tronix®, and closely resemble the *type IV* WIM designation, based on ASTM standards (ASTM, 2009). The difference between these scales as currently operating and *type IV* WIM systems is that only the following data items are measured (manually) at the scales: axle group loads, GVW, vehicle classification, lane/direction of travel, and date/time of passage. Although the load cells at these scales are types of WIM, in this research, these sites will be referred to as static weigh scales, rather than WIM.

They are typically calibrated once every two years, and must be capable of measuring vehicle weights which officers may use to legally enforce applicable truck weight regulations. Each load cell is supported by four 27 215 kg (60 000 lb) capacity weigh bars; one in each corner. Data is transmitted from the load cells to an electronic display inside the scale building. The system can also be wired to direct data to a printer, or electronically store the data in a computer (Ross Veldkamp, personal communication, December 10, 2016). Figure 2 shows the load cell used to weigh westbound traffic at the Headingley weigh scale.

Figure 2: Load cell surveying westbound truck traffic at the Headingley static weigh scale on Manitoba's PTH 1. Taken by Steven Wood on October 9, 2016.

When the scales are in operation, all trucks of FHWA Class 5 or higher (see Appendix A), as well as FHWA Class 3 vehicles pulling heavily-loaded trailers are required by law to pull through the scale lane and over the load cell. Upon pulling through the scale lanes, vehicles are required to come to a complete stop prior to being directed by the officer to pull onto the scale. Vehicles typically "roll" over the scale at a slow speed of approximately

5 km/h, since coming to a complete stop for each axle group is a slow process, leading to hazardous truck traffic queues, and potentially causing an undesirable lurching effect on the load cell equipment. Although these scales are typically referred to as static weigh scales, no WIM device, including the load cells installed at these sites, is capable of measuring the true static loads of a vehicle (Davies and Sommerville, 1987).

If an axle group or the GVW of the truck is near or exceeds the legal limits, the officer directs the truck to backup and carefully re-weigh each axle group. In this case, each axle group must come to a complete stop on the scale, and the officer observes weights once the weight readings have stabilized (after 5-10 seconds). These careful readings are used to bill the parties responsible for configuring the vehicle (if applicable). Otherwise, the truck will proceed out of the weigh scale lane and merge back onto the highway.

In past years, the University of Manitoba Transport Information Group (UMTIG) has conducted weigh scale surveys at these three primary static weigh scales. These surveys include the following data fields, observed manually: time of passage, truck configuration, body type, lift axles (if applicable), weights of each axle group (taken from the electronic display), and any other relevant information relating to truck appearance, such as color. The surveys taken in recent years follow:

- Headingley (2016): Nearly 800 vehicles were observed during surveys conducted on March 1-2, 2016, and June 21, 2016.
- Headingley (2015): Over 2100 vehicles were observed during surveys conducted on June 18, 2015, July 29-30, 2015, and November 25-26, 2015.
- Headingley (2013): Over 2500 vehicles were observed between August 14, 2013 and August 16, 2013.

- West Hawk (2013): Over 1200 vehicles were observed between July 11, 2013 and July 12, 2013.
- Emerson (2013): Over 1100 vehicles were observed between August 12, 2013 and August 14, 2013.

As discussed in Appendix B, different regulatory conditions exist during different seasons of the year, including winter weight premiums and spring road restrictions. Therefore, it is preferable to perform weigh scale surveys throughout the year such that effects of these seasons and regulatory conditions can be observed and studied. Figure 3 superimposes the 2015 and 2016 weigh scale surveys at Headingley with the four seasons and applicable weight premiums in effect at this location in Manitoba.

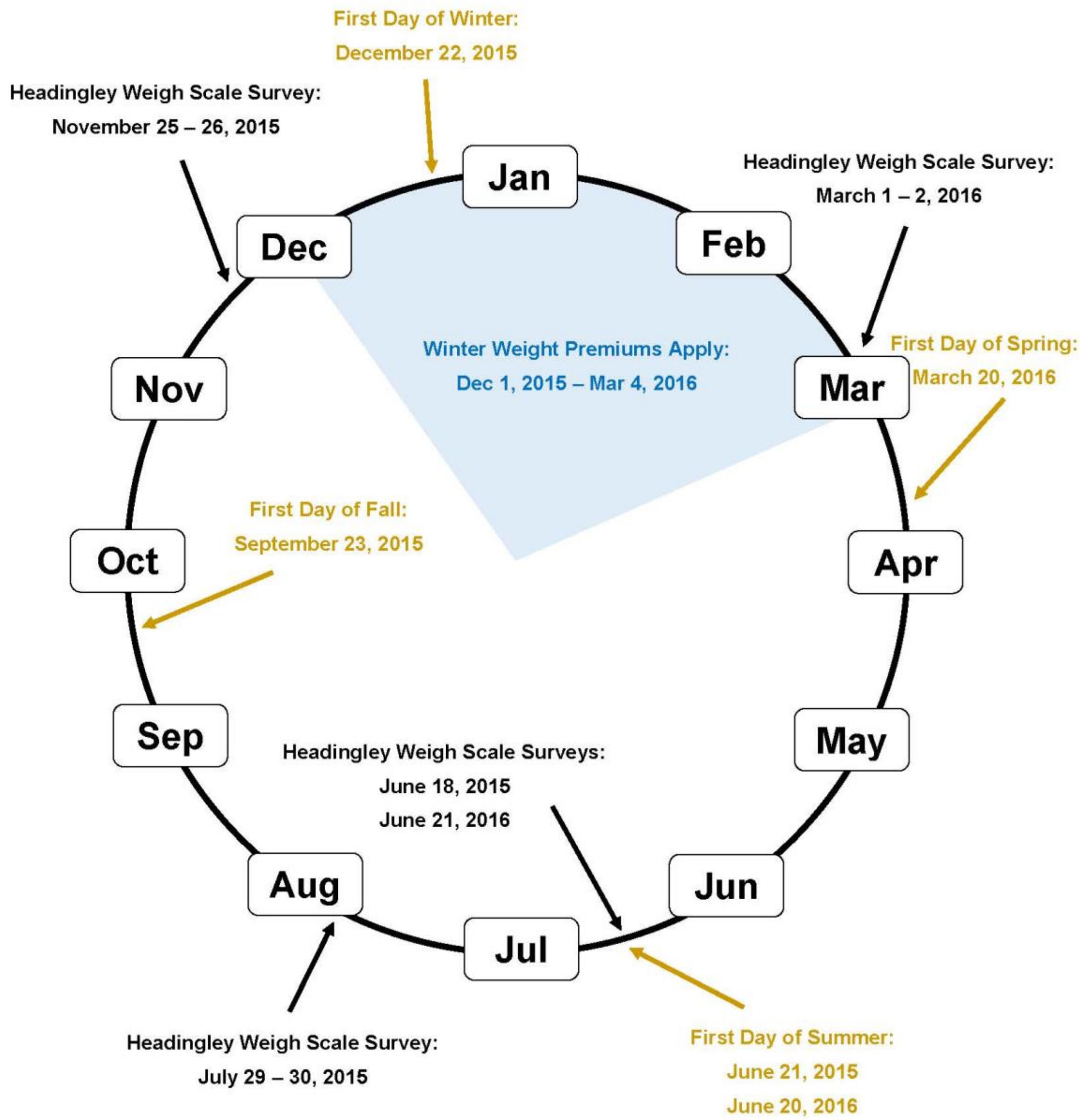


Figure 3: Dates of 2015 and 2016 Headingley weigh scale surveys superimposed with the four seasons and applicable weight premiums/restrictions.

During these surveys, the normal procedure for observing and recording an acceptable reading of an axle group load is as follows:

1. Wait for the axle group to roll approximately to the middle of the load cell.
2. When the load readings on the electronic display are stable (no abrupt changes in load readings), record the load created by the axle group.

3. Repeat the procedure for the next axle group.

3.1.2 Permanent Count Stations with Piezoelectric Strip Sensors

There are six WIM sites (12 lanes of WIM total) equipped with piezoelectric sensors in Manitoba, from which reasonably recent data can be retrieved:

1. Station 61, located on PTH 1 (four-lane, divided highway) near the Brokenhead River crossing. This site had sensors installed in both the eastbound and westbound drive lanes. This site no longer has WIM sensors, as they were removed due to construction in 2016.
2. Station 62, located on PTH 1 (four-lane, divided highway) near Oak Lake, Manitoba. This site has sensors installed in both the eastbound and westbound drive lanes.
3. Station 63, located on PTH 75 (four-lane, divided highway) near Glenlea, Manitoba. This site had sensors installed in both the northbound and southbound drive lanes until 2015, when the northbound sensors were removed due to construction. Long term plans involve the removal of the southbound sensors, and subsequent installation of more sophisticated piezo-quartz strip sensors in the northbound and southbound drive lanes.
4. Station 65 is located on PTH 1 (four-lane, divided highway) near MacGregor, Manitoba. This site had sensors installed in both the eastbound and westbound drive lanes until 2016, when the westbound sensors were removed due to construction. Long term plans involve the removal of the eastbound sensors, and subsequent installation of more sophisticated piezo-quartz strip sensors in the eastbound and westbound drive lanes.

5. Station 66 is located on PTH 2 (two-lane, undivided highway) near Nesbitt, Manitoba. This site has sensors installed in both the eastbound and westbound lanes.
6. Station 80 is located on PTH 16 (two-lane, undivided highway) near Russell, Manitoba. This site has sensors installed in both the eastbound and westbound lanes.

Figure 1 shows the locations of these WIM stations.

These piezoelectric WIM sites were installed starting in the late 1990's as a replacement to the previous sensors manufactured by Golden River Traffic®, and fall into the *type II* WIM designation, based on ASTM specifications. The current sensors are manufactured by International Road Dynamics®, and two sensors are installed per lane of traffic surveyed. Both sensors in a WIM lane are strip sensors running the width of the traffic lane, and are separated by approximately 2.7 to 3.7 metres (9 to 12 feet) (Craig Lobban, personal communication, November 25, 2016). Figure 4 shows the typical sensor setup at these sites. To minimize the effects of drifts of the axle load measurements over time, these sites are calibrated on approximately an annual basis. Basic corrections are currently applied in Manitoba to account for factors known to produce systematic drifts in axle load measurements produced over time.

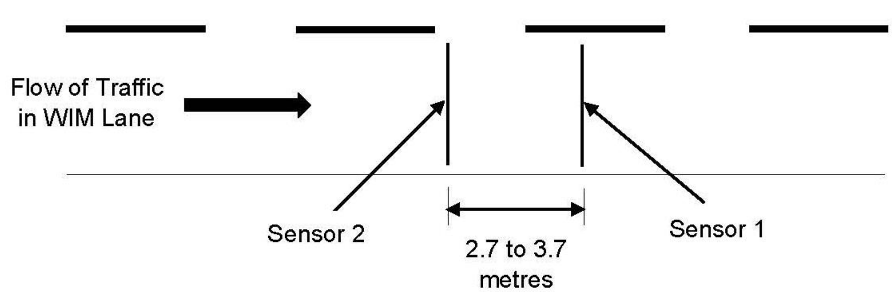


Figure 4: Schematic diagram of sensor setup at Manitoba piezoelectric WIM stations.

Data produced at these sites is used to support pavement design research/projects in Manitoba, and also supports initiatives by the LTPP program, operated by FHWA. These sites are also prone to periodic equipment malfunction, causing erroneous traffic counts or axle load data, or complete equipment shutdown. Reasons for equipment malfunction typically include degradation due to equipment aging or weather conditions, or loss of power to the equipment. Before use, this data is inspected by personnel from the Manitoba Highway Traffic Information System (MHTIS) to ensure it has not been affected by such equipment malfunction.

3.1.3 Permanent Count Stations with Piezo-Quartz Strip Sensors

There is currently one WIM site equipped with piezo-quartz sensors in Manitoba. It is designated as Station 99, and is located on PTH 190 (CentrePort Canada Way, four-lane, undivided highway), approximately 1.3 km east of PTH 101 near Summit Road. This site measures axle loading data in the westbound drive lane only. The sensors are manufactured by Kistler Instruments® and fall into the *type I* WIM designation, based on ASTM specifications.

The current setup includes four sensors in the westbound drive lane. The sensors are arranged into two strips, spaced approximately 1.8 metres (6 feet) apart. Figure 5 shows the sensor setup at this site. Each strip is composed of two sensors, each of which spans half the width of the traffic lane. Therefore, the sensors have the capability to distinguish between loads of the right-side and left-side of vehicles (Craig Lobban, personal communication, November 25, 2016). Figure 1 shows the location of this WIM site.

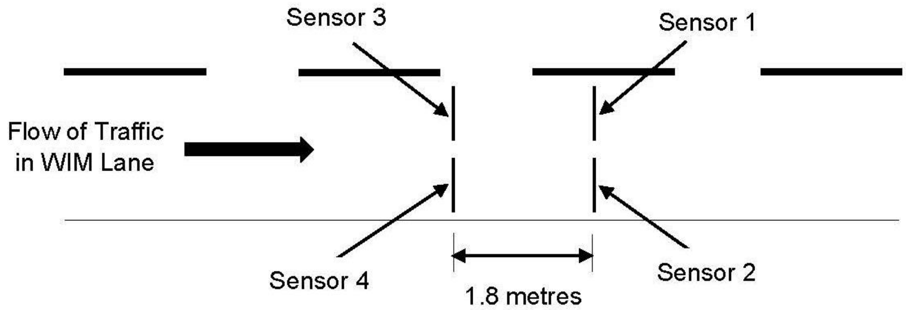


Figure 5: Schematic diagram of sensor setup at Manitoba piezo-quartz WIM station.

This site was installed in 2014, shortly after the completion of Centreport Canada Way. Station 99 is unique from the other six WIM sites in that it is the first piezo-quartz WIM site to be installed in Manitoba, and is located on a new highway segment with major anticipated upcoming developments in the nearby area related to CentrePort Canada. Maranchuk (2016) used data from this site to benchmark the volume and axle load characteristics of traffic using CentrePort Canada Way prior to these anticipated developments.

Similar to piezoelectric WIM sites in Manitoba, the piezo-quartz site is calibrated approximately on an annual basis in order to minimize the effects of any drifts in axle load measurements over time. Currently, data from this station is used to support pavement design initiatives in Manitoba. The equipment at this station is prone to periodic malfunction, similar to the other WIM sites, and the data produced by this site is inspected by personnel from MHTIS to ensure that equipment malfunction does not hinder data quality. Figure 6 shows the sensors at this site.

Figure 6: Piezo-quartz sensors installed at WIM Station 99 on Manitoba's PTH 190. Photo taken by Steven Wood on October 9, 2016.

3.2 APPROACH TO EVALUATING DATA SOURCES

Based on the available sources for monitoring axle loads in Manitoba, four options are identified for providing axle loading data:

1. *Option 1* involves using data from the six Manitoba WIM sites equipped with piezoelectric sensors. Based on historical validity of this equipment, the use of data extracted in the period just after the most recent on-site calibration may be more valid than datasets representing an entire year.
2. *Option 2* involves using a longer-term sample of data from the six Manitoba WIM sites equipped with piezoelectric sensors. This option may involve some form of data correction, based on data analyses performed in this research.
3. *Option 3* involves using data from the 2013, 2015, and 2016 surveys taken at the three primary static weigh scales in Manitoba (i.e., Headingley, West Hawk, and Emerson).

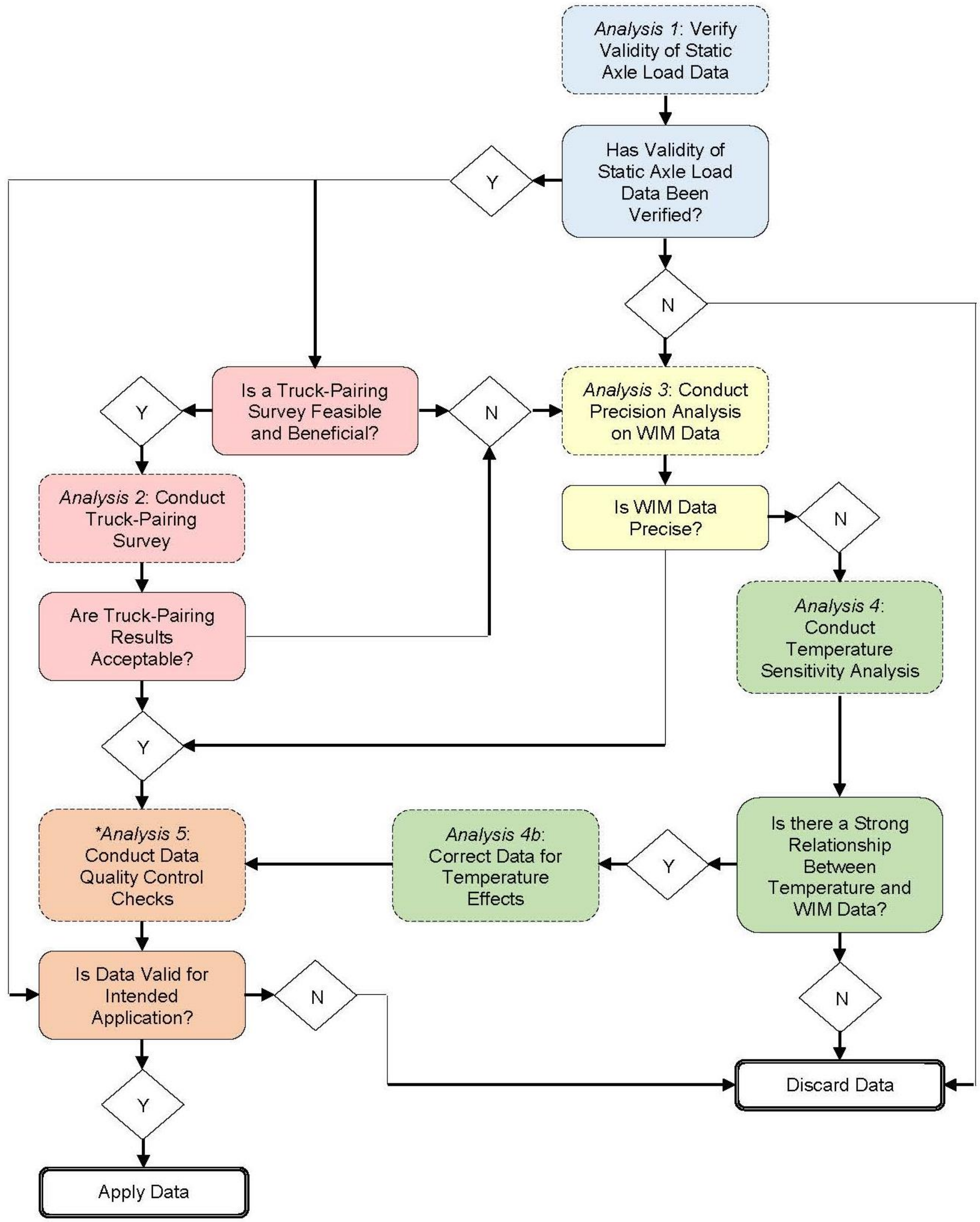
4. *Option 4* involves using data from the Manitoba WIM site equipped with piezo-quartz sensors.

In order to determine the feasibility of these options for providing reliable axle load data, they must be evaluated against data quality principles, which have been designed to represent the primary considerations which pertain to the quality of the data. These data quality principles are as follows:

1. *Validity*: This principle involves using equipment producing data to best represent the true axle loads created by vehicles passing over the equipment. Ideally, valid data will be both precise and accurate. This principle is important, since equipment which does a poor job of capturing true loads may provide inaccurate and imprecise data with limited relevance to its intended purpose.
2. *Geographic Coverage*: This principle involves utilizing data collected at geographically diverse locations. It is important to consider geographic coverage, since truck axle load characteristics may vary by region in Manitoba (due to different industries/trucking activity). Additionally, the road classifications in Manitoba (i.e., RTAC, Class A1, Class B1) may also have a systematic impact on axle load characteristics, since freight conditions and legal allowances are different among the different road classes. Ideally, the data should sufficiently represent the different regions and load classifications.
3. *Temporal Coverage*: This principle involves utilizing data from the longest possible time period (up to a full year). Temporal coverage is an important principle because truck axle loads may vary throughout the year due to changing (seasonal) industry demands and changes in legal weight limits (i.e., spring weight restrictions and winter weight premiums). Ideally, axle load data should be available year-round, and adequately represent all 12 months.

4. *Data Availability*: This principle considers the effort and resources required to collect the data as well as future plans for equipment use. It is important to consider current and future data availability, since there is a periodic need to re-develop axle load data such that designs and decisions can be made with data that is up-to-date. It is ideal that data sources are in operation in the future, and provide data that is readily available for use.

In order to gain the required knowledge to adequately evaluate the options against the relevant data quality principles, and to understand the significance of selecting one option over another, a series of five analyses are conducted on data available from the various sources. Figure 7 provides an overview of the framework of these analyses.



**Analysis 5* does not need to include the precision analysis component if *Analysis 3* has already been conducted with satisfactory precision for the applicable data upon arrival at *Analysis 5* in this flow chart.

Figure 7: Approach for evaluating axle load data sources.

These five analyses are described in more detail as follows:

1. *Analysis 1* involves studying the Headingley static weigh scale data using qualitative and quantitative measures. Qualitative measures involve observing typical scale procedures and evaluating the impacts of these procedures on data quality. Quantitative measures involve determining the precision of the data, given the operating procedures and scale characteristics.
2. *Analysis 2* involves evaluating the validity of the WIM site equipped with piezo-quartz sensors. This is done using a series of truck-pairing surveys which involve performing static weigh scale surveys and identifying when a truck passes over both the piezo-quartz sensors and the Headingley static weigh scale in the same trip. The axle loads as measured by the piezo-quartz WIM site are compared to the same axle loads as measured at the static weigh scale, and the results are compared against standardized criteria. For the purposes of this research, such a survey was less feasible for WIM sites equipped with piezoelectric sensors.
3. *Analysis 3* involves investigating the precision of WIM sites equipped with piezoelectric sensors. This involves first using applicable literature and/or static weigh scale data to confirm the consistency of steering axle loads of select trucks in Manitoba over time. The steering axle loads as measured by piezoelectric WIM sites in the post-calibration period are then analyzed to determine if these known consistencies can be replicated.
4. *Analysis 4* involves investigating the validity of WIM sites equipped with piezoelectric sensors more closely as well as the factors influencing validity. Following *Analysis 3*, WIM output signals for steering axles are checked for correlation with temperature. This analysis will determine the strength, characteristics, and temporal scope of this relationship in the post-calibration

period. Furthermore, if strong correlations are found, *Analysis 4* also involves correcting piezoelectric WIM data to account for site-specific temperature effects (denoted as *Analysis 4b* in Figure 7).

5. *Analysis 5* involves performing quality control checks on WIM data. Precision of steering axle loads and percent of trucks measured over/under reasonable GVWs are used to evaluate data quality for the following: (1) data from piezoelectric WIM sites as currently processed in Manitoba (only for the purpose of comparing validity), (2) data from piezoelectric WIM sites corrected to account for site-specific temperature effects, and (3) data from the piezo-quartz site.

3.3 VALIDITY OF STATIC WEIGH SCALES IN MANITOBA (ANALYSIS 1)

This analysis provides insight into the feasibility of using data from the three primary static weigh scales in Manitoba (i.e., Headingley, West Hawk, and Emerson). This analysis addresses three main concerns regarding the data collected at these weigh scales, and determines if these concerns hinder data validity. The three concerns are as follows:

1. The data collected at these weigh scales represents a sample of trucks from the highways on which they are located. Furthermore, these samples are influenced by the operational hours (i.e., no trucks surveyed when no data loggers are present). Can these samples be considered representative of traffic on the respective highways?
2. In most cases (when a violation is not detected), the trucks "roll" over the load cell at the scale at approximately 5 km/h, rather than coming to a complete stop. Does this affect the accuracy of the readings?
3. Since most trucks "roll" over the scale, the resulting forces measured are dynamic, and fluctuations can be observed on the electronic display, even as a single axle group rolls over the load cell. In an environment where the data-observer must pick

the "true" weight from a fluctuating reading, can these readings be considered precise?

Limited documentation of the day-to-day operations at the three primary weigh scales was uncovered, so to determine the typical procedures at the weigh scales, the operations of the Headingley scale were observed during all surveys conducted at this scale from 2015 to 2016 (see Section 3.1.1). Observing the practices first-hand allows for the determination of whether these samples are an appropriate representation of the traffic stream on PTH 1 near Headingley, Manitoba.

To address the concern of weigh scale accuracy, it is necessary to wait until a truck is billed at the static weigh scale. In this case, a set of typical "rolling" weights has already been observed and recorded prior to the officer declaring that an axle group or the GVW is likely overweight. When the truck axle groups are re-weighed (so that the officer has an official reading), these readings are also observed and recorded and are compared to the "rolling" readings initially recorded. This was done for every truck which was billed during the surveys of November 2015, March 2016, and June 2016. These comparisons reveal whether there is a significant difference between official weights and weights taken at a speed of approximately 5 km/h during normal scale operation.

Finally, to address the concern about precision of the measurements, the standard procedure for measuring acceptable axle group loads (see Section 3.1.1) during the surveys of July 2015, November 2015, and March 2016 was modified such that two acceptable readings were taken for each axle group. This is possible due to the slow speed of the trucks rolling over the load cell at the scale. This is intended to simulate a scenario where the observer records an axle group load using the standard procedure, and then is allowed to redo the load measurement by recording the load again for the same axle group. The differences between the two measurements for each axle group will provide a measure of precision of axle group load measurements at the primary static weigh scales.

3.4 VALIDITY OF PIEZO-QUARTZ SENSORS IN MANITOBA (ANALYSIS 2)

The primary method of evaluating the piezo-quartz WIM sites in Manitoba is to conduct a series of truck-pairing surveys to evaluate the discrepancies between axle loads measured at WIM Station 99 and axle loads measured at the nearby Headingley weigh scale. Assuming that the validity of the Headingley weigh scale is confirmed, axle loads measured at this weigh scale are taken as the closest possible representation of the true static weighs of the vehicles, and are referred to as "ground truth" axle loads. These surveys will therefore provide insights into the validity of axle loads produced by the piezo-quartz WIM site at Station 99 at a given length of time after calibration.

The objective of a truck-pairing survey is to identify trucks which pass over both the site to be evaluated (the sensor at Station 99 in this case), as well as a "ground truth" (the static weigh scale in Headingley in this case) during the same trip and carrying the same load. To accomplish this, a high-resolution camera was placed near the sensors at Station 99 by the Traffic Engineering Division at MI on the days of June 18, 2015, and June 21, 2016, for two separate studies. The high-resolution camera was focussed on the piezo-quartz sensors at WIM Station 99 such that all details of the trucks passing by could be identified, as well as the time which the truck passed over the sensors. Figure 8 shows imagery produced by the high-resolution camera.

Figure 8: Imagery of a flatbed truck captured by the high-resolution camera at WIM Station 99 on June 21, 2016. Provided with the written consent of Craig Lobban, Traffic Engineering, Manitoba Infrastructure.

In these studies, the video survey times coincided with the surveys conducted at the Headingley weigh scale. Image files from the camera and truck descriptions recorded during these two weigh scale surveys helped identify when the same truck passed over the sensors at Station 99 and the Headingley weigh scale, while carrying the same load. It was concluded that this was the case when the truck descriptions recorded at the static weigh scale matched the information from the camera imagery in the following ways:

- Time lag from Station 99 to Headingley weigh scale was approximately 15 minutes, based on a trial run in a vehicle. Therefore, only trucks which took between 10 and 20 minutes (5-minute leeway) to travel from Station 99 to the Headingley weigh scale were considered in this study.

- Body type matched. As recommended by ASTM (ASTM, 2009), tank and livestock body types were excluded, due to their unstable loads and resulting increased dynamic forces.
- Axle configuration matched.
- Description of the truck appearance matched. Specifically, this included: color of cab/trailer(s), description of load carried (in the case of trucks with uncovered loads), or other descriptive notes.

When trucks were matched in this way, the data from the two sources (Station 99 and the Headingley weigh scale) for the corresponding truck were referred to as “paired”. In such a case, the WIM records from Station 99 are then retrieved for the positively-identified truck using the known vehicle characteristics and time stamp from the camera footage. The WIM records contain the loads for each axle as measured by the piezo-quartz WIM site (Station 99). When the WIM records are retrieved, they are checked to ensure that the time stamp matches the time of passage (as recorded by the camera), and the axle spacings match the truck description. Classifying the vehicle configuration of all WIM records from the day of the study according to the Highway Traffic Act, Regulation 575/88 (MI, 2017) expedited the process of matching the axle spacings.

When data is paired for a given truck, it is then possible to compare the weights measured by the WIM site at Station 99 with the weights recorded at the Headingley weigh scale for the same axle groups of the same trucks. Assuming the axle group loads measured at the Headingley weigh scale are deemed to be valid, if the loads of the same axle groups of the same trucks as measured by Station 99 are similar, they are also deemed to be valid.

A truck-pairing survey such as this is referred to by ASTM as a *type-approval test* for a *type I* or *type II* WIM system. ASTM designation E1318-09 (ASTM, 2009) specifies the criteria for such a test; these criteria are referred to as functional performance requirements for WIM systems. These criteria specify tolerances for WIM errors, calculated as percent differences between axle loads from the WIM site in question and the “ground truth” (see Equation 1). Table 1 shows these standards.

Table 1: WIM performance criteria as specified by ASTM. Adapted from ASTM designation E1318-09 (ASTM, 2009).

Function	Tolerance for 95 % Compliance				
	Type I	Type II	Type III	Type IV	
				Value ≥ kg	± lb
Wheel Load	± 25 %	-	± 20 %	2268	136
Axle Load	± 20 %	± 30 %	± 15 %	5443	227
Axle-Group Load	± 15 %	± 20 %	± 10 %	11 340	544
Gross-Vehicle Weight	± 10 %	± 15 %	± 6 %	27216	1134

The criteria set out by ASTM differs depending on the type of WIM system being tested (i.e., *type I*, *type II*, *type III*, or *type IV*). WIM Station 99 is classified as a *type I* system, and therefore the results of this study are compared to the ASTM tolerances in the *type I* field in Table 1. ASTM also recommends a minimum of 51 vehicles to be included in this test. The axle loads from the truck data-pairs were evaluated against these criteria, for both the June 18, 2015 and the June 21, 2016 studies.

These studies were strategically completed based on the calibration schedule of Station 99, such that one study was completed in the short-term after calibration, and the other was completed in the long-term after calibration. This allows for an evaluation of the validity of the piezo-quartz sensors as time elapses after calibration. Table 2 shows the calibration dates and the dates of the truck-pairing surveys.

Table 2: Times between calibration and each truck-pairing study.

Date of Calibration	Date of Truck-Pairing Survey	Difference in Dates
November 26, 2014	June 18, 2015	29 weeks, 1 day (approximately 7 months)
June 2, 2016	June 21, 2016	2 weeks, 5 days

3.5 VALIDITY OF PIEZOELECTRIC WIM STATIONS IN MANITOBA (ANALYSES 3 AND 4)

This analysis addresses the validity of the piezoelectric WIM sites in Manitoba. Two analyses are involved when determining the validity of these sensors: (1) an analysis which identifies whether the measured axle loads are valid, and (2) an analysis which identifies the validity as influenced by external factors. These are discussed in Sections 3.5.1, and 3.5.2 below.

3.5.1 Precision Testing Using Post-Calibration Data

It is well known that characteristics of certain axles within specific trucking configurations are predictable. FHWA (2001) identifies an expected range of 3630 to 5440 kg (8000 to 12 000 lbs) for single axles of FHWA Class 9 vehicles. Work done by Tan (2002) further reveals findings which allow for a better understanding of steering axle loads in Manitoba. Using data collected at the three primary static weigh scales in Manitoba from 2001, Tan identified similarities between the steering axles of certain trucking configurations over time. Specifically, when looking at the steering axle load distributions for 3-S2, 3-S3, and 3-S3-S2 trucks (see Table 3) from weigh scale data over all four seasons (spring, summer, fall, winter), Tan noticed that the average of the steering axle loads never changed by more than 1.5 percent over the course of the year 2001.

Table 3: Schematic of 3-S2, 3-S3, and 3-S3-S2 trucks.

Configuration	FHWA Classification	Schematic of Vehicle
3-S2	Class 9	
3-S3	Class 10	
3-S3-S2 (8-Axle B-Train)	Class 13	

Based on these results, it is hypothesized that mean steering axle loads of these trucks observed in Manitoba are precise in the post-calibration time periods. This analysis starts by testing this hypothesis using statistical significance testing. The steering axle loads to be tested come from the 2015 and 2016 weigh scale surveys conducted at the Headingley static weigh scale, (see Section 3.1.1). These surveys are the best available representation of true axle loading conditions, assuming data observed at the static weigh scales is deemed valid. Since these surveys were taken at a common location at different times of the year, the steering axle loads can be analysed in order to verify their consistency. To identify similarities between the steering axle loads from different periods of the year, they will be subjected to a series of independent samples T-tests. The procedure is as follows:

- Two weigh scale samples are identified, and the mean steering axle weights of 3-S2, 3-S3, and 3-S3-S2 trucks are computed.
- A T-statistic is calculated using Equations 4 and 5.
- The p-value is calculated as the proportion of area under the T-distribution (with n degrees-of-freedom, calculated using Equation 6) beyond ± T standard deviations (both tails).

- This test is repeated with two different weigh scale samples until all combinations have been exhausted.

Calculating a T-statistic:

$$t = \frac{(\overline{x}_1 - \overline{x}_2)}{S.E.} \tag{4}$$

Where: t *is the T-statistic,* $\overline{x}_1$ *is the average steering axle load from the first sample,* $\overline{x}_2$ *is the average steering axle load from the second sample, and* $S.E.$ *is the standard error for the difference between the means of the two samples, calculated as follows:*

$$S.E. = \sqrt{\frac{{S_1}^2}{n_1} + \frac{{S_2}^2}{n_2}} \tag{5}$$

Where: S_1 *is the sample standard deviation of the first sample,* S_2 *is the sample standard deviation of the second sample,* n_1 *is the size of the first sample, and* n_2 *is the size of the second sample.*

Calculating degrees of freedom for selection of appropriate T-distribution:

$$df = n_1 + n_2 - 2 \tag{6}$$

Where: df *is the degrees-of-freedom,* n_1 *is the size of the first sample, and* n_2 *is the size of the second sample.*

If the computed p-value is low (i.e., $p < 0.05$), the two samples are more different than expected had they been taken from the same population; hence they are not "statistically similar". If the computed p-value is high (i.e., $p \geq 0.05$), the samples are similar enough to pass as being from the same population, regardless of whether they actually are from the same population; hence they are "statistically similar". This procedure will statistically confirm whether steering axle loads are consistent over time in Manitoba.

Assuming steering axle loads are deemed to be consistent over time, steering axle loads as measured by piezoelectric WIM sites in Manitoba can be analysed based on this knowledge. If these piezoelectric WIM sites produce valid loads, then it can be expected that steering axle loads for the same truck configurations (i.e., 3-S2, 3-S3, and 3-S3-S2) should not significantly change over time. However, if it is found that these steering axle loads significantly change over time (i.e., distributions separated by time are not "statistically similar"), it is likely that axle loads (for all axle groups) measured by piezoelectric WIM sites are drifting with time, and hence are not completely valid.

In order to test the consistency of steering axle loads from piezoelectric WIM sites, axle loading data from all six piezoelectric WIM stations is analyzed, in the time period following the most recent site calibration. The time immediately following calibration is preferable here, since this is the time when the sensors are most likely to still be within calibration (equipment has been recently verified). Therefore, if large fluctuations are found in the observed steering axle loads post-calibration, and this data is not found to be completely valid, then the data validity at these sites should be investigated further.

The time period of analysis is set to four-weeks post-calibration, since out of all static weigh scale surveys at Headingley which were analyzed for consistent steering axle loads, the two with the smallest temporal difference are approximately one month apart. Fluctuations within four-weeks post-calibration are abnormal and indicative of a poor ability of the WIM sites to capture the true axle loads. Table 4 shows the most recent calibration dates and subsequent selected analysis periods.

Table 4: Most recent calibration date for each WIM station in Manitoba equipped with piezoelectric sensors, and subsequent periods selected for analysis of measured steering axle loads.

Station	Direction of Traffic Flow	Most Recent Day of Calibration	Period Selected for Post-Calibration Analysis
61 – Brokenhead	EB/WB	Nov 27, 2014	Nov 28 – Dec 25, 2014
62 – Oak Lake	EB/WB	Dec 18, 2014	Dec 19, 2014 – Jan 15, 2015
63 – Glenlea	NB/SB	Nov 26, 2014	Nov 27 – Dec 24, 2014
65 – MacGregor	EB/WB	Dec 16, 2014	Dec 17, 2014 – Jan 13, 2015
66 – Nesbitt	EB/WB	Dec 15, 2014	Dec 16, 2014 – Jan 11, 2015 *
80 - Russell	EB/WB	Dec 17, 2014	Dec 18, 2014 – Jan 14, 2015

* Indicates that not all data from the original intended analysis period was able to be analyzed. In this case, Station 66 encountered equipment malfunction in the eastbound and westbound WIM lanes starting on January 12, 2015. Therefore, no data was available on this day for analysis.

The same independent samples T-test used to compare steering axle loads measured at the static weigh scales is used to compare steering axle loads measured by the piezoelectric WIM sites. The only difference is that the goal is to identify similarities in this data from one-week post-calibration to the next for a period of four weeks. The procedure for these T-tests is as follows:

- Separate the post-calibration data measured by a piezoelectric WIM station in a given traffic lane into four one-week periods.
- Compare the first week post-calibration to the second week post-calibration by computing the mean steering axle weights of 3-S2, 3-S3, and 3-S3-S2 trucks. The algorithms used to confirm the FHWA classification of these trucks based on axle spacing are based on the Highway Traffic Act, Regulation 575/88 (MI, 2017), and are shown in Appendix F.
- Calculate the T-statistic (see Equations 4 and 5 above).
- Calculate p-value in the same manner as calculated when running the T-test on the static weigh scale data.

- The T-test is run twice more comparing the first week post-calibration to the third week post-calibration, and comparing the first week post-calibration to the fourth week post-calibration.
- Repeat the procedure for each WIM lane of each piezoelectric WIM site.

The results from these T-tests help to determine the validity of axle loads measured by piezoelectric sensors in Manitoba.

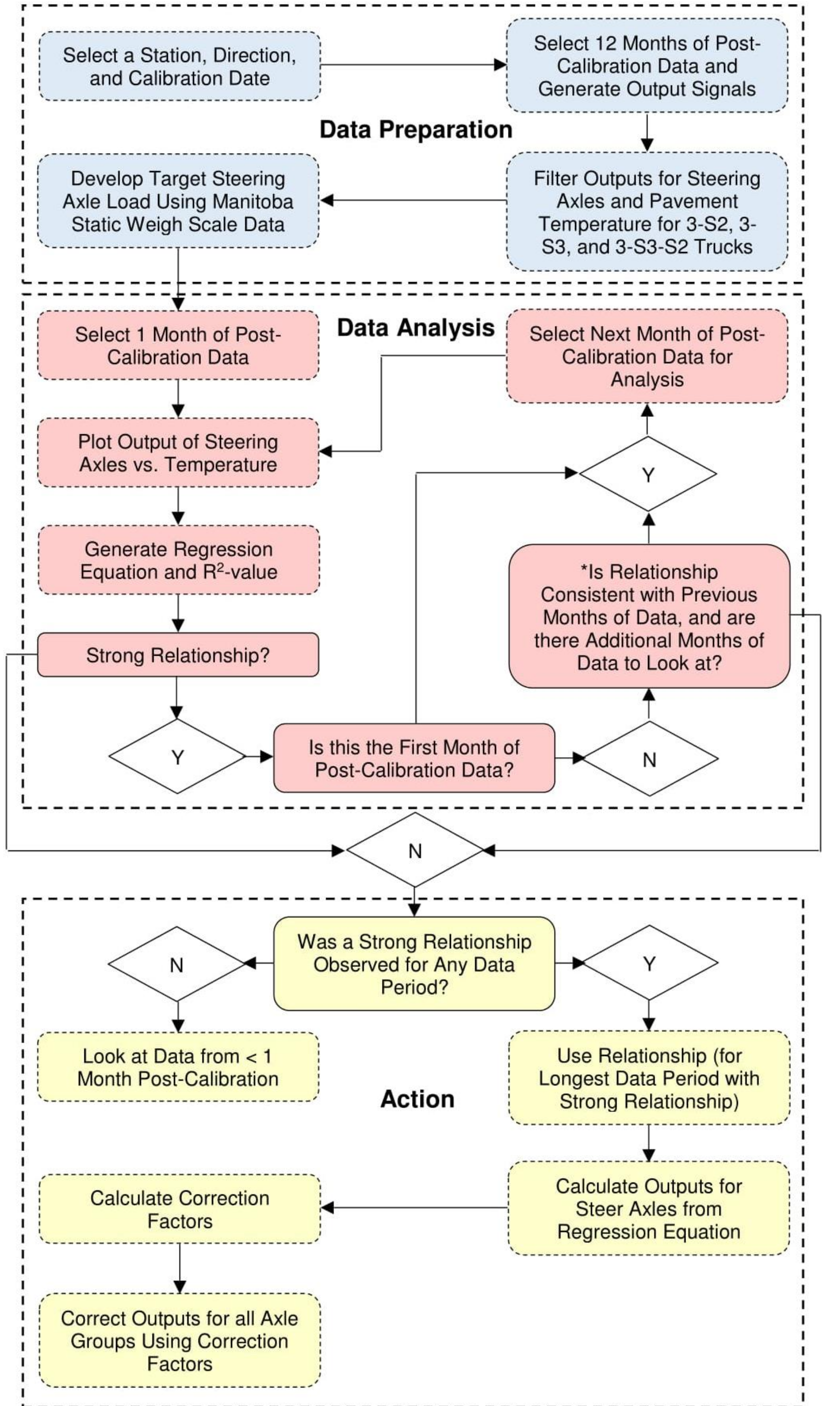
3.5.2 Sensitivity to Temperature

Piezoelectric WIM systems in Manitoba currently use generic factory default correction factors (i.e., $F_{Correction}$, Equation 2) developed by the WIM vendor to compensate for the effects of temperature. Hence, there is opportunity to produce similar but more accurate temperature correction factors using site-specific data from Manitoba's WIM stations. This research develops these factors using a similar procedure to the one recommended by IRD. However, the procedure used in this research has additional goals as follows:

1. Determine the strength of the relationship between temperature and the WIM output signal for steering axles of selected trucks using site-specific Manitoba WIM data.
2. Determine the length of time post-calibration for which the relationship between output signal and temperature remains strong and the procedure can be reasonably applied.
3. Determine the nature of the relationship between temperature and output (i.e., linear, multi-linear, quadratic, exponential, etc.).
4. Use target steering axle loads from Manitoba static weigh scale data which best represent the location of the piezoelectric WIM site. These target loads reflect the average steering axle loads from 3-S2, 3-S3, and 3-S3-S2 trucks.

Following the studies discussed in Section 3.5.1, in this analysis, the principle of steady steering axle loads applies to 3-S2, 3-S3, and 3-S3-S2 configuration trucks, as the steering axle loads for all of these trucks are tested for similarities over time in Manitoba. Therefore, if no site-specific correction factors were required, the WIM output signals for these select steering axles would remain consistent.

The methodology for developing these temperature correction factors and further investigating the relationship between temperature and steering axle loads is outlined in the flow chart in Figure 9.



*When examining output-temperature relationships for consistency, compare to the month of data nearest to calibration, with the largest temperature-range overlap. Criteria for comparisons are outlined in this section.

Figure 9: Procedure used for developing and evaluating temperature correction factors for Manitoba WIM sites equipped with piezoelectric sensors.

After selecting the 12 months of post-calibration data for this analysis, it is crucial to understand any data processing occurring prior to receipt of the data. Two types of in-service adjustments may be made to the WIM output signal between on-site calibrations (see Equation 2):

- Periodic adjustments to $F_{Calibration}$, carried out by technicians.
- Automatic system adjustments to compensate for temperature, based on a set of temperature correction factors. In this case, the output signal is always multiplied by the $F_{Correction}$ corresponding to the pavement temperature at the time of load measurement.

Historical system settings for the piezoelectric WIM sites were checked (see "Data Preparation" in Figure 9) to determine if/how the in-service adjustments were carried out prior to receipt of data. If it is found that $F_{Calibration}$ was adjusted after the most recent calibration, such an adjustment must be undone so that the data is reflective of a constant $F_{Calibration}$ for the entire data analysis period. Additionally, since a primary goal of this analysis is to account for the effects of pavement temperature on axle loads, any data adjustments made to account for temperature (i.e., $F_{Calibration}$) must be undone such that the data is not biased.

The WIM system settings for stations 63, 66, and 80 were checked by analysts at IRD to determine the set of correction factors used (i.e., $F_{Correction}$). For these three stations (six WIM lanes total), it was confirmed that the axle loads had been multiplied by the factory default temperature correction factors. Therefore, these adjustments made based on $F_{Correction}$ are undone. The default factors are shown in Appendix C. Unfortunately, IRD analysts were unable to confirm the correction factors for stations 61, 62, and 65. Therefore, these stations were excluded from this analysis.

Furthermore, it was confirmed by technicians that in-service adjustments were made to $F_{Calibration}$ in the WIM system settings between on-site calibrations. Table 5 shows the dates of these adjustments, as well as the calibration factors applied to the output signal. These adjustments were undone, such that the axle loads consistently reflect the $F_{Calibration}$ set at the most recent on-site calibration for the entire analysis period.

Table 5: Calibration factors used at WIM stations 63, 66, and 80.

WIM Lane	Most Recent On-Site Calibration	Calibration Factor Set at Most Recent On-Site Calibration	Date of Calibration Factor Adjustment	Calibration Factor Used After Adjustment
Station 63 NB	Nov 26, 2014	1.19	April 1, 2015	0.56
Station 63 SB	Nov 26, 2014	1.12	April 1, 2015	0.49
Station 66 EB	Dec 15, 2014	0.89	August 28, 2015	0.57
Station 66 WB	Dec 15, 2014	0.68	August 28, 2015	0.46
Station 80 EB	Dec 17, 2014	0.97	March 26, 2015	0.56
Station 80 WB	Dec 17, 2014	0.70	March 26, 2015	0.40

When adjustments made based on $F_{Calibration}$ and $F_{Correction}$ are undone in this manner, the remaining data representes the raw, unadjusted output signal (see Equation 2). These output signals are reflective of: (1) a consistent $F_{Calibration}$, and (2) no adjustments accounting for temperature. These output signals can be investigated at different temperature ranges to determine whether site-specific $F_{Correction}$ are beneficial.

The procedure outlined in Figure 9 produces a relationship between pavement temperature (independent variable), and WIM output signal for steering axles (dependent variable), and identifies whether this relationship deteriorates with elapsed time after calibration. It is critical to understand whether this output-temperature relationship maintains its characteristics over time, since it can be used to generate site-specific temperature correction factors. If the output-temperature relationship remains consistent over time, then the site-specific temperature correction factors will contribute to the validity of the axle load data long after calibration.

In determining the consistency of the output-temperature relationship, it is broken into 1-month long post-calibration sections, and the relationships generated for each month-long time period can be compared against one-another. Different months will reveal this relationship within different temperature ranges (i.e., some months are warmer/colder than others). In this analysis, the output-temperature relationship for a given month is compared against the output-temperature relationship from the previous month nearest to calibration, with the largest overlap in temperature range. Since some degree of robustness is required for comparison, three criteria are established which reveal consistency in the relationships:

- Similar coefficients of determination (R^2 values) (pragmatically assigned a grade of 1 if R^2 is within 0.25, 0.5 if R^2 is within 0.5, 0 otherwise).
- Similar relationship shapes (pragmatically assigned a grade from 0 to 1; qualitatively assigned based on eye-test).
- Root-mean square error (RMSE) between output signals at similar temperatures from one month to another is reasonably low (pragmatically assigned a grade from 0 to 3, see Table 6).

The output-temperature relationships for month-long periods are compared quantitatively, based on similarities in the outputs (dependent variable) at similar temperatures. The RMSE is used to evaluate the degree-of-similarity of the relationships, calculated using Equation 7.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (7)$$

Where: y_i *is the output signal for the second comparison month at the i*th *temperature range,* $\hat{y}_i$ *is the output signal for the first comparison month at the i*th *temperature range, and* n *is the number of overlapping temperature ranges.*

Table 6 shows the points assigned based on RMSE:

Table 6: Points awarded for RMSE in test of output-temperature relationship continuity over post-calibration time elapsed.

RMSE Within (% of Average Output Signal)	Points Awarded
Infinity	0
18	0.5
15	1
12	1.5
9	2
6	2.5
3	3

A total score out of five is used to pragmatically describe the degree to which the output-temperature relationship remains constant after calibration. A score from 0 to 2 indicates that the relationship does not remain constant during/after the month being evaluated. In this case, output signals measured at a WIM lane would be unpredictable with respect to temperature. A score from 2.5 to 3.5 indicates that the relationship remains constant to an acceptable degree. A score from 4 to 5 indicates that the relationship remains constant with a high degree of confidence. In this case, output signals measured at a WIM lane would have a response to temperature which can be trusted long-term (barring physical changes at the WIM site).

A regression formula is produced for this output-temperature relationship, using data from all post-calibration months for which the relationship holds constant. The relationship expresses observed output signals for steering axles as a function of pavement temperature for a given WIM lane. Using this relationship, correction factors are calculated in a similar manner as discussed in Section 2.2, as follows:

- For each temperature value, find the typical output signal using the regression equation developed.
- Divide the target steering axle load by the output signal to yield the correction factor for the particular temperature value.

This procedure to develop calibration factors is applied to data from WIM sites 63, 66, and 80 (for each lane separately).

It should be noted that this output-temperature relationship is not intended as a model with which output signals or axle loads can be predicted. This relationship is strictly developed to observe output signals at various temperature ranges and determine correction factors which can be used to compensate for site-specific temperature effects and potentially report WIM axle loads with increased validity. Additionally, use of the improved site-specific correction factors limits the need to adjust calibration factors between on-site calibrations. As per standard practices (Roy Czinku, personal communication, January 3, 2017), the calibration factors may be applied to all axle groups of all truck configurations, and not just the steering axle groups from select configurations, as temperature will affect all of these axle groups similarly.

Based on experience by IRD (Roy Czinku, personal communication, May 3, 2016), a significant change or degradation in WIM site conditions will likely result in a significant change in the output-temperature relationship. Therefore, if a significant change occurs in a Manitoba WIM site, the output-temperature relationship may be significantly altered and must be re-developed. Any adjustments made to the calibration factor after on-site calibration also affect the output signal. Additionally, a significant degradation of the output-temperature relationship may indicate that site conditions have been altered either abruptly or over time. This would warrant investigation into the history of the WIM site.

3.6 DATA QUALITY CHECKS AND COMPARISON OF WIM DATA (ANALYSIS 5)

After investigating the validity of piezoelectric and piezo-quartz WIM sites in Manitoba, three data options warrant further investigation and comparison through standard quality checks:

1. Data from piezoelectric WIM sites, as received. With this data, the effects of temperature have been compensated for using the default correction factors (i.e., $F_{Correction}$, Equation 2) developed by the vendor, as well as adjustments to the WIM calibration factors (i.e., $F_{Calibration}$, Equation 2) (*Option 1* from Section 3.2). In this research, this is referred to as data "as currently processed in Manitoba".
2. Corrected data from piezoelectric sites. With this data, all adjustments to calibration/correction factors have been undone (calibration factors remain the same as set during most recent on-site calibration), and the effects of temperature have been compensated for using the site-specific temperature correction factors developed in this research (*Option 2* from Section 3.2). In this research, this is referred to as "site-specific corrected" data.

3. Data from the piezo-quartz WIM site installed in Manitoba (*Option 4* from Section 3.2).

These three options warrant further comparison and investigation due to the similarities in equipment. Unlike the case with the static weigh scales, all of these options involve high-speed *type I* or *type II* WIM equipment (as designated by ASTM) and data retrieval is possible with no major on-site upgrades beyond regular maintenance.

These three options will first be compared by means of the statistical independent samples T-Test using steering axle load data, discussed in Section 3.5.1. Section 3.5.1 describes the procedure for determining piezoelectric WIM precision through testing the consistency of steering axle loads for select truck configurations. This same test will be performed for the site-specific corrected data from the piezoelectric WIM sites. The same 4-week post-calibration time periods used for the T-test on the data as currently processed in Manitoba (see Section 3.5.1) will be used for the T-test on the site-specific corrected data.

Similarly, this T-test will also be performed for the data from the piezo-quartz WIM site in Manitoba (WIM Station 99). In the case of WIM Station 99, calibration was most recently performed on June 2, 2016. Therefore, the post-calibration time period to be used for the T-test on this data will range from June 3 to June 25, 2016. This analysis period was initially set for longer to capture a full four-weeks post-calibration; however, equipment malfunction at this site starting on June 26, 2016 prevented any data analysis past June 25. The relative results of these T-tests will help to determine whether correcting data from piezoelectric sensors using site-specific studies, or upgrading to piezo-quartz sensors will yield improvements in data validity.

The final means of comparison for these three options involves a basic GVW check to identify potentially invalid data. A typical quality check used by LTPP (FHWA, 2001a) is to filter out GVW measurements for FHWA Class 9 trucks and analyze the observations near the top-end of the GVW spectra. A high number of Class 9 GVW observations exceeding legal weight limits is unusual for most jurisdictions (with the exception of areas providing high numbers of overweight permits) and is a possible indication of questionable WIM calibration. To confirm that this is the case in Manitoba, it is prudent to study Class 9 GVWs near and above the legal limits.

The legal Class 9 GVW limit in Manitoba is 40 000 kg (39 500 kg before the year 2016) (MI, 2017). Analysis of data from the 2013, 2015 and 2016 Manitoba primary static weigh scale surveys (see Section 3.1.1), allows for the determination of Class 9 GVWs in Manitoba which are rarely exceeded. From these surveys, the maximum observed GVW from approximately 3800 Class 9 vehicles was 40 570 kg. This figure was rounded-up to 41 000 kg, to produce a conservative value. Therefore, data from all three options discussed in this section were screened for Class 9 GVWs exceeding 41 000 kg, representing a reasonable maximum GVW for these vehicles in Manitoba.

Similarly, trucks observed below the typical empty GVW are also abnormal. In studying the same static weigh scale surveys, the minimum observed GVW from approximately 3800 Class 9 vehicles was 11 240 kg. This was rounded down, producing a reasonable minimum GVW for these vehicles of 11 000 kg in Manitoba. Therefore, data from all three options discussed in this section were screened for Class 9 GVWs below 11 000 kg. A high percentage of trucks observed either above or below these respective thresholds is thus a sign of invalid data.

4 ANALYSIS AND DISCUSSION

This chapter presents the results of the data analyses, and evaluates the axle load data sources against relevant data quality principles.

4.1 STATIC WEIGH SCALE VALIDITY RESULTS (ANALYSIS 1)

This section presents the results of the static weigh scale qualitative and quantitative analyses conducted from 2015 to 2016 at the Headingley weigh scale. Key findings from qualitative observations of operations at the weigh scale are as follows:

- The temporal scope of data collection depends on availability of personnel to observe data. As with any traffic monitoring equipment, the absence of data from any parts of the day may lead to an under-representation of some vehicles.
- All vehicles of FHWA Class 5 or higher are required by law to pull through the scale. Although FHWA Class 4 vehicles (i.e., buses) are commonly used in pavement design applications, these vehicles are not always weighed.
- Given the number of possible routes, it is impossible for the static weigh scales to survey 100% of trucks operating on the main highway corridors in Manitoba.
- During peak hours, when the queue for the weigh scale reaches a critical length, excess trucks are waived by for safety purposes. Therefore, trucks operating at excessively busy times – such as peak daytime hours – may be under-represented.

When comparing official “billed” weights to typical “rolling” weights at the Headingley weigh scale, only a very limited number of overweight instances were observed. In total, four overweight violations were captured and recorded in this study. One of the trucks was carrying livestock and is not presented in these results due to instability of loads associated with vehicles carrying livestock. The other three observations are summarized in Table 7 and Table 8.

Table 7: Raw results from comparison between official "billed" weights and typical "rolling" weights at Headingley weigh scale.

Observation	Configuration	Body Type	Measurement Type	Axle Group 1 (kg)	Axle Group 2 (kg)	Axle Group 3 (kg)
1	Steering-Tandem-Tandem	Flat	Rolling 1	4730	18 920	*
			Rolling 2	4930	18 610	*
			Billed	4730	18 450	13 260
2	Steering-Tandem-Tridem-Tandem*	Hopper	Rolling 1	5450	16 960	*
			Rolling 2	5650	*	*
			Billed	5520	16 820	23 420
3	Steering-Tandem	Dump	Rolling 1	6250	18 250	N/A
			Rolling 2	*	*	N/A
			Billed	6220	18 370	N/A

* Indicates that a measurement was not able to be made for particular axle group

Table 8: Percent differences between official "billed" weights and typical "rolling" weights at Headingley weigh scale.

Observation	Percent Difference: Rolling - Billed	
	Axle Group 1 (Steering)	Axle Group 2 (Tandem)
1	0.00	2.55
	4.23	0.87
2	-1.27	0.83
	2.36	*
3	0.48	-0.65

* Indicates that a measurement was not able to be made for particular axle group

Table 7 and Table 8 reveal that although the sample size is small, no axle group was observed at more than 4.23 percent from its respective billed weight while rolling over the scale. While it would certainly be valuable to observe more such results over a much longer time period, these results serve as a preliminary check, and suggest that data validity is not a significant issue at this scale; even considering that the majority of observations are made as trucks roll over the scale at approximately 5 km/h.

This section also contains results of the study which tested precision of weights observed and recorded at static weigh scales by comparing the two successive load readings recorded for each axle group while slowly rolling over the load cell at the scale. Over the three applicable surveys at the Headingley weigh scale (see Section 3.1.1), 1011, 100, 1748, and 192 such comparisons were made for steering axles, single axles, tandem axles, and tridem axles, respectively. The lower number of comparisons for single and tridem axle groups is a result of the lower frequency of observations of these axle groups relative to steering and tandem axle groups. Figure 10 shows the results of this study.

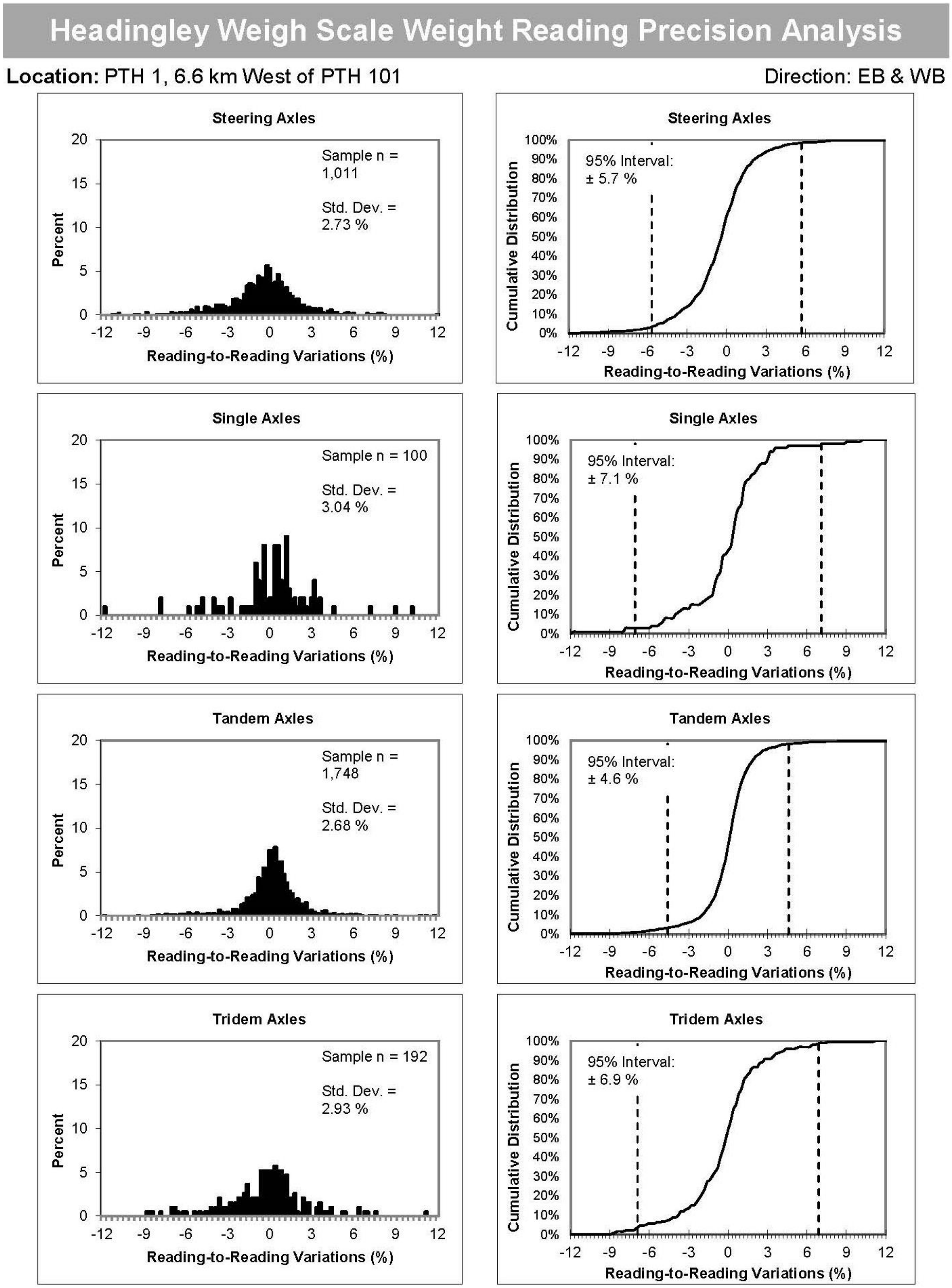


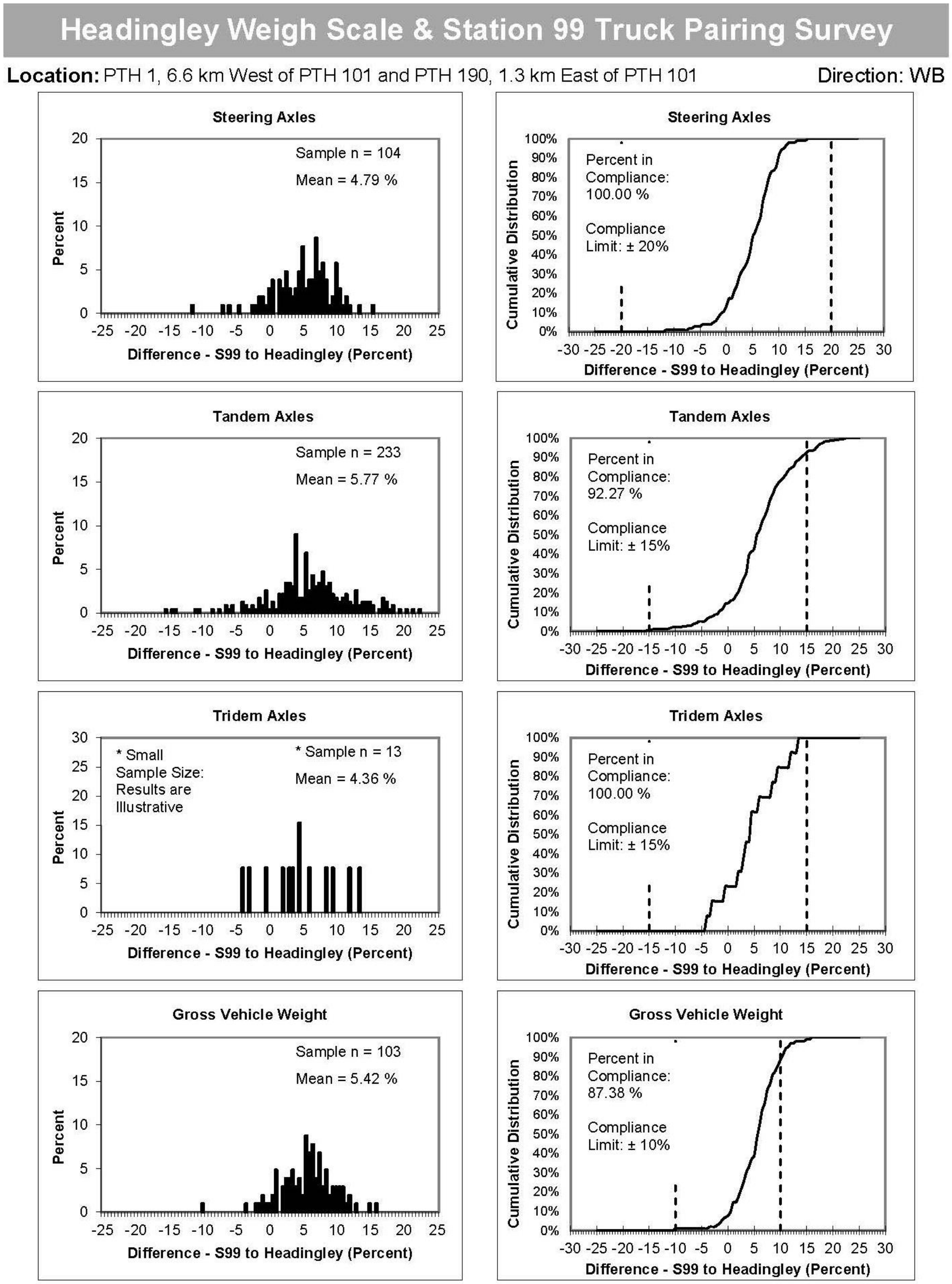
Figure 10: Results for steering axles, single axles, tandem axles and tridem axles for axle load measurement precision studies conducted at the Headingley weigh scale.

Figure 10 reveals the degree-of-precision of axle load measurements recorded at the Headingley weigh scale. 95 percent of axle group load reading-to-reading variations were within ± 5.7 percent, ± 7.1 percent, ± 4.6 percent and ± 6.9 percent for steering, single, tandem, and tridem axle groups, respectively. These results suggest that if a given axle group were repeatedly weighed by the load cell at the scale under normal operating conditions, differences would be unlikely to exceed 7 percent.

4.2 PIEZO-QUARTZ VALIDITY RESULTS (ANALYSIS 2)

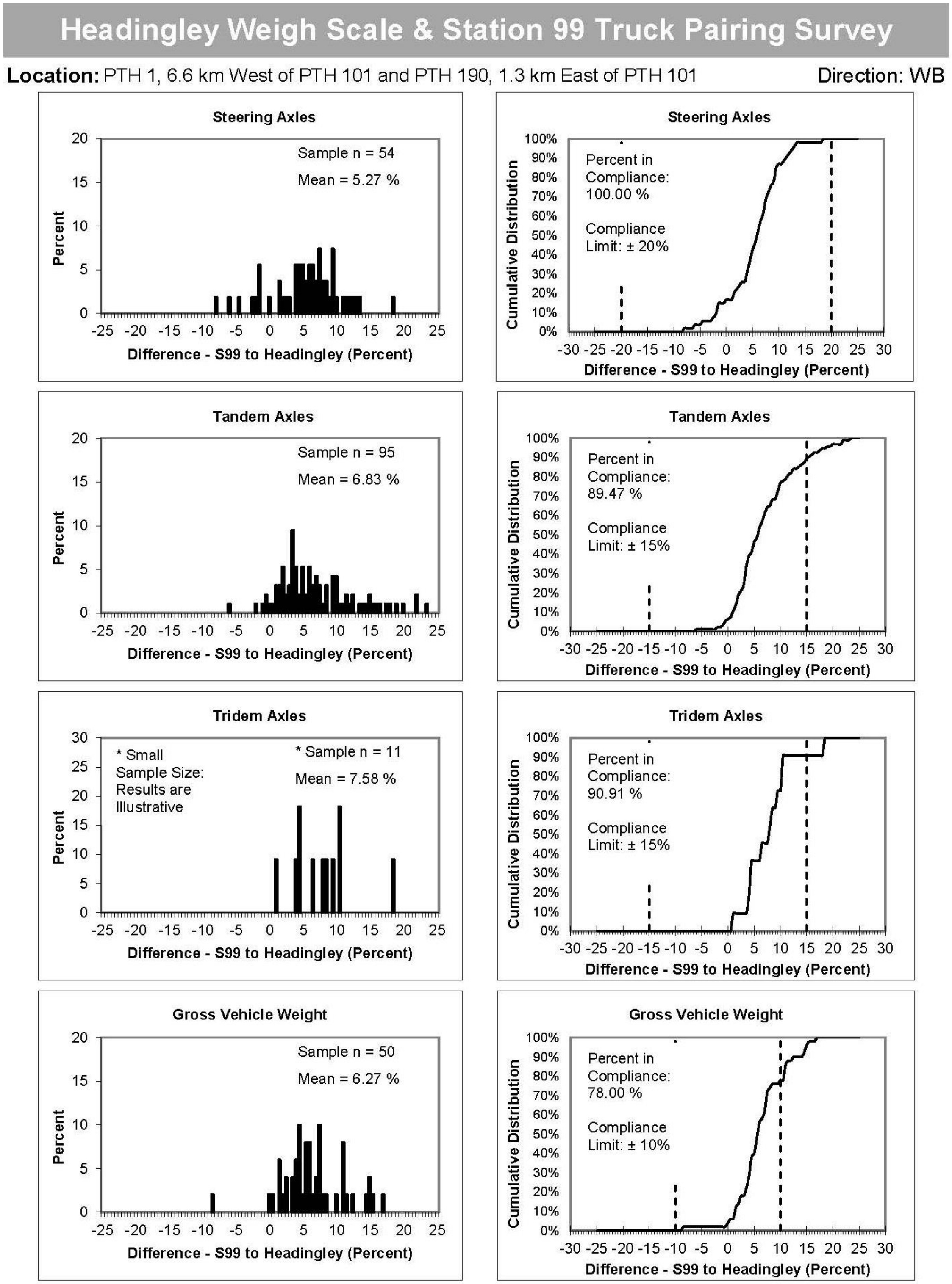
This section presents the results of the truck-pairing surveys conducted between WIM Station 99, located on PTH 190, and the static weigh scale located on PTH 1 in Headingley, Manitoba. The truck-pairing survey completed on June 18, 2015 produced 110 trucks for which loads recorded by Station 99 could be compared to the same loads recorded at the Headingley weigh scale. The truck-pairing survey completed on June 21, 2016 produced 55 trucks for which loads recorded by Station 99 could be compared to the same loads recorded at the Headingley weigh scale. Both surveys satisfy the recommended minimum number of 51 trucks with paired load data, as specified by ASTM.

Figure 11 and Figure 12 show the results of the June 18, 2015 and June 21, 2016 surveys, respectively.



* Note: Percent in compliance refers to compliance with ASTM standards, not the legal weight limits.

Figure 11: Results for steering axles, tandem axles, tridem axles, and GVW for Station 99-Headingley truck-pairing survey conducted on June 18, 2015.



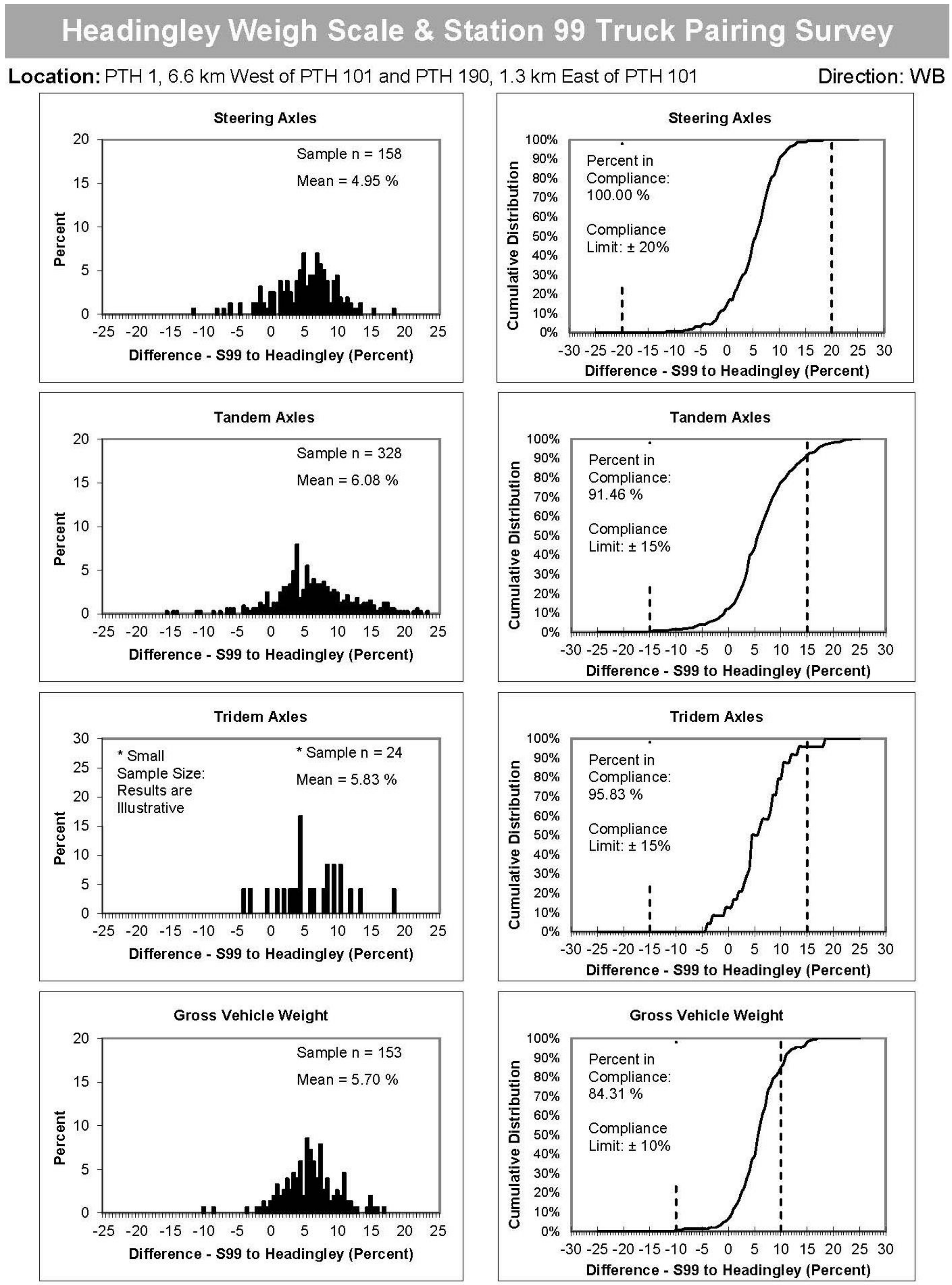
* Note: Percent in compliance refers to compliance with ASTM standards, not the legal weight limits.

Figure 12: Results for steering axles, tandem axles, tridem axles, and GVW for Station 99-Headingley truck-pairing survey conducted on June 21, 2016.

For the June 18, 2015 survey, loads recorded by Station 99 were slightly higher than loads recorded at the Headingley weigh scale. This bias ranged from between 4.36 percent to 5.77 percent for the various axle groups. Additionally, the compliance rates with ASTM specifications for steering axles, tandem axles, tridem axles, and GVWs were 100.00 percent, 92.27 percent, 100.00 percent, and 87.38 percent, respectively. The compliance rates for steering axles and tridem axles surpass ASTM specifications, while the compliance rates for the other axle groups are slightly below ASTM specifications.

For the June 21, 2016 survey loads recorded by Station 99 were also slightly higher than loads recorded at the Headingley weigh scale. This bias ranged from between 5.27 percent to 7.58 percent for the various axle group types. Additionally, the compliance rates with ASTM specifications for steering axles, tandem axles, tridem axles, and GVWs were 100.00 percent, 89.47 percent, 90.91 percent, and 78.00 percent, respectively. The compliance rate for steering axles surpass ASTM specifications, while the compliance rates for the other axle groups are slightly below ASTM specifications.

Based on these results, there is little difference between performance of WIM Station 99 at approximately seven months (June 18, 2015 survey) and three weeks (June 21, 2015 survey) post-calibration, relative to the Headingley weigh scale. The distributions describing WIM performance have similar shapes, spreads, and (positive) biases. Therefore, in this research, no significant deterioration in WIM site performance was found as post-calibration time elapsed. For these reasons, it was decided to “pool” the results of both studies, in order to describe the general performance of WIM Station 99 in Manitoba. Figure 13 shows these pooled results.



* Note: Percent in compliance refers to compliance with ASTM standards, not the legal weight limits.

Figure 13: Pooled results for steering axles, tandem axles, tridem axles, and GVW for both Station 99-Headingley truck-pairing surveys.

For the pooled results, similar observations can be made as compared to the individual surveys. Loads recorded by Station 99 were slightly higher than loads recorded at the Headingley weigh scale. This bias ranged from between 4.95 percent to 6.08 percent for the various axle group types. Additionally, the compliance rates with ASTM specifications for steering axles, tandem axles, tridem axles, and GVWs were 100.00 percent, 91.46 percent, 95.83 percent, and 84.31 percent, respectively. The compliance rates for steering axles and tridem axles surpass ASTM specifications, while the compliance rates for the other axle groups are slightly below ASTM specifications.

In these results, strong sample sizes are available for steering and tandem axles, as well as GVWs. Due to the relatively rare occurrence of tridem axles, the sample sizes observed were not as large and thus more tridem axles should be surveyed in order to obtain more concrete results.

It is also useful to determine the percent error between loads measured at WIM Station 99 and the Headingley weigh scale at 95 percent confidence (i.e., the interval capturing 95 percent of errors). Table 9 shows these intervals for the pooled results.

Table 9: Percent error at 95 % confidence for steering, tandem and tridem axles, and GVW.

Axle Group	Steering	Tandem	Tridem	GVW
Percent Error at 95 % Confidence	± 11.5 %	± 17.1 %	± 13.5 %	± 12.5 %

Table 9 shows that the errors at 95 percent confidence are close to specifications set by ASTM. It can be seen that for tandem axles and GVW, the errors at 95 percent confidence are outside the respective errors of 15 percent and 10 percent set out by ASTM. For steering and tridem axles, the errors at 95 percent confidence are within the respective errors of 20 percent and 15 percent set out by ASTM.

4.3 PIEZOELECTRIC SENSOR VALIDITY RESULTS (ANALYSES 3 AND 4)

4.3.1 Steering Axle Characteristics at Static Weigh Scales

Analysis of data from the five surveys conducted at the Headingley static weigh scale in 2015 and 2016 (see Section 3.1.1) reveals similarities between the steering axle load measurements of 3-S2, 3-S3, and 3-S3-S2 configuration trucks. Table 10 shows the average steering axle loads recorded for each of the five weigh scale surveys.

Table 10: Characteristics of steering axle loads from 3-S2, 3-S3, and 3-S3-S2 configuration trucks at the Headingley static weigh scale.

Survey Date	Survey Number	Sample Size of 3-S2, 3-S3, and 3-S3-S2 Trucks	Average Load (kg)	Standard Deviation of Loads (kg)
June 18, 2015	1	520	5252	367
July 29-30, 2015	2	493	5229	344
Nov 25-26, 2015	3	456	5201	349
Mar 1-2, 2016	4	345	5149	337
June 21, 2016	5	237	5192	313

Table 11 shows the results of the independent samples T-tests used to determine similarities in measured steering axle values. One statistical T-test was performed for each survey pair to establish similarities or differences between each of the surveys; therefore, ten such T-tests were performed.

Table 11: T-test results for identifying similarities in steering axle load data recorded during Headingley static weigh scale surveys.

Static Weigh Scale Survey Pair	T-Value	p-Value	Difference in Mean Steering Axle Load (%)
1 & 2	-1.00	0.32	-0.42
1 & 3	-2.19	0.03	-0.96

1 & 4	-4.24	< 0.001	-1.96
1 & 5	-2.30	0.02	-1.13
2 & 3	-1.25	0.21	-0.54
2 & 4	-3.38	< 0.001	-1.54
2 & 5	-1.46	0.15	-0.71
3 & 4	-2.15	0.03	-1.01
3 & 5	-0.35	> 0.5	-0.18
4 & 5	1.58	0.12	0.84

Table 10 and Table 11 reveal that five of the ten T-tests (not highlighted in Table 11) show that steering axle load distributions for the weigh scale surveys being compared were statistically similar. Thus, these distributions were so similar that they could reasonably be assumed to be from the same population, despite being from different populations (different time periods). With regards to the other five T-tests (highlighted in Table 11), steering axle load distributions for the weigh scale surveys being compared were not statistically similar, but were still found to be similar with regards to percent differences of means.

These similarities have a practical meaning, because of the time lags between the surveys, and the differing overarching conditions at the times of the surveys. As seen in Figure 3 (see Section 3.1.1), the weigh scale surveys were performed months apart, during different seasons, with trucks operating under differing weight limits. These study results support the hypothesis that steering axle loads from these vehicles in Manitoba are precise over elapsed time periods (see Section 3.5.1).

4.3.2 Statistical T-Test Using WIM Data

This section shows the results of the independent samples T-tests performed using data as currently processed in Manitoba from the six piezoelectric WIM sites. These tests are intended to identify similarities in steering axle loads for 3-S2, 3-S3, and 3-S3-S2 configuration trucks observed at these WIM sites. This is done by comparing loads measured the first week post-calibration to loads measured in subsequent weeks. Table 12 and Table 13 show the results of these T-tests.

Table 12: Characteristics of steering axle load data from piezoelectric WIM stations in Manitoba in post-calibration period.

Station	Steering Axle Parameter	1 Week Post-Calibration	2 Weeks Post-Calibration	3 Weeks Post-Calibration	4 Weeks Post-Calibration
61 Eastbound	Mean	6452	6572	6070	6074
	Difference in Means (%)	-	1.87	-5.92	-5.85
61 Westbound	Mean	6018	6303	5898	6284
	Difference in Means (%)	-	4.74	-2.00	4.42
62 Eastbound	Mean	6672	5585	5072	5428
	Difference in Means (%)	-	-16.30	-23.99	-18.65
62 Westbound	Mean	6955	5520	5039	5536
	Difference in Means (%)	-	-20.63	-27.55	-20.41
63 Northbound	Mean	4764	5271	5858	5896
	Difference in Means (%)	-	10.65	22.97	23.75
63 Southbound	Mean	5295	6491	7242	7311
	Difference in Means (%)	-	22.58	36.75	38.06
65 Eastbound	Mean	5800	5023	4438	4330
	Difference in Means (%)	-	-13.40	-23.48	-25.35
65 Westbound	Mean	5994	5197	4797	4768

	Difference in Means (%)	-	-13.31	-19.98	-20.45
66 Eastbound	Mean	4815	4949	3875	3737
	Difference in Means (%)	-	2.78	-19.53	-22.38
66 Westbound	Mean	5144	4747	4083	3913
	Difference in Means (%)	-	-7.72	-20.62	-23.94
80 Eastbound	Mean	5334	3951	3427	3838
	Difference in Means (%)	-	-25.93	-35.75	-28.05
80 Westbound	Mean	6254	4644	4443	4771
	Difference in Means (%)	-	-25.75	-28.96	-23.70

Table 13: T-test results for identifying similarities in currently processed steering axle load data from piezoelectric WIM stations in Manitoba in post-calibration period.

Station	Statistical Parameter	2 Weeks Post-Calibration	3 Weeks Post-Calibration	4 Weeks Post-Calibration
61 Eastbound	T-value	3.99	-12.30	-11.92
	p-value	< 0.001	< 0.001	< 0.001
61 Westbound	T-value	13.82	-6.34	11.73
	p-value	< 0.001	< 0.001	< 0.001
62 Eastbound	T-value	-50.07	-83.45	-67.80
	p-value	< 0.001	< 0.001	< 0.001
62 Westbound	T-value	-61.38	-92.73	-65.71
	p-value	< 0.001	< 0.001	< 0.001
63 Northbound	T-value	24.97	48.90	51.38
	p-value	< 0.001	< 0.001	< 0.001
63 Southbound	T-value	38.99	48.18	46.70
	p-value	< 0.001	< 0.001	< 0.001

65 Eastbound	T-value	-25.77	-70.00	-84.56
	p-value	< 0.001	< 0.001	< 0.001
65 Westbound	T-value	-34.64	-63.40	-75.02
	p-value	< 0.001	< 0.001	< 0.001
66 Eastbound	T-value	1.62	-17.36	-25.56
	p-value	0.11	< 0.001	< 0.001
66 Westbound	T-value	-5.29	-21.12	-23.17
	p-value	< 0.001	< 0.001	< 0.001
80 Eastbound	T-value	-26.76	-39.73	-34.65
	p-value	< 0.001	< 0.001	< 0.001
80 Westbound	T-value	-36.48	-48.44	-39.57
	p-value	< 0.001	< 0.001	< 0.001

Table 12 and Table 13 reveal considerable variations in mean steering axle loads measured at piezoelectric WIM sites in Manitoba in the post-calibration weeks. Only one post-calibration week-long data sample from one piezoelectric WIM lane (station 66 eastbound lane) showed statistical similarities to the corresponding week-long data sample immediately following calibration. For this particular WIM lane (highlighted in Table 13), the mean steering axle loads were consistent from the first post-calibration week to the second post-calibration week. No other data samples from any other piezoelectric WIM lanes showed any evidence of statistical similarity.

Furthermore, many of the computed T-values and percent fluctuations in mean steering axle loads were more extreme than those same parameters in the case of the Headingley static weigh scale. In some cases, T-values exceeded ± 50 standard deviations and differences exceeded ± 25 %. These parameters illustrate less statistical similarity in steering axle data measured by piezoelectric WIM sites over time, as compared to such data observed at the Headingley static weigh scale. These fluctuations in weights suggest that the precision of these WIM systems degrades substantially even after only one-week post-calibration.

4.3.3 Validity When Considering Temperature

This section presents the results of the investigation of output signals measured at piezoelectric WIM sites over a range of pavement temperatures. Following the results in Section 4.3.1 demonstrating the consistency of steering axle loads for 3-S2, 3-S3, and 3-S3-S2 configuration vehicles in Manitoba, a baseline for such steering loads at piezoelectric sites in Manitoba is first established. These baselines were determined from averaging such steering axle loads observed during the 2013, 2015, and 2016 (see Section 3.1.1) primary static weigh scale surveys in Manitoba, and are referred to as "target" loads. Based on results from Section 4.3.1, a properly-functioning WIM should be recording steering axle loads within close range of these target loads on a consistent basis. Table 14 summarizes the target loads:

Table 14: Target steering axle loads for 3-S2, 3-S3, and 3-S3-S2 configuration trucks as developed at Manitoba's primary static weigh scales.

Station	Static Weigh Scale Representing Target Steering Axle Load	Number of Steering Axle Observations at Static Weigh Scale	Target Steering Axle Load (kg)
63	Emerson	1075	4876
66	Headingley	3840	5162
80	Headingley	3840	5162

Next, steering axle loads for 3-S2, 3-S3, and 3-S3-S2 configuration trucks observed at WIM stations 63, 66, and 80 (six WIM lanes total) are un-factored into output signals and broken into 1-month long post-calibration sections, which are checked for correlation with pavement temperature. This output-temperature relationship is studied on a month-by-month basis to determine if the relationship remains consistent over time elapsed after calibration. Results shown in Appendix D indicate the presence of strong consistency in output-temperature relationships as long as 12 months after on-site WIM calibration. Therefore, in developing and using these relationships to account for sensitivity of WIM sensors to temperature, all months of post-calibration data can reasonably be used up until the recommended re-calibration period of 12 months (ASTM, 2009).

The curves detailing the response of WIM output signals for 3-S2, 3-S3, and 3-S3-S2 steering axles to temperature therefore use all available data up until 12-months post-calibration (when possible), and are shown in Figure 14 through Figure 19 below. In these graphs, $F_{Calibration}$ remains consistent (remains the same as it was set at last on-site calibration), and the default correction factors (i.e., $F_{Correction}$) are not reflected in the data. These output signals are therefore not intended to represent physical axle loads, as they have not been refined by the required factors (see Equation 2).

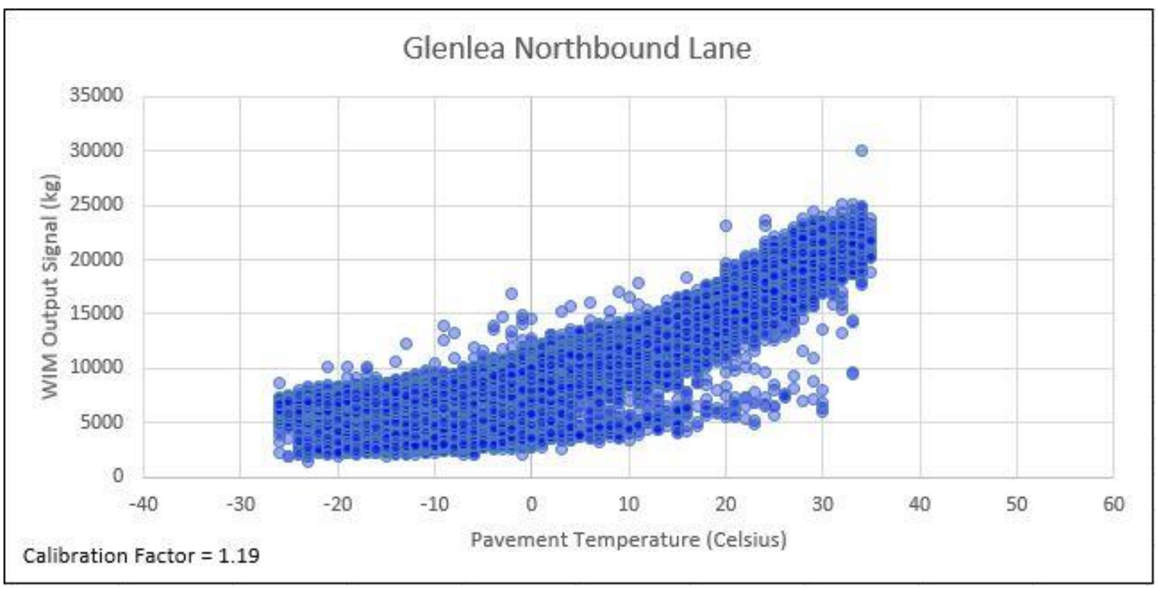


Figure 14: Relationship between WIM output signals for 3-S2, 3-S3, and 3-S3-S2 steering axles and temperature for Station 63 northbound.

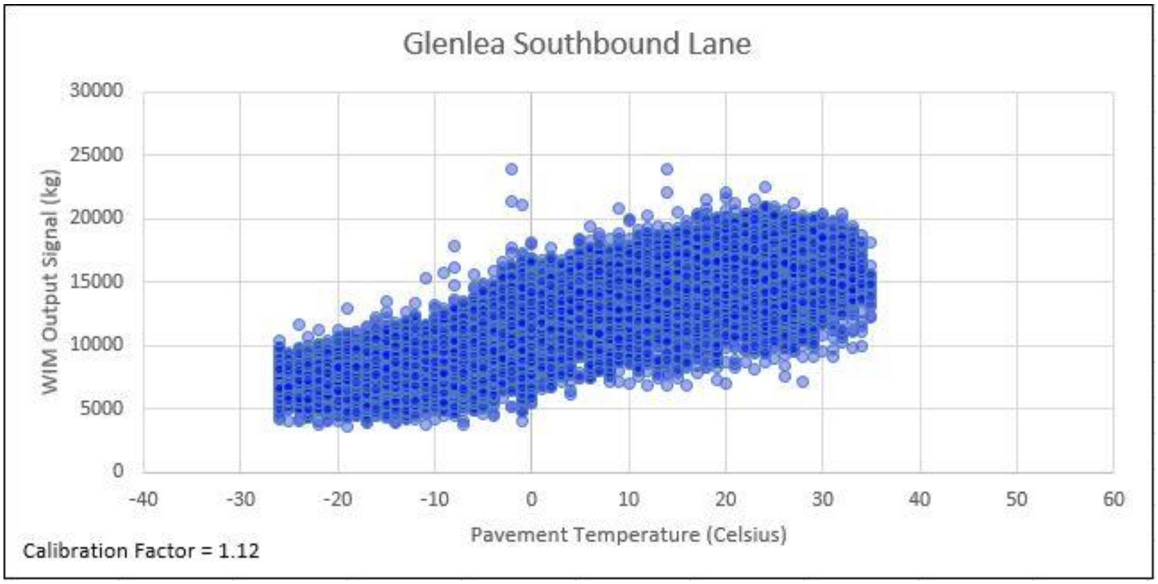


Figure 15: Relationship between WIM output signals for 3-S2, 3-S3, and 3-S3-S2 steering axles and temperature for Station 63 southbound.

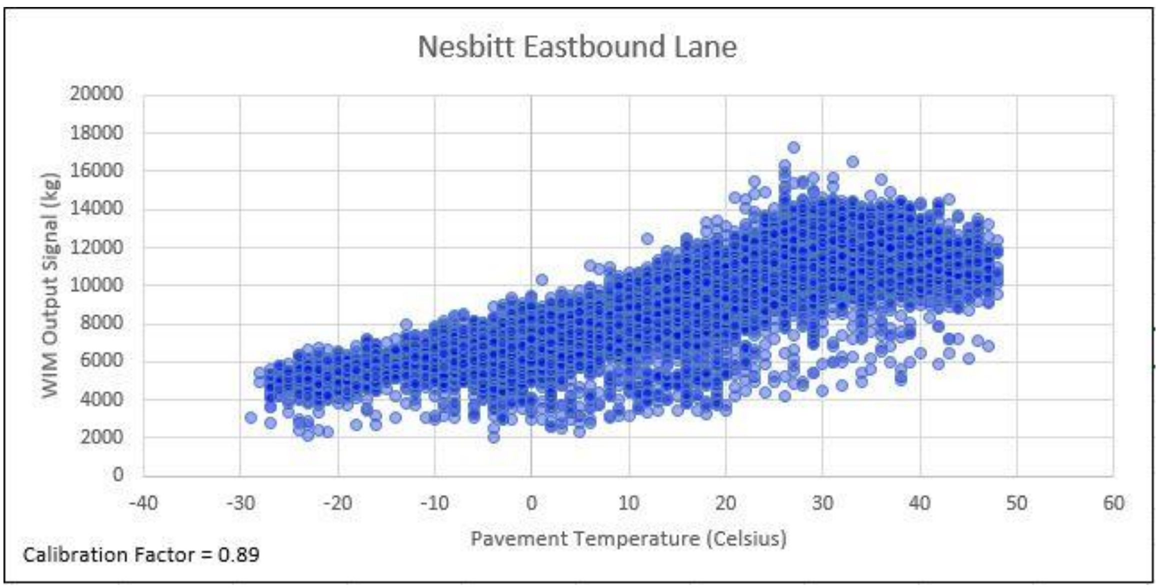


Figure 16: Relationship between WIM output signals for 3-S2, 3-S3, and 3-S3-S2 steering axless and temperature for Station 66 eastbound.

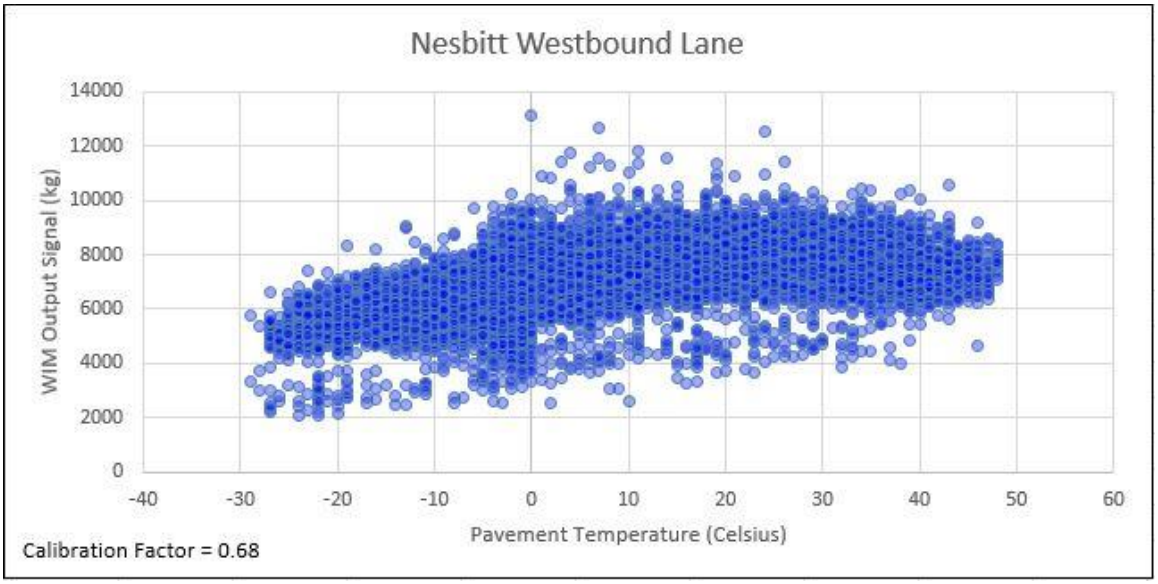


Figure 17: Relationship between WIM output signals for 3-S2, 3-S3, and 3-S3-S2 steering axles and temperature for Station 66 westbound.

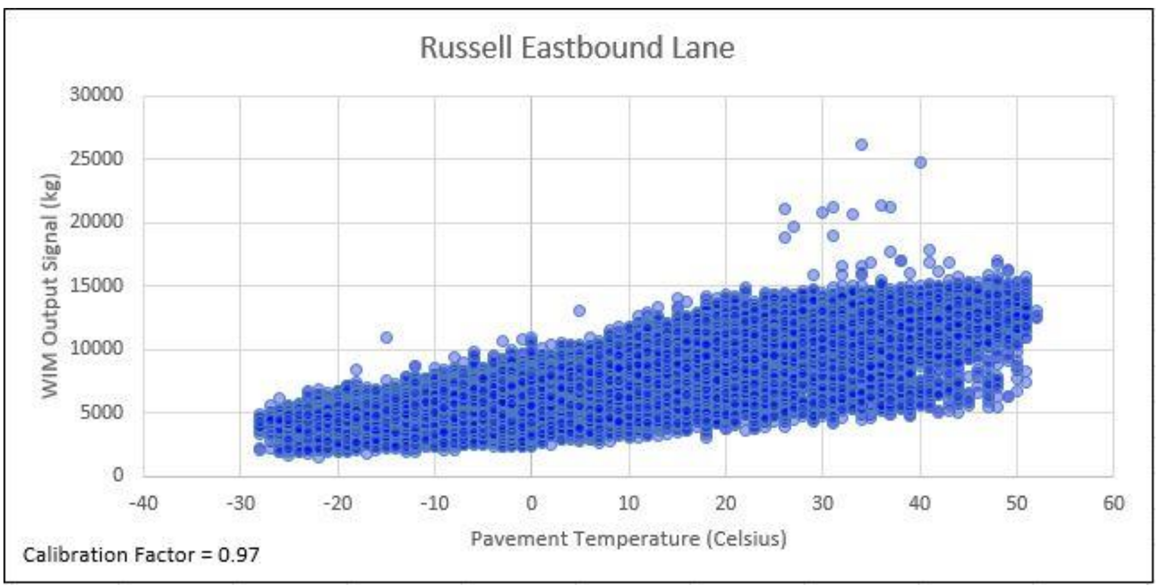


Figure 18: Relationship between WIM output signals for 3-S2, 3-S3, and 3-S3-S2 steering axles and temperature for Station 80 eastbound.

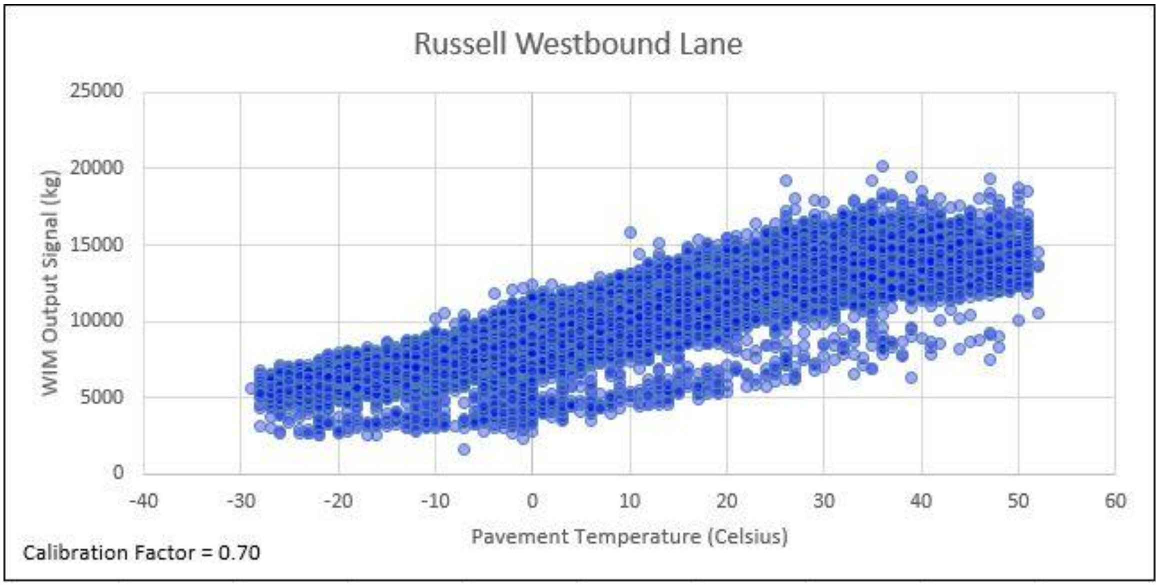


Figure 19: Relationship between WIM output signals and 3-S2, 3-S3, and 3-S3-S2 steering axles and temperature for Station 80 westbound.

Figure 14 through Figure 19 show the output-temperature relationships as “bands” of individual points. Upon analysis, the general shapes of the trends can be identified. In general, for all WIM sites, higher temperature ranges were associated with larger output signals. Thus, temperature corrections at these ranges should scale the output signals down to be within range of the target loads shown in Table 14, and vice-versa.

Four of the six WIM lanes (Station 63 northbound, Station 66 eastbound, Station 80 westbound, and Station 80 eastbound) show clear increases in output signal with respect to temperature in the intermediate temperature ranges, while output signal does not substantially change in the lower and upper temperature ranges. One site (Station 66 westbound) shows clear increases in output signal with respect to temperature in the lower temperature ranges, while output signal does not substantially change in the upper temperature ranges. The final site (Station 63 northbound) shows an increase in output signal with respect to temperature in all temperature ranges.

These output-temperature relationships are influenced by many factors, including pavement type (i.e. flexible or rigid), pavement condition, and subtleties of each individual sensor installation (Roy Czinku, personal communication, January 3, 2017) and detailed analysis of the relationships is outside the scope of this research. However, regression lines for these relationships should account for these trends as thoroughly as possible. Quadratic least-squares regression lines were computed to describe these relationships and to allow for the calculation of site-specific temperature correction factors.

Quadratic regression lines were selected due to their improved ability to fit the relationships compared to linear regression lines. R^2-values of approximately 0.5 or greater were typical, except for parts of the relationships where concavity has changed and a separate regression line is computed for a small temperature range. In the case of the higher R^2 values observed (0.42 to 0.81), between 42 % and 81 % of variations in output signal of steering axles is accounted for by changes in pavement temperature. These regression lines along with their R^2-values are shown in Appendix C.

It should also be noted that these relationships exist only for the post-calibration time periods specified. In the case of Stations 66 and 80, this time period includes the 12 months since the most recent calibration (see Table 4). In the case of Station 63 northbound, the removal of the piezoelectric sensors prevented data analyses beyond May 11, 2015. In the case of Station 63 southbound, removal of the temperature sensor prevented data analyses beyond May 21, 2015. Re-calibration or significant physical alteration at the WIM sites could fundamentally change the relationships.

Using these regression lines, appropriate temperature correction factors were developed by dividing the applicable target steering axle load by the output signals at each temperature. These factors were developed separately for each of the six piezoelectric WIM lanes, and are shown in Appendix C.

4.4 RESULTS OF DATA QUALITY CHECKS (ANALYSIS 5)

The site-specific temperature correction factors for piezoelectric WIM data developed as part of this research were used to correct the WIM output signals for all axle groups observed in the 1-year period following most recent calibration at WIM Stations 66, and 80 (for Station 63, this was approximately 6 months due to equipment removal). Section 4.3.2 shows the unsteadiness of the mean steering axle loads observed at the six piezoelectric WIM stations (12 WIM lanes total) with data as currently processed in Manitoba. Similar independent samples T-tests were performed on site-specific corrected data from WIM stations 63, 66, and 80, as well as data from WIM station 99. Table 15 and Table 16 show these results:

Table 15: Characteristics of steering axle load data from the piezo-quartz WIM station in Manitoba and site-specific corrected steering axle load data for piezoelectric WIM stations in Manitoba in post-calibration period.

Station	Steering Axle Parameter	1 Week Post-Calibration	2 Weeks Post-Calibration	3 Weeks Post-Calibration	4 Weeks Post-Calibration
63 Northbound	Mean	4640	4671	4628	4689
	Difference in Means (%)	-	0.66	-0.27	1.06
63 Southbound	Mean	4548	4676	4466	4341
	Difference in Means (%)	-	2.83	-1.80	-4.54
66 Eastbound	Mean	5542	5613	5158	5134
	Difference in Means (%)	-	1.28	-6.93	-7.37
66 Westbound	Mean	5555	5502	5407	5331
	Difference in Means (%)	-	-0.97	-2.67	-4.04

80 Eastbound	Mean	5586	5352	4998	5192
	Difference in Means (%)	-	-4.20	-10.53	-7.06
80 Westbound	Mean	5338	5150	5209	5189
	Difference in Means (%)	-	-3.51	-2.41	-2.79
99 Westbound	Mean	5336	5343	5363	5372
	Difference in Means (%)	-	0.13	0.50	0.67

Table 16: T-test results for identifying similarities in steering axle load data from the piezo-quartz WIM station in Manitoba and in site-specific corrected steering axle load data from piezoelectric WIM stations in Manitoba in post-calibration period.

Station	Statistical Parameter	2 Weeks Post-Calibration	3 Weeks Post-Calibration	4 Weeks Post-Calibration
63 Northbound	T-value	1.75	0.74	2.68
	p-value	0.08	0.46	0.01
63 Southbound	T-value	7.82	4.72	10.24
	p-value	< 0.001	< 0.001	< 0.001
66 Eastbound	T-value	1.14	-6.69	-8.91
	p-value	0.26	< 0.001	< 0.001
66 Westbound	T-value	-0.87	-2.89	-3.69
	p-value	0.39	0.004	< 0.001
80 Eastbound	T-value	-4.37	-9.66	-8.39
	p-value	< 0.001	< 0.001	< 0.001
80 Westbound	T-value	-5.21	-3.88	-5.14
	p-value	< 0.001	< 0.001	< 0.001
99 Westbound	T-value	0.54	2.11	1.79
	p-value	> 0.5	0.04	0.08

Table 15 and Table 16 reveal that with site-specific corrected data from piezoelectric WIM sites, steering axle load measurements are far more consistent than with WIM data as currently processed in Manitoba. Four of the week-long post-calibration data samples (at three different WIM lanes) (highlighted in Table 16) shared statistical similarities with the corresponding week-long data sample immediately following calibration. Even when such statistical similarities were not shared, variations in week-long post-calibration data samples rarely exceeded ± 7 percent as compared to the corresponding week-long data sample immediately following calibration. This is in contrast to piezoelectric WIM data as currently processed, where such variations exceeded ± 25 percent in some cases.

The performance of the piezo-quartz WIM site was the most precise of all, when considering stability of steering axle loads in the post-calibration weeks. Two of three week-long post-calibration data samples shared statistical similarities with the corresponding week-long data sample immediately following calibration. Furthermore, variations in week-long post-calibration data samples never exceeded ± 0.67 percent as compared to the corresponding week-long data sample immediately following calibration. These results are similar to those performed on data from the Headingley weigh scale (see Section 4.3.1) and suggest station 99 is producing results which vary within normal ranges in the post-calibration period.

An additional quality check was performed on GVW data from FHWA Class 9 vehicles for the following WIM sites: stations 63, 66, and 80 (data as currently processed in Manitoba), stations 63, 66, and 80 (site-specific corrected data), and station 99. This FHWA Class 9 data was tested for percent GVW below 11 000 kg and percent GVW above 41 000 kg. For the purposes of this study, any results more than five percent over/under the specified thresholds is declared to have failed these tests. Table 17 shows these results:

Table 17: Percent of FHWA Class 9 GVW above and below key thresholds for currently processed/site-specific corrected piezoelectric WIM data and piezo-quartz WIM data.

Station	Percent Class 9 GVW < 11 000 kg	Percent Class 9 GVW > 41 000 kg
63 Northbound (Currently Processed)	1.16	14.67
63 Northbound (Site-Specific Corrected)	1.04	0.09
63 Southbound (Currently Processed)	0.67	23.01
63 Southbound (Site-Specific Corrected)	1.69	0.33
66 Eastbound (Currently Processed)	3.86	22.55
66 Eastbound (Site-Specific Corrected)	0.63	1.00
66 Westbound (Currently Processed)	1.84	17.03
66 Westbound (Site-Specific Corrected)	0.42	1.29
80 Eastbound (Currently Processed)	9.60	6.75
80 Eastbound (Site-Specific Corrected)	3.61	2.12
80 Westbound (Currently Processed)	0.68	11.84
80 Westbound (Site-Specific Corrected)	0.19	0.40
All Piezoelectric (Currently Processed)	2.22	16.64
All Piezoelectric (Site-Specific Corrected)	1.44	0.59
99 Westbound (Piezo-Quartz)	0.39	1.66

Table 17 reveals a stark contrast in the validity of piezoelectric WIM Class 9 GVW data as currently processed in Manitoba versus such data when corrected for site-specific temperature effects. All data from these sites as currently processed in Manitoba failed the percent GVW above 41 000 kg test, and data from one WIM lane failed the percent below 11 000 kg test (highlighted in Table 17). In some cases, the percent GVW exceeding the threshold exceeded 20 percent, which is unusual given the findings from the static weigh scale surveys conducted in Manitoba (see Section 3.6). In contrast, all site-specific corrected data from piezoelectric WIM sites passed both the percent GVW above 41 000 kg test and the percent GVW below 11 000 kg test. Data from the piezo-quartz WIM site also passed these tests and yielded results similar to the site-specific corrected data from piezoelectric WIM sites.

4.5 LIMITATIONS OF THE RESEARCH

There are a number of limitations within this research. They are described as follows:

- Although it was confirmed that all three primary static weigh scales in Manitoba are equipped with the same scale technology, validity studies were only conducted at the Headingley scale.
- When comparing “rolling” weights at the Headingley weigh scale to “billed” weights, only a small number of billed trucks were observed.
- Evaluation of the piezo-quartz WIM site was made based on the one WIM site currently installed in Manitoba.
- Evaluation of the piezo-quartz WIM site occurred under the assumption that axle loads from the Headingley weigh scale were the “ground truth” loads. However, it is not possible to measure the true static loads of a vehicle and therefore any subtle imperfections in the static weigh scale will inherently affect the results of the truck-pairing studies.
- Although validity studies were conducted on the piezoelectric WIM sensors, no truck-pairing survey was performed to evaluate this equipment against ASTM standards.
- The influences of temperature on output signals measured at piezoelectric WIM sites was only studied for a period of 1-year post-calibration. This research does not verify this relationship over a period longer than this.

- This research does not go into depth when analyzing the relationships between WIM output signal and pavement temperature; this would require detailed analysis of on-site installations and other factors influencing the equipment.
- Since this research provides information on the performance of axle load data sources using various statistics and principles, it remains a challenge to compare all sources using consistent measures.
- Although data quality checks were performed on data from available options, no sensitivity studies were conducted to determine the direct impacts of selecting certain data options on pavement designs.

4.6 FEASIBILITY OF OPTIONS RELATIVE TO DATA QUALITY PRINCIPLES

This section reviews the results of the analyses conducted in this research and discusses their impact on the four data quality principles established in Section 3.2. These data quality principles consider aspects of: (1) data validity, (2) geographic coverage, (3) temporal coverage, and (4) data availability.

The performance of all sources of axle load data relative to the data quality principles help provide a measure of overall data quality and feasibility of using axle load data from these sources for pavement design purposes.

4.6.1 Data Validity

Based on results from this research outlined in Sections 4.1 to 4.4, the four main options for producing axle load data are ranked as follows in terms of data validity:

1. Data from Manitoba's three primary static weigh scales (*Option 3*).
2. Data from the Manitoba WIM site equipped with piezo-quartz sensors (*Option 4*).
3. Data from the six Manitoba WIM sites equipped with piezoelectric sensors, with data corrected based on site-specific output-temperature relationships (*Option 2*).

4. Data from the six Manitoba WIM sites equipped with piezoelectric sensors, with data processed as per current procedures in Manitoba (*Option 1*).

Data from the primary static weigh scales is deemed the most valid, due to the quality of measurements produced and the existing survey methods. As mentioned in Section 2.2, higher speeds lead to an increase in variations of loads measured by WIM systems (Papagiannakis and Masad, 2008). Therefore, the slower operating speeds associated with the static weigh scales as compared to piezoelectric and piezo-quartz WIM sites help to reduce these variations. These scales are also certified in Manitoba for issuing legal overweight citations and are carefully maintained on a bi-annual basis (Ross Veldkamp, personal communication, December 10, 2016).

Based on this research, initial concerns with data collected at these primary weigh scales were not found to adversely affect the data. These concerns centered around the potential for dynamic effects to influence the loads with vehicles rolling on and off the scale at speeds of approximately 5 km/h. However, when comparing each of the two load readings recorded for each axle group passing over the scale, it was found that variations were insignificant. Additionally, when comparing “rolling” weights to official “billed” weights for given trucks, no significant differences were found. Study results suggest that there are no concerns related to accuracy or precision when these scales operate under normal conditions, with vehicles slowly rolling over the scale.

The next best option for producing valid axle load data is the piezo-quartz WIM site. This site performed accurately and precisely based on the results of the two truck-pairing surveys between then WIM site and the Headingley static weigh scale. When weights as recorded by this WIM site were matched with the weights as recorded at the Headingley weigh scale, and results either surpassed or were slightly below ASTM specifications.

Furthermore, performance of the piezo-quartz WIM site was similar in both truck-pairing surveys; one survey was performed shortly after calibration and the other was performed several months after calibration. This suggests that performance of the piezo-quartz WIM is consistent over time.

Additionally, data produced at the piezo-quartz WIM site excelled based on the data quality checks performed (see Section 4.4). The WIM site performed very well in terms of precision of mean steering axle weights in the post-calibration weeks, with T-test results being comparable in the case of the piezo-quartz WIM site and the Headingley weigh scale. The data quality checks which screened for abnormal Class 9 GVWs also showed favorable results. For the piezo-quartz WIM site, few observations of Class 9 GVW above 41 000 kg or below 11 000 kg were reported.

The piezoelectric WIM sites with site-specific temperature-corrected data rank third out of four options in terms of data validity. These sites performed well in terms of precision of the mean steering axle in the post-calibration weeks, with T-tests results being nearly as strong as the T-test results for the piezo-quartz WIM site. Additionally, these piezoelectric WIM sites performed comparably to the piezo-quartz WIM site in terms of observations of Class 9 GVW above 41 000 kg or below 11 000 kg. However, an additional element of uncertainty arises with this data; although correcting for the site-specific effects of temperature improves the data validity at these sites, this process can potentially be subjective and can introduce bias if these temperature effects are misinterpreted or analyzed using inadequate data.

The piezoelectric WIM sites with data as currently processed in Manitoba rank fourth, due to their poor performance in terms of steering axle precision in the post-calibration weeks. T-test results indicated that data precision degrades substantially as soon as one-week post-calibration. Additionally, some of these sites experienced a high percentage of Class 9 GVWs above 41 000 kg or below 11 000 kg, which is uncharacteristic of truck loads in Manitoba. Caution should be exercised when using data from these sites as currently processed.

4.6.2 Geographic Coverage

Geographic coverage is a key consideration when planning an axle load monitoring program. Locations of WIM equipment in Manitoba are currently in a state of change, but in terms of the current network, the data options are ranked as follows based on geographic coverage:

1. Data from the six Manitoba WIM sites equipped with piezoelectric sensors (*Options 1 and 2*).
2. Data from Manitoba's three primary static weigh scales (*Option 3*).
3. Data from the Manitoba WIM site equipped with piezo-quartz sensors (*Option 4*).

Manitoba's piezoelectric WIM sites have a geographic advantage over other options, due to the number of sites and variety of industries served by those sites. Although some of these WIM sensors have been removed due to construction, recent data exists from six different sites, with 12 lanes of WIM total. All six sites are located on RTAC routes, but one of these sites (Station 66) is not part of the National Highway System (NHS), unlike the other five sites. Appendix B describes the seven truck traffic patterns evident on Manitoba highways, and highways with piezoelectric WIM sites installed serve three such patterns:

- Pattern Group 2: WIM stations 61, 62, 65, and 80 are located on major east-west routes on the NHS, transporting a broad mix of commodities.

- Pattern Group 3: WIM Station 66 is located on a route serving long-distance and/or agriculture-related trips.
- Pattern Group 6: WIM Station 63 is located on a route which serves long-distance trips to the United States.

Manitoba's primary weigh scales also offer some geographic diversity, although not as much as that offered by the piezoelectric WIM network. The primary weigh scales are located at three sites, surveying five lanes of traffic total. However, two of these scales (Headingley and West Hawk) are located on routes as part of Pattern Group 2, and one of these scales (Emerson) is located on a route as part of Pattern Group 6. Furthermore, all scales are part of the RTAC network as well as the NHS. Therefore, there are some key truck traffic patterns in Manitoba which are not sampled by the primary static weigh scales.

Since there is only one piezo-quartz WIM site in Manitoba, this option provides the poorest geographic coverage. Planned expansions of the piezo-quartz network should provide significant improvements in geographic coverage.

4.6.3 Temporal Coverage

Based on characteristics of available weight data sources, they can be ranked in terms of temporal coverage as follows:

1. Data from the Manitoba WIM site equipped with piezo-quartz sensors (*Option 4*).
2. Data from the six Manitoba WIM sites equipped with piezoelectric sensors, with data corrected based on site-specific output-temperature relationships (*Option 2*).
3. Data from Manitoba's three primary static weigh scales (*Option 3*).

4. Data from the six Manitoba WIM sites equipped with piezoelectric sensors, with data processed as per current procedures at Manitoba Infrastructure (*Option 1*).

Data from the piezo-quartz WIM site in Manitoba is generally available year-round, barring periodic equipment malfunction. In addition, this research has verified the validity of the data in the short-term and long-term periods after calibration. Therefore, quality data should be available for the majority of a calendar year, provided the site is properly calibrated and maintained on an annual basis.

Data from the piezoelectric WIM sites in Manitoba, which has been corrected using site-specific temperature correction factors, is also available year-round barring equipment malfunction. This research has also verified the validity of this data in the short-term and long-term and the output-temperature relationships used to develop the temperature correction factors have been verified by this research for up to a 1-year period post-calibration. Therefore, as long as the equipment is properly maintained and calibrated on an annual basis, and output-temperature relationships are re-verified after each calibration, quality data should be available.

Manitoba's three primary static weigh scales offer poorer temporal coverage. Since current data collection efforts at these scales are performed manually, data collection is limited to the human resources which can reasonably be assigned to work at the scale. Furthermore, the fundamentals of the static weigh scales may limit the throughput of trucks, especially during busy mid-day hours. In these cases, not all trucks may get surveyed, leading to a possible under-representation of trucks passing the scale during peak periods. Therefore, despite best efforts, maintaining steady data collection on a frequent basis at these scales is a challenge.

Finally, data as currently processed from the piezoelectric WIM sites in Manitoba does not offer as much temporal coverage as the other sources of data. Results of this research have shown that the precision of this data can degrade substantially, even within one-week of calibration in some cases. Therefore, if this data is to be used, caution is recommended when selecting a sample size of post-calibration data.

4.6.4 Data Availability

Data availability is largely reliant on future plans for equipment measuring truck weight data, as well as the resources required for data collection and processing. Equipment can be ranked based on data availability as follows:

1. Data from the Manitoba WIM site equipped with piezo-quartz sensors (*Option 4*).
2. Data from Manitoba's three primary static weigh scales (*Option 3*).
3. Data from the six Manitoba WIM sites equipped with piezoelectric sensors, with data processed as per current procedures at Manitoba Infrastructure (*Option 1*).
4. Data from the six Manitoba WIM sites equipped with piezoelectric sensors, with data corrected based on site-specific output-temperature relationships (*Option 2*).

Piezo-quartz WIM sensors in Manitoba produce data which is most readily available. This data can be retrieved from the current WIM site using WIM system software and requires little subsequent data processing, with the exception of data screening. In addition, there are future plans for these sensors to be installed in both traffic lanes at WIM Station 63, as well as both traffic lanes at WIM Station 65. The ease of data retrieval and ongoing adaptation of the technology makes piezo-quartz WIM sites a strong option for retrieving quality axle load data.

Manitoba's three primary static weigh scales provide the next most readily-available source of axle load data. Enforcement is important to the protection of infrastructure in Manitoba and it appears that operations will continue at these scales well into the future. Rather, the difficulty in obtaining the data stems from the methods required to collect it. Currently, axle load data from these scales is collected on a manual basis, requiring human resources and post-collection data screening. However, these weigh scales are equipped with the technology required to electronically collect the data (Ross Veldkamp, personal communication, December 10, 2016). Despite this potential, two distinct challenges must be overcome to allow for electronic data collection at these scales:

- There must be a means of identifying whether measured loads are part of a single, tandem, or tridem axle group, as well as whether successive axle groups are part of the same truck configuration. Incorporating camera technology into the axle load collection system may be a solution to this issue.
- Since these scales issue legal citations for overweight trucks, it may be considered a breach of carrier privacy to permanently record axle loads and other information regarding offending trucks.

Data as currently processed from the piezoelectric WIM sites in Manitoba provides the next most readily-available data. It is a developing challenge to retrieve this data, since this technology is becoming dated, and some of these WIM sites are being phased out of Manitoba's axle load monitoring network. Piezoelectric sensors at the following sites have recently been removed or are intended to be removed in the near future:

- Station 61 eastbound and westbound lanes. No WIM replacement is planned in the near future.

- Station 63. Northbound lane removed in 2015, with plans to remove southbound lane in near future. Both lanes are to be fitted with piezo-quartz sensors.
- Station 65. Westbound lane removed in 2016, with plans to remove eastbound lane in near future. Both lanes are to be fitted with piezo-quartz sensors.

Data from piezoelectric WIM sites in Manitoba corrected using site-specific temperature correction factors is the most challenging to retrieve. Not only are some of these sensors being phased-out, but this data requires extra effort to properly develop site-specific temperature correction factors and re-develop the factors after every site calibration or significant change in site conditions. Based on these characteristics, it is an ongoing challenge to retrieve and develop this data.

Cost is another key aspect relating to data availability. According to a study conducted by Bushman and Pratt (1998), the typical installation cost of one lane of load cell WIM is approximately five times the installation cost of one lane of piezoelectric WIM. Furthermore, the cost of annual operation of one lane of load cell WIM is nearly double the annual operation cost of one lane of piezoelectric WIM. Furthermore, Zhang et al. (2007) report that the installation cost of one lane of piezo-quartz WIM is approximately double the installation cost of one lane of piezo-electric WIM, while the operational costs of piezo-quartz WIM are comparable to the operational costs of load cell WIM.

It is apparent that different WIM technologies may have significantly different associated installation and operational costs. Cost is certainly a factor which impacts data availability and influences the feasibility of selecting WIM equipment. However, due to the challenges of weighing cost priorities of a jurisdiction in relation to other priorities relating to data quality, cost is not explicitly considered in the data quality analyses in this research.

4.6.5 Summary of Data Feasibility

This section summarizes the feasibility of axle load data options relative to the four data quality principles. Table 18 summarizes the relevant considerations when evaluating the options against the data quality principles.

Table 18: Summary of axle load data options as evaluated against data quality principles.

Options for Providing Axle Load Data	Data Quality Principles			
	***Principle 1*: Data Validity**	***Principle 2*: Geographic Coverage**	***Principle 3*: Temporal Coverage**	***Principle 4*: Data Availability**
***Option 1*: Piezoelectric WIM Sites – Data as Currently Processed**	- Known inconsistencies in data resulting from temperature sensitivity - Adequate if no alternatives	- Adequate geographic coverage - No data coverage off RTAC routes	- Limited if using small sample of post-calibration data	- Some sites being phased-out and replaced with *Option 4*
***Option 2*: Piezoelectric WIM Sites – Site-Specific Corrected Data**	- Reasonably consistent data if properly corrected for temperature on a site-specific basis - Data validity is superior to *Option 1*	- Adequate geographic coverage - No data coverage off RTAC routes	- Available year-round if properly maintained, calibrated, and corrected for temperature	- Some sites being phased-out and replaced with *Option 4* - Effort is required to properly correct data for temperature on a site-specific basis
***Option 3*: Three Primary Static Weigh Scales**	- Certified to issue legal citations - Data validity is superior to all other options	- Poorer geographic coverage as compared to *Option 1* and *Option 2*	- Better temporal coverage than *Option 1* - Temporal coverage is limited to availability of personnel to collect data	- Superior data availability compared to *Option 1* and *Option 2* - Manual data collection requires resources - Electronic data collection a possibility, but challenges exist
***Option 4*: Piezo-quartz WIM Sensors**	- Data validity is superior to *Option 1* and *Option 2*	- Poor geographic coverage - Future planned installations should improve geographic coverage	- Available year-round if properly maintained and calibrated	- Superior data availability compared to all other options considering future planned installations

5 CONCLUSIONS

This chapter summarizes the key findings and implications of this research and identifies opportunities to enhance axle load data monitoring programs.

5.1 SUMMARY OF KEY FINDINGS AND IMPLICATIONS

This research evaluates four options for producing axle load data in Manitoba: (1) data as currently processed from piezoelectric WIM sites in Manitoba (*Option 1*), (2) data from piezoelectric WIM sites with data corrected for site-specific temperature effects (*Option 2*), (3) data from primary static weigh scales (*Option 3*), and (4) data from a piezo-quartz WIM site (*Option 4*). The four options are evaluated using four data quality principles, namely: data validity, geographic coverage, temporal coverage, and data availability. While all principles are considered, the research contributes particularly in the development and application of an integrated and sequential approach to assess data validity for the four options. This approach involved:

- Assessing the validity of the static weigh scale data.
- Conducing a truck-pairing survey to determine validity of the piezo-quartz WIM data.
- Determining the reliability of the piezoelectric WIM data.
- Identifying the sensitivity of piezoelectric WIM data to changes in pavement temperature and calculating correction factors.
- Applying data quality control checks to assess the validity of the data for *Option 1*, *Option 2*, and *Option 4*.

In terms of data validity, *Option 3* ranks the highest due to the decreased dynamic effects resulting from low vehicle speeds, as well as the certification of these scales to issue legal citations based on vehicle weight. *Option 4* ranks next based on the favorable results from the truck-pairing surveys, which were generally in compliance with industry standards. *Option 2* ranks third, since data validity is significantly improved when correcting for site-specific temperature effects, even if these corrections involve a potential element of subjectivity. Finally, *Option 1* ranks fourth, due to the fluctuations observed in select axle loads in the post-calibration periods.

The overall evaluation revealed the following key findings:

- *Option 1* offers adequate geographic coverage, but known inconsistencies may reduce data validity and therefore caution should be exercised when using the data.
- *Option 2* offers the same geographic coverage as *Option 1*, but site-specific temperature correction yields significant improvements in data validity, allowing for data to be used over a longer post-calibration time period.
- *Option 3* offers highly valid data, but the personnel requirements to collect this data under current scale operations makes it a challenge to collect large samples of data.
- *Option 4* provides data validity similar to that of *Option 3*, but offers poor geographic coverage. Planned expansions of equipment as part of *Option 4* will improve geographic coverage of this option.

All options require regular maintenance and calibration of equipment to reach their highest potential levels of data quality.

The findings have several implications for pavement design and management. Generally, if unrepresentative axle load data is used in design and management decisions, it will lead to a misunderstanding of local traffic conditions and the over or under-designing of infrastructure (Prozzi et al., 2008; Haider at al., 2010; Smith and Diefenderfer, 2010;

Ahammed at al., 2011; Nassiri et al., 2013; Tarefder and Rodriguez-Ruiz, 2013; Selezneva et al., 2016). Therefore, it is in the best interest for jurisdictions to use the highest-quality data possible, to ensure the usage of appropriate designs and proper asset management practices. More specific implications for designing and implementing an axle load data monitoring program follow:

- One of the primary challenges associated with WIM equipment is the valid representation of actual axle loads measured at a site. In this research, some of the data options produced variable axle load data which were beyond the reasonable range of expected axle loads. Some of these options also produced uncharacteristically high percentages of heavy or light trucks. The selection of axle load monitoring options and practices can have a significant impact on data produced, even at a fixed location and time.
- In a given jurisdiction, there may be a wide range of trucking activities to be investigated, and in some cases, they may not all be surveyed by an axle load data monitoring program. In studying axle load data from Manitoba's three static weigh scales from a similar time period (July – August, 2013) (see Appendix E), ALS from common truck configurations (3-S2, 3-S3, 3-S3-S2) were found to be significantly different at the different locations in terms of average loads and distribution shapes. At Headingley, many of these axle load distributions were approximately bimodal in nature. At West Hawk, these axle load distributions were approximately uniform, with loaded peaks in some cases. At Emerson, these axle load distributions show strong loaded peaks. Based on these observations, axle load characteristics may vary significantly from region-to-region, and it is a challenge to design infrastructure in areas where these characteristics are not fully known and understood.

- The month and season of year can have a significant impact on axle load characteristics in a given region (Nassiri et al., 2013). In some cases, due to data validity concerns or equipment malfunction, not all months or seasons of the year may be captured. This may produce data which misrepresents loading conditions leading to complications when using the ME design method, especially since it is intended for the traffic loading inputs to interact with seasonal weather patterns (ARA, 2004). Using small samples of data is also problematic if anomalies exist in the traffic loads recorded during sampling periods. It is in the best interest for jurisdictions to understand axle load characteristics for a wide temporal scope to ensure accurate pavement designs.
- Data from some options may be more difficult to retrieve or develop than with other options. In some cases, assets must be spent for site installation, upgrades, and regular maintenance. In other cases, significant efforts must be made in data processing and quality control. Equipment should continue to provide quality data long after site installation, such that it is worth investments put forth by jurisdictions.

Ultimately, it is up to jurisdictions to weigh their options when deciding on what equipment to select and how the ensuing data will be handled within an axle load data monitoring program. It is important to have an understanding of the unique benefits and challenges of each option and of which data quality principles are truly important when considering specific data applications and reasonable tolerances. Jurisdictions should carefully consider the relative importance of relevant data quality principles, so that an axle load data monitoring program can suit the specific needs of personnel responsible for highway infrastructure design and management.

5.2 OPPORTUNITIES FOR FUTURE DATA MONITORING IMPROVEMENTS

Based on the findings of this research, there are various opportunities to improve upon the existing axle load data monitoring network in Manitoba:

- Due to the high level of validity associated with axle load data from the primary static weigh scales in Manitoba, there may be benefits associated with strengthening data collection programs at these sites. One option would be to organize a more extensive program to manually observe and record axle loads passing through the scale. Another option would be to utilize existing electronic data logging capabilities, perhaps with the inclusion of video-recording technology.
- The ability of piezo-quartz sensors to provide reliable data in large samples makes this equipment a strong candidate for additional installations beyond the existing westbound lane at Station 99 and the planned installations at Stations 63 and 65, including the eastbound lane at Station 99.
- If piezoelectric WIM sensors are part of long-term plans, it is beneficial to the validity of the data to monitor site-specific impacts of temperature and correct the data as per these relationships. If data validity is a concern, it may be possible to conduct a similar truck-pairing survey as completed in this research to evaluate a sample of site-specific corrected data at a piezoelectric WIM station.
- Data coverage is critical in jurisdictions with diverse traffic characteristics. In the case of Manitoba, it could be of significant value to observe axle loading characteristics in regions representative of all Pattern Groups, as well as in regions off the RTAC network (i.e., A1 and B1 routes, see Appendix B). This could involve investments in portable WIM equipment, or upgrading existing automatic vehicle classifier (AVC) sites to WIM.
- It may be useful to conduct additional studies to determine the significance of selecting one data option over another in the context of pavement design. An

understanding of the impacts to the pavement structure and service life of highway infrastructure assets will aid in proper data selection.

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APPENDIX A: FHWA 15-CLASS VEHICLE SCHEME

Table 19: FHWA 15-class vehicle scheme.

	FHWA Class 1 - Motorcycles
	FHWA Class 2 - Passenger Vehicles (With 1- or 2-Axle Trailers)
 	FHWA Class 3 - 2-Axles, 4-Tire Single Units, Pickup or Van (With 1- or 2-Axle Trailers)
  	FHWA Class 4 - Buses
  	FHWA Class 5 - 2D - 2 Axles, 6-Tire Single Units (Includes Handicapped-Equipped Bus and Mini School Bus)
	FHWA Class 6 - 3 Axles, Single Unit
	FHWA Class 7 - 4 or More Axles, Single Unit
	FHWA Class 8 - 3 to 4 Axles, Single Trailer
	FHWA Class 9 - 5 Axles, Single Trailer
	FHWA Class 10 - 6 or More Axles, Single Trailer
	FHWA Class 11 - 5 or Less Axles, Multi-Trailers
	FHWA Class 12 - 6 Axles, Multi-Trailers
	FHWA Class 13 - 7 or 8 Axles, Multi-Trailers
	FHWA Class 14 - 9 or 10 Axles, Multi-Trailers

	FHWA Class 15 - 11 or More Axles, Multi-Trailers

APPENDIX B: BACKGROUND OF MANITOBA HIGHWAY SYSTEM

The highway system in Manitoba is divided on the basis of various classification methods. All highways are broadly classified as either Provincial Trunk Highways (PTHs), Provincial Roads (PRs), or “other” roads. Of the approximately 17 800 km of rural highway in Manitoba, PTHs, PRs, and other roads make-up approximately 7400 km, 10 300 km, and 90 km, respectively. PTHs are typically major roads, with a number designation from 1 to 190. PRs are typically minor roads, numbered from 200 to 596. Roads classified as “other” include sections of PTH 10 through Riding Mountain National Park, and sections of PTH 75 and PR 200 just south of Winnipeg.

In addition, all highways are classified under the Manitoba Highway Classification System, which identifies roads as either RTAC, Class A1, or Class B1. RTAC highways have the most relaxed weight restrictions imposed on them, and typically consist of heavily-travelled PTHs and PRs. Class A1 highways have stricter weight restrictions and typically consist of non-RTAC PTHs and select PRs. Finally, Class B1 highways have the strictest weight limits, and typically consist of minor highways which have not been designated as RTAC or Class A1, and typically have number designations greater than 110 (Manitoba Infrastructure, 2017a). Table 20 shows basic axle-group weight restrictions for each type of highway in Manitoba.

Table 20: Basic axle-group weight limits for RTAC, A1, and B1 highway classifications in Manitoba. Adapted from the *Manitoba Vehicle Weights and Dimensions Guide* (Manitoba Infrastructure, 2017a).

Maximum Weight Category	RTAC	Class A1	Class B1
Tractor			
Steering Axle	6000 kg	6000 kg	6000 kg

Single Axle	9 100 kg	9 100 kg	8 200 kg
Tandem Axle:	---		
Axle Spread 1.0 m – 1.85 m	17 000 kg	16 000 kg	14 500 kg
Semi Trailer			
Single Axle	9 100 kg	9 100 kg	8 200 kg
Tandem Axle:			
Axle Spread 1.0 m – 1.85 m	17 000 kg	16 000 kg	14 500 kg
Tridem Axle:			
Axle Spread 2.4 m – less than 3.0 m	21 000 kg	21 000 kg	20 000 kg
Axle Spread 3.0 m – less than 3.6 m	23 000 kg	23 000 kg	20 000 kg
Axle Spread 3.6 m – 3.7 m	24 000 kg	23 000 kg	20 000 kg

These enforceable weight limits change the basic truck weight fundamentals of vehicles using Manitoba's highway system, depending on the particular route. Figure 20 maps the current network of RTAC, Class A1, and Class B1 highways.

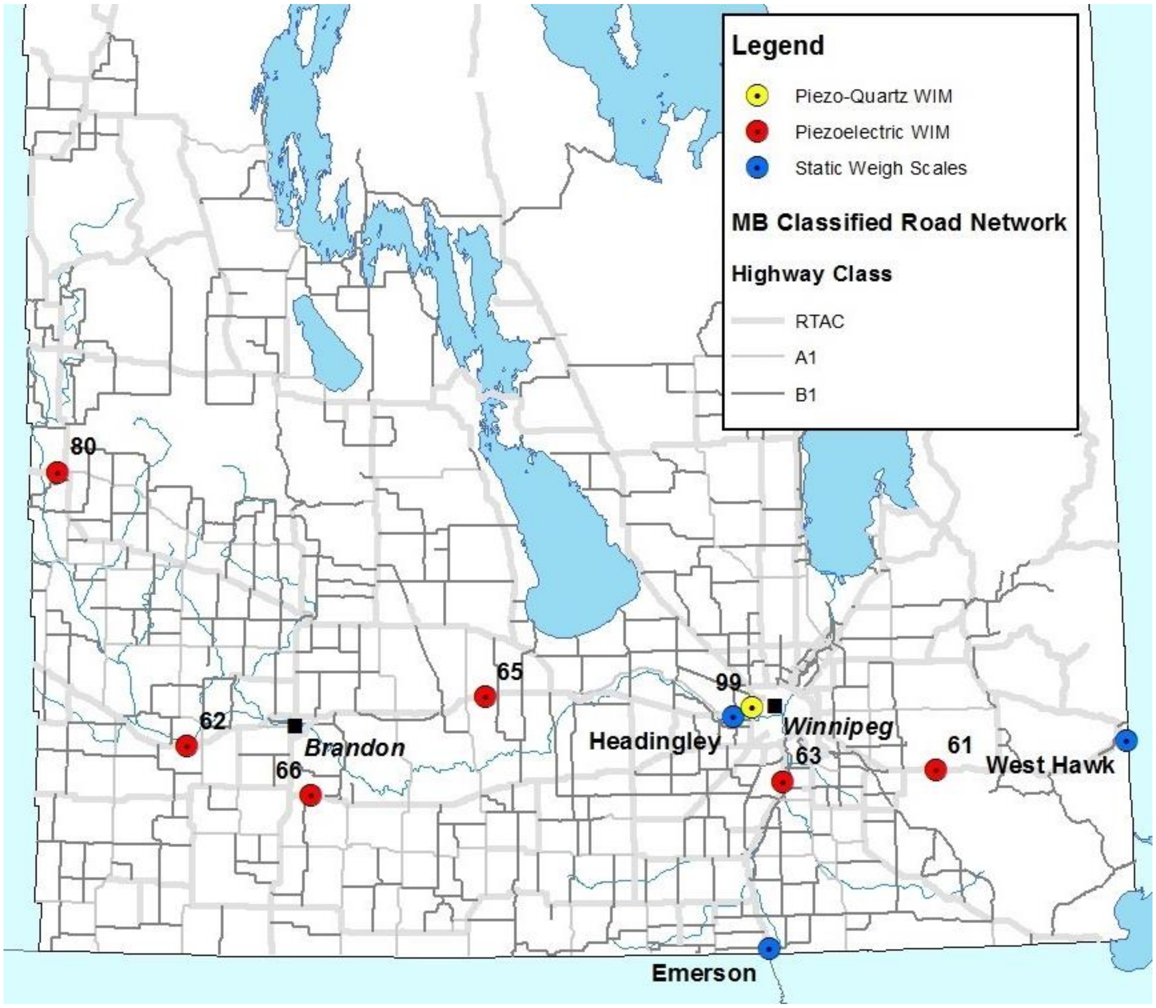

Figure 20: Map showing RTAC, A1, and B1 routes in Manitoba, superimposed with weight data collection sites.

These basic weight limits are also adjusted according to subsurface highway conditions, which correspond with certain seasons of the year. These adjustments are referred to as spring road restrictions, and winter weight premiums. Spring road restrictions account for soft subsurface conditions, and can be classified into two categories, as defined by the Manitoba Spring Road Restrictions Program (Manitoba Infrastructure, 2017): (1) Level 1 restrictions, and (2) Level 2 restrictions. Key restrictions are listed below.

Level 1 spring restrictions (this list excludes restrictions for tandem steering axles of straight trucks, or steering axles for straight trucks or tractors with tridem drive axles):

- 10 kg/mm tire width up to a maximum of 5500 kg on single steering axles of tractors with single or tandem drive axles, for all highways.
- 9 kg/mm tire width up to a maximum of 90 % of the basic legal axle group weights for all other axle groups, for all highways.

Level 2 spring restrictions (this list excludes restrictions for tandem axles of straight trucks):

- 6.5 kg/mm tire width up to a maximum of 65 % of the legal axle group weights for all axle groups, on Class A1 and B1 highways.

Level 1 and 2 spring road restrictions apply only to certain roads specified by Manitoba Infrastructure. In the year 2016, Level 1 restrictions applied to select RTAC, Class A1, and Class B1 roads, while Level 2 restrictions applied to select Class A1 and Class B1 roads. Additionally, in 2016, the spring road restrictions applied from March 11 to May 31.

Winter weight premiums are designed to increase basic axle weight limits to account for the increased load-bearing capacity of highways during months when the ground temperature is low. These premiums are defined under the Manitoba Highway Winter Seasonal Weights program (Manitoba Infrastructure, 2017b). Key weight premiums are listed below.

Winter weight premiums for RTAC vehicles (this list excludes restrictions for non-RTAC vehicles or restrictions to gross vehicle weights):

- 10 % increase in basic weight limits for single axles on RTAC routes
- 10 % increase in basic weight limits for tandem axles on RTAC routes, subject to a maximum of 17 600 kg

- 10 % increase in basic weight limits for single and tandem axles on Class A1 and B1 highways.
- No increases for tridem axles on RTAC, Class A1, or Class B1 highways.
- No increases for GVWs on RTAC, Class A1, or Class B1 highways.

Winter weight restrictions apply to all Manitoba routes, and during the 2015 to 2016 winter season, were in effect from December 1, 2015 to March 4, 2016. The winter seasonal weights program also involves the temporary reclassification of Class A1 and B1 routes to higher weight designations during the winter weight restriction period.

The final method of highway classification in Manitoba involves the classification of the National Highway System (NHS). The NHS largely provides interprovincial commodity flows in Canada, and in Manitoba, is comprised of the following PTHs: 1, 6, 16, 75, 100, 101.

The Manitoba highway network serves a variety of industries, all which significantly influence the types of commodities carried and the weights of trucks carrying those commodities. Work done by Jablonski et al. (2010) analyzed truck traffic at Manitoba's Permanent Count Stations (PCS) using data from the year 2008, and identified patterns in the temporal and vehicle classification characteristics of trucks. Based on similarities between these characteristics at different stations, five distinct regions of Manitoba were identified as having their own specific truck traffic temporal and vehicle classification patterns. These patterns were refined using trucking industry knowledge, and are defined as follows:

1. Pattern Group 1: This group consists of stations located on routes in close proximity to the city of Winnipeg. These routes serve to transport a broad mix of commodities.

2. Pattern Group 2: This group consists of stations located on major east-west routes on the NHS. These routes serve to transport a broad mix of commodities.
3. Pattern Group 3: This group consists of stations located near major population centres, or major grain delivery points, such as Boissevain and Souris, Manitoba. These routes serve long-distance and/or agriculture-related trips.
4. Pattern Group 4: This group consists of stations located in the vicinity of Swan River. These routes serve forestry-related trips.
5. Pattern Groups 5: This group consists of stations located in northwestern Manitoba, in the vicinity of The Pas and Flin Flon.
6. Pattern Group 6: This group consists of stations located on routes which serve long-distance trips to the United States.

Work done by Wood et al. (2016) confirmed the validity of these patterns using truck traffic data from Manitoba's PCSs from the year 2013. In addition to these patterns, Reimer (2015) identified temporal truck patterns and truck classification distributions which were unique to the southwest corner of Manitoba, due to activities related to the petroleum industry. Wood et al. (2016) developed a new pattern group comprised of stations located on routes located in the southwest of Manitoba, which serve petroleum-related trips. This group can be referred to as Pattern Group 7, and must be considered in addition to the other five mentioned above.

APPENDIX C: DEFAULT AND SITE SPECIFIC TEMPERATURE CORRECTION FACTORS FOR PIEZOELECTRIC WIM SENSORS

This appendix contains the factory default temperature correction factors which were applied to axle load data as currently processed from piezoelectric WIM sensors in Manitoba. This appendix also contains the site-specific temperature correction factors developed for each piezoelectric WIM site as part of this research, and the regression equations used in developing the factors.

Table 21: Default temperature correction factors applied to axle load data from piezoelectric WIM sensors as currently processed.

Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor
-50 to -15	0.720	**9**	0.872	**33**	1.064
-14	0.724	**10**	0.880	**34**	1.072
-13	0.728	**11**	0.888	**35**	1.080
-12	0.732	**12**	0.896	**36**	1.088
-11	0.736	**13**	0.904	**37**	1.096
-10	0.740	**14**	0.912	**38**	1.104
-9	0.744	**15**	0.920	**39**	1.112
-8	0.748	**16**	0.928	**40**	1.120
-7	0.752	**17**	0.936	**41**	1.128
-6	0.756	**18**	0.944	**42**	1.136
-5	0.760	**19**	0.952	**43**	1.144
-4	0.768	**20**	0.960	**44**	1.152
-3	0.776	**21**	0.968	**45**	1.160
-2	0.784	**22**	0.976	**46**	1.164

-1	0.792	**23**	0.984	**47**	1.168
0	0.800	**24**	0.992	**48**	1.172
1	0.808	**25**	1.000	**49**	1.176
2	0.816	**26**	1.008	**50**	1.180
3	0.824	**27**	1.016	**51**	1.184
4	0.832	**28**	1.024	**52**	1.188
5	0.840	**29**	1.032	**53**	1.192
6	0.848	**30**	1.040	**54**	1.196
7	0.856	**31**	1.048	**55 to 95**	1.200
8	0.864	**32**	1.056	**-**	-

Table 22: Site-specific temperature correction factors for Station 63 northbound lane.

Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor
-26	0.744	**-5**	0.638	**16**	0.361
-25	0.745	**-4**	0.629	**17**	0.351
-24	0.744	**-3**	0.620	**18**	0.341
-23	0.743	**-2**	0.611	**19**	0.331
-22	0.741	**-1**	0.601	**20**	0.321
-21	0.739	**0**	0.534	**21**	0.312
-20	0.736	**1**	0.524	**22**	0.303
-19	0.733	**2**	0.514	**23**	0.295
-18	0.729	**3**	0.504	**24**	0.286
-17	0.724	**4**	0.493	**25**	0.278
-16	0.719	**5**	0.482	**26**	0.270
-15	0.714	**6**	0.471	**27**	0.262
-14	0.708	**7**	0.459	**28**	0.255
-13	0.701	**8**	0.448	**29**	0.248

-12	0.695	**9**	0.437	**30**	0.241
-11	0.688	**10**	0.426	**31**	0.234
-10	0.680	**11**	0.414	**32**	0.227
-9	0.672	**12**	0.403	**33**	0.221
-8	0.664	**13**	0.392	**34**	0.215
-7	0.656	**14**	0.382	**35**	0.209
-6	0.647	**15**	0.371	**-**	-

Table 23: Site-specific temperature correction factors for Station 63 southbound lane.

Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor
-26	0.643	**-5**	0.477	**16**	0.329
-25	0.649	**-4**	0.463	**17**	0.327
-24	0.653	**-3**	0.450	**18**	0.325
-23	0.657	**-2**	0.438	**19**	0.323
-22	0.659	**-1**	0.426	**20**	0.321
-21	0.659	**0**	0.416	**21**	0.320
-20	0.658	**1**	0.407	**22**	0.318
-19	0.656	**2**	0.398	**23**	0.317
-18	0.653	**3**	0.390	**24**	0.317
-17	0.649	**4**	0.383	**25**	0.316
-16	0.643	**5**	0.376	**26**	0.316
-15	0.636	**6**	0.370	**27**	0.316
-14	0.628	**7**	0.364	**28**	0.316
-13	0.619	**8**	0.359	**29**	0.316
-12	0.609	**9**	0.354	**30**	0.316
-11	0.599	**10**	0.349	**31**	0.317
-10	0.587	**11**	0.345	**32**	0.318

-9	0.575	**12**	0.341	**33**	0.319
-8	0.563	**13**	0.338	**34**	0.320
-7	0.550	**14**	0.335	**35**	0.322
-6	0.537	**15**	0.332	**-**	-

Table 24: Site-specific temperature correction factors for Station 66 eastbound lane.

Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor
-29	1.056	**-3**	0.792	**23**	0.494
-28	1.051	**-2**	0.779	**24**	0.486
-27	1.046	**-1**	0.766	**25**	0.479
-26	1.040	**0**	0.753	**26**	0.472
-25	1.033	**1**	0.741	**27**	0.467
-24	1.026	**2**	0.728	**28**	0.462
-23	1.019	**3**	0.716	**29**	0.458
-22	1.010	**4**	0.703	**30**	0.454
-21	1.002	**5**	0.691	**31**	0.451
-20	0.992	**6**	0.679	**32**	0.449
-19	0.983	**7**	0.667	**33**	0.447
-18	0.973	**8**	0.655	**34**	0.445
-17	0.962	**9**	0.643	**35**	0.445
-16	0.951	**10**	0.632	**36**	0.444
-15	0.940	**11**	0.620	**37**	0.445
-14	0.929	**12**	0.609	**38**	0.446
-13	0.917	**13**	0.598	**39**	0.447
-12	0.905	**14**	0.587	**40**	0.449
-11	0.893	**15**	0.577	**41**	0.452
-10	0.881	**16**	0.566	**42**	0.455

-9	0.868	**17**	0.556	**43**	0.459
-8	0.856	**18**	0.546	**44**	0.463
-7	0.843	**19**	0.536	**45**	0.468
-6	0.830	**20**	0.524	**46**	0.474
-5	0.817	**21**	0.513	**47**	0.480
-4	0.805	**22**	0.503	**48**	0.488

Table 25: Site-specific temperature correction factors for Station 66 westbound lane.

Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor
-29	1.232	**-3**	0.758	**23**	0.658
-28	1.195	**-2**	0.751	**24**	0.657
-27	1.161	**-1**	0.744	**25**	0.657
-26	1.129	**0**	0.737	**26**	0.656
-25	1.100	**1**	0.730	**27**	0.656
-24	1.072	**2**	0.724	**28**	0.656
-23	1.047	**3**	0.718	**29**	0.656
-22	1.023	**4**	0.713	**30**	0.657
-21	1.000	**5**	0.708	**31**	0.657
-20	0.979	**6**	0.703	**32**	0.658
-19	0.959	**7**	0.698	**33**	0.659
-18	0.941	**8**	0.694	**34**	0.661
-17	0.923	**9**	0.690	**35**	0.662
-16	0.907	**10**	0.686	**36**	0.664
-15	0.891	**11**	0.683	**37**	0.666
-14	0.876	**12**	0.679	**38**	0.668
-13	0.862	**13**	0.676	**39**	0.670
-12	0.849	**14**	0.673	**40**	0.672

-11	0.837	**15**	0.671	**41**	0.675
-10	0.825	**16**	0.668	**42**	0.678
-9	0.814	**17**	0.666	**43**	0.681
-8	0.803	**18**	0.664	**44**	0.685
-7	0.793	**19**	0.663	**45**	0.688
-6	0.784	**20**	0.661	**46**	0.692
-5	0.775	**21**	0.660	**47**	0.697
-4	0.767	**22**	0.659	**48**	0.701

Table 26: Site-specific temperature correction factors for Station 80 eastbound lane.

Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor
-28	1.214	**-1**	0.749	**26**	0.480
-27	1.197	**0**	0.734	**27**	0.477
-26	1.178	**1**	0.720	**28**	0.473
-25	1.160	**2**	0.706	**29**	0.470
-24	1.142	**3**	0.693	**30**	0.467
-23	1.123	**4**	0.680	**31**	0.463
-22	1.105	**5**	0.667	**32**	0.460
-21	1.086	**6**	0.654	**33**	0.457
-20	1.068	**7**	0.642	**34**	0.454
-19	1.049	**8**	0.629	**35**	0.452
-18	1.031	**9**	0.617	**36**	0.449
-17	1.013	**10**	0.606	**37**	0.446
-16	0.995	**11**	0.594	**38**	0.444
-15	0.977	**12**	0.583	**39**	0.441
-14	0.959	**13**	0.572	**40**	0.439
-13	0.941	**14**	0.562	**41**	0.437

-12	0.924	**15**	0.551	**42**	0.434
-11	0.907	**16**	0.541	**43**	0.432
-10	0.890	**17**	0.531	**44**	0.430
-9	0.873	**18**	0.521	**45**	0.428
-8	0.857	**19**	0.512	**46**	0.426
-7	0.840	**20**	0.505	**47**	0.424
-6	0.824	**21**	0.501	**48**	0.423
-5	0.809	**22**	0.496	**49**	0.421
-4	0.793	**23**	0.492	**50**	0.419
-3	0.778	**24**	0.488	**51**	0.418
-2	0.763	**25**	0.484	**52**	0.416

Table 27: Site-specific temperature correction factors for Station 80 westbound lane.

Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor	Temperature (degrees C)	Correction Factor
-29	0.949	**-1**	0.616	**27**	0.394
-28	0.938	**0**	0.605	**28**	0.390
-27	0.927	**1**	0.595	**29**	0.387
-26	0.916	**2**	0.584	**30**	0.384
-25	0.904	**3**	0.574	**31**	0.381
-24	0.892	**4**	0.564	**32**	0.378
-23	0.880	**5**	0.554	**33**	0.376
-22	0.868	**6**	0.544	**34**	0.374
-21	0.855	**7**	0.535	**35**	0.372
-20	0.843	**8**	0.525	**36**	0.370
-19	0.831	**9**	0.516	**37**	0.369
-18	0.818	**10**	0.507	**38**	0.368
-17	0.806	**11**	0.498	**39**	0.367

-16	0.793	**12**	0.489	**40**	0.366
-15	0.781	**13**	0.481	**41**	0.366
-14	0.769	**14**	0.472	**42**	0.365
-13	0.756	**15**	0.464	**43**	0.365
-12	0.744	**16**	0.456	**44**	0.365
-11	0.732	**17**	0.448	**45**	0.366
-10	0.720	**18**	0.440	**46**	0.366
-9	0.708	**19**	0.433	**47**	0.367
-8	0.696	**20**	0.432	**48**	0.368
-7	0.684	**21**	0.425	**49**	0.369
-6	0.672	**22**	0.419	**50**	0.371
-5	0.661	**23**	0.413	**51**	0.373
-4	0.649	**24**	0.408	**52**	0.375
-3	0.638	**25**	0.403	**-**	-
-2	0.627	**26**	0.398	**-**	-

The correction factors developed in this research used the following regression equations from the relationships between WIM output signal and pavement temperature (shown in Figure 14 to Figure 19).

Station 63 NB:

$$Output = 2.6165 * T^2 + 132.99 * T + 8238.5, T < 0, R^2 = 0.1757$$

$$Output = 6.9027 * T^2 + 163.84 * T + 9128.7, T \geq 0, R^2 = 0.8081$$

Station 63 SB:

$$Output = 7.4369 * T^2 + 312.75 * T + 10685, T < -5, R^2 = 0.1464$$

$$Output = -5.0416 * T^2 + 274.59 * T + 11714, T \geq -5, R^2 = 0.4888$$

Station 66 EB:

$$Output = 1.6486 * T^2 + 115.42 * T + 6850.7, T < 20, R^2 = 0.5861$$

$$Output = -7.0235 * T^2 + 504 * T + 2572, T \geq 20, R^2 = 0.1768$$

Station 66 WB:

$$Output = -1.1651 * T^2 + 63.374 * T + 7006.4, R^2 = 0.4206$$

Station 80 EB:

$$Output = 1.31 * T^2 + 135.95 * T + 7029.9, T < 20, R^2 = 0.5977$$

$$Output = -0.7156 * T^2 + 119.85 * T + 8110.7, T \geq 20, R^2 = 0.1043$$

Station 80 WB:

$$Output = 1.5185 * T^2 + 150.56 * T + 8526.4, T < 20, R^2 = 0.7437$$

$$Output = -4.2053 * T^2 + 359.48 * T + 6453.1, T \geq 20, R^2 = 0.267$$

Where: $Output$ *is the output signal from the WIM sensor, and* T *is the pavement temperature as measured by the WIM equipment.*

APPENDIX D: CONSISTENCY OF OUTPUT-TEMPERATURE RELATIONSHIPS IN POST-CALIBRATION PERIODS

This appendix presents the results which evaluated the consistency of the output-temperature relationships for piezoelectric WIM sites in the post-calibration months. An explanation of the scores evaluating consistency can be found in Section 3.5.2.

Table 28: Results of output-temperature relationship consistency test for Station 63 northbound.

Month Under Evaluation (Post Calibration)	Month Compared to (Post Calibration)	Relationship Similarity	Similarity in R^2	RMSE	Total Score (out of 5)
2	1	1	1	3	5
3	2	1	1	2.5	4.5
4	2	0.5	0.5	1.5	2.5
5	4	1	1	2.5	4.5
6	5	1	1	2.5	4.5

* Note: For this particular station, only approximately 6 months of post-calibration data was captured due to WIM sensor and temperature sensor removal in May, 2015 during construction.

Table 29: Results of output-temperature relationship consistency test for Station 63 southbound.

Month Under Evaluation (Post Calibration)	Month Compared to (Post Calibration)	Relationship Similarity	Similarity in R^2	RMSE	Total Score (out of 5)
2	1	1	1	1.5	3.5
3	2	1	1	2	4
4	2	0.5	1	2	3.5
5	4	1	1	2.5	4.5
6	5	1	1	1.5	3.5

* Note: For this particular station, only approximately 6 months of post-calibration data was captured due to WIM sensor and temperature sensor removal in May, 2015 during construction.

Table 30: Results of output-temperature relationship consistency test for Station 66 eastbound.

Month Under Evaluation (Post Calibration)	Month Compared to (Post Calibration)	Relationship Similarity	Similarity in R^2	RMSE	Total Score (out of 5)
2	1	1	0.5	3	4.5
5	1	1	0.5	2	3.5
6	1	1	1	3	5
7	6	1	1	2.5	4.5
8	7	1	1	2.5	4.5
9	6	1	1	2.5	4.5
10	6	1	1	2	4
11	6	1	1	3	5
12	1	1	1	1.5	3.5

* Note: For this particular station, data was not available from February through April of 2015 due to equipment malfunction.

Table 31: Results of output-temperature relationship consistency test for Station 66 westbound.

Month Under Evaluation (Post Calibration)	Month Compared to (Post Calibration)	Relationship Similarity	Similarity in R^2	RMSE	Total Score (out of 5)
2	1	0.5	0.5	1.5	2.5
3	1	1	1	2	4
4	3	1	0.5	2.5	4
5	4	0.5	1	3	4.5
6	5	1	1	3	5
7	6	1	1	3	5
8	7	1	1	3	5
9	6	1	1	3	5
10	5	1	1	3	5
11	4	1	1	3	5
12	3	1	0.5	3	4.5

Table 32: Results of output-temperature relationship consistency test for Station 80 eastbound.

Month Under Evaluation (Post Calibration)	Month Compared to (Post Calibration)	Relationship Similarity	Similarity in R^2	RMSE	Total Score (out of 5)
2	1	1	1	3	5
3	2	1	1	2.5	4.5
4	3	1	1	3	5
5	4	1	1	1.5	3.5
6	5	1	1	1.5	3.5
7	6	1	1	2.5	4.5
8	7	1	1	3	5
9	6	1	1	3	5
10	5	1	1	2.5	4.5
11	4	1	1	2	4
12	3	1	0.5	3	4.5

Table 33: Results of output-temperature relationship consistency test for Station 80 westbound.

Month Under Evaluation (Post Calibration)	Month Compared to (Post Calibration)	Relationship Similarity	Similarity in R^2	RMSE	Total Score (out of 5)
2	1	1	1	3	5
3	2	1	1	3	5
4	3	1	1	3	5
5	4	1	1	3	5
6	5	1	1	2.5	4.5
7	6	1	1	2.5	4.5
8	6	1	1	2.5	4.5
9	6	1	1	2.5	4.5

10	5	1	1	2	4
11	4	1	1	2	4
12	3	0.5	0	2	2.5

APPENDIX E: AXLE LOAD SPECTRA FROM PRIMARY MANITOBA WEIGH SCALES

This appendix presents the results of the 2013 surveys conducted by UMTIG at the Headignley, West Hawk, and Emerson static weigh scales. To aid in comparing results, Table 34 presents a summary of the weigh scale data.

Headingley Weigh Scale, August 2013

Location: PTH 1, 6.6 km West of PTH 101 Direction: EB

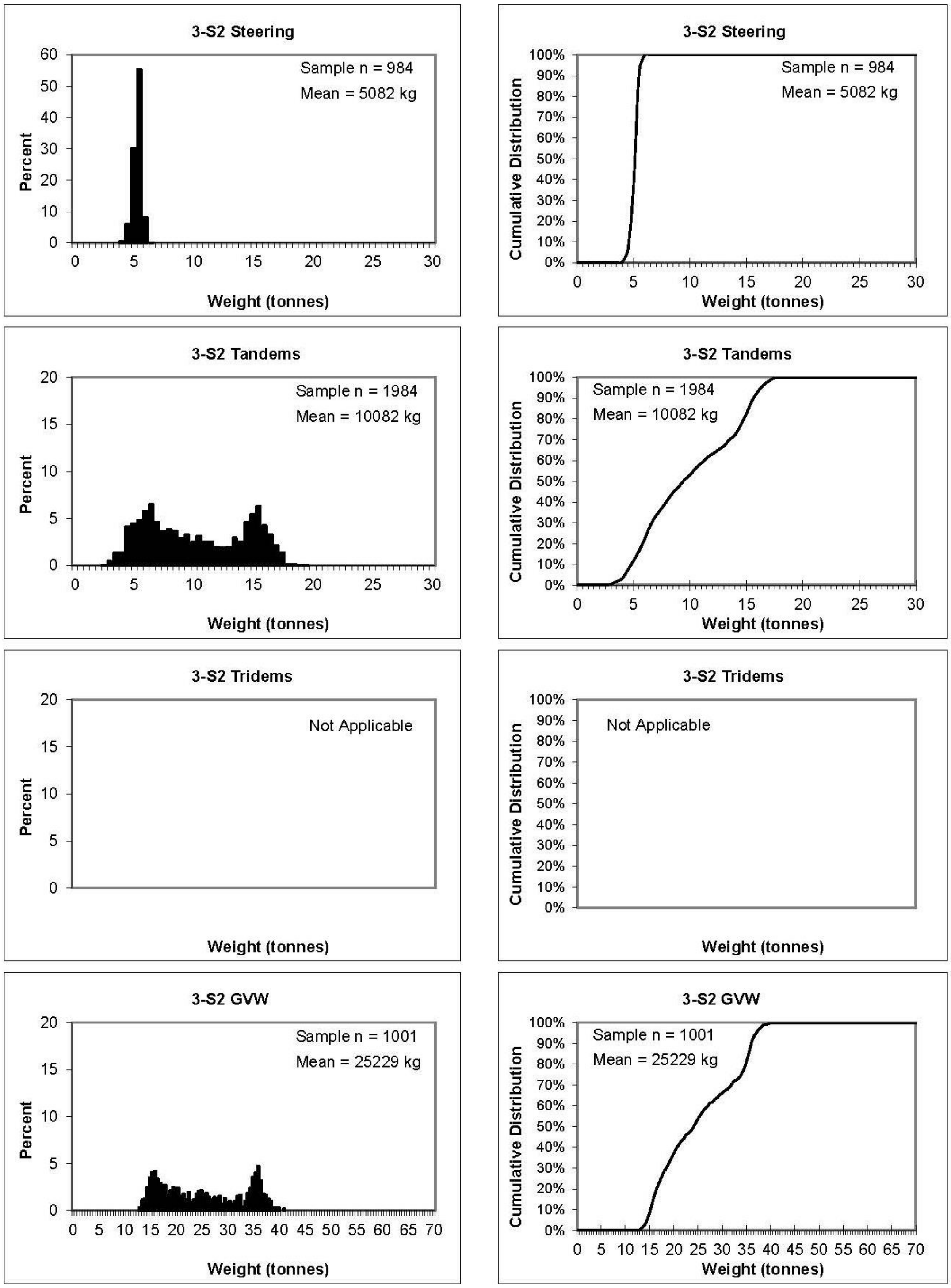

Figure 21: ALS for steering, tandem, and tridem, axles and GVW for 3-S2 configuration trucks at the Headingley static weigh scale from August 14-16, 2013.

Headingley Weigh Scale, August 2013

Location: PTH 1, 6.6 km West of PTH 101 Direction: EB

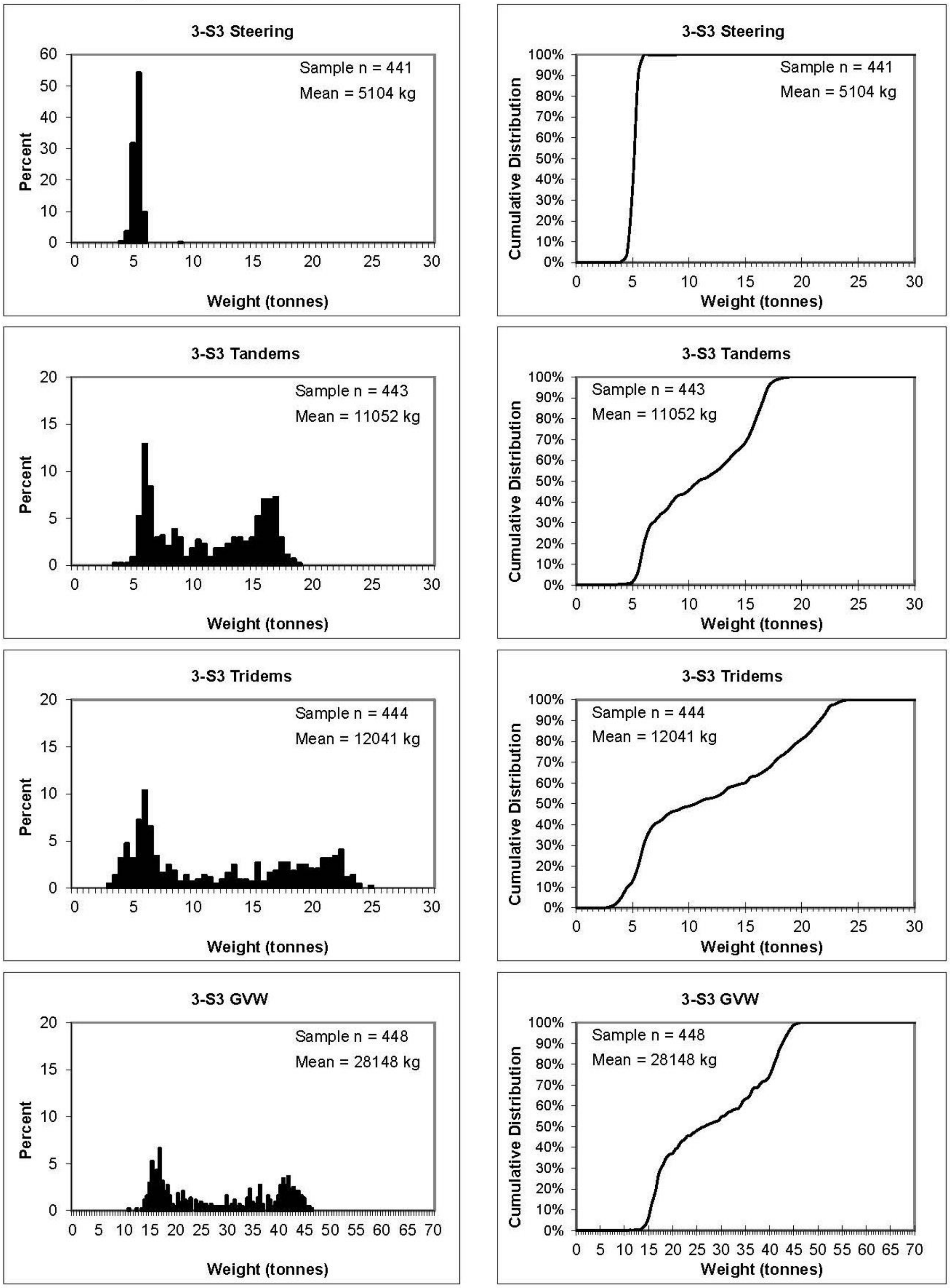

Figure 22: ALS for steering, tandem, and tridem, axles and GVW for 3-S3 configuration trucks at the Headingley static weigh scale from August 14-16, 2013.

Headingley Weigh Scale, August 2013

Location: PTH 1, 6.6 km West of PTH 101 Direction: EB

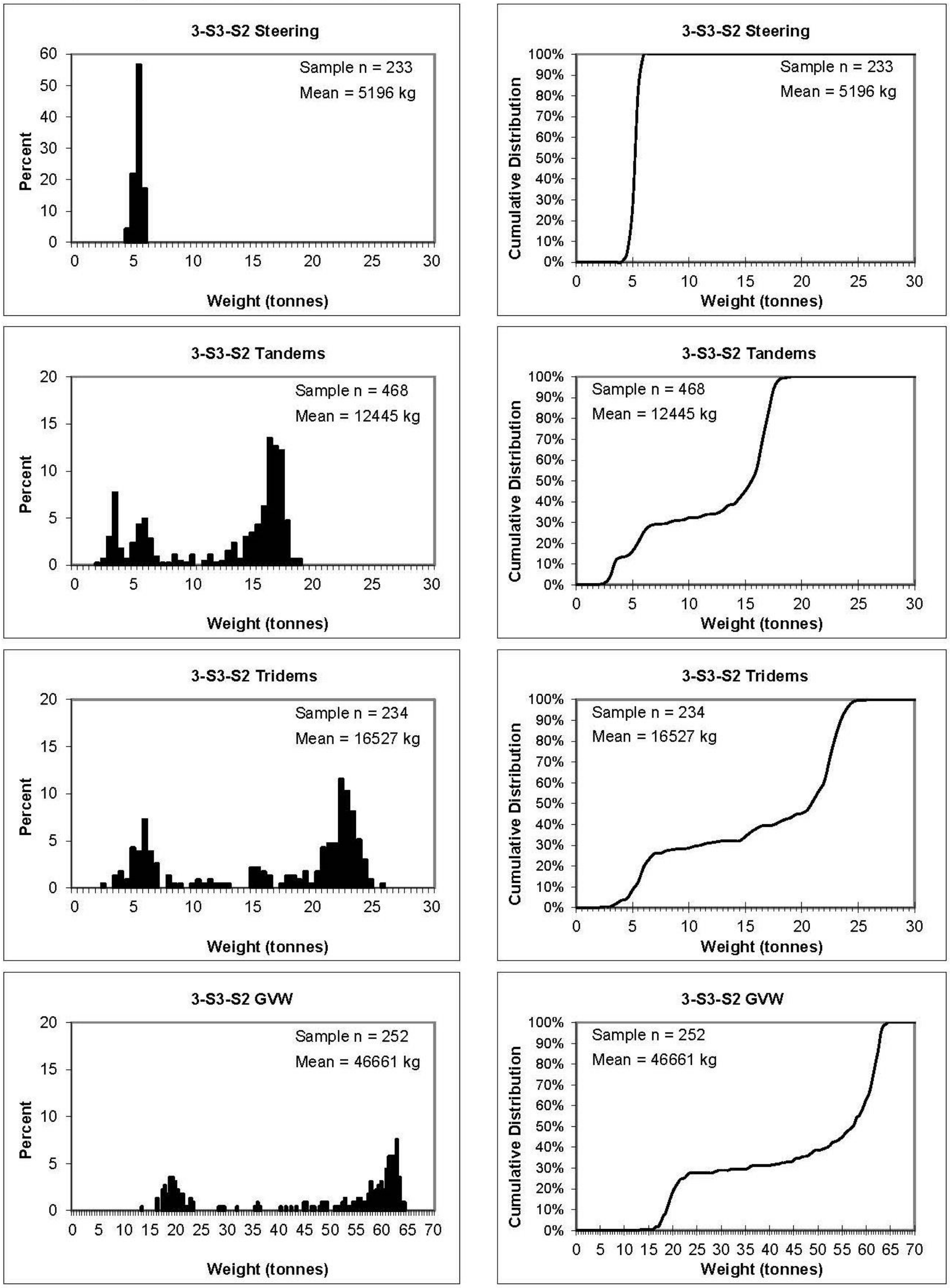

Figure 23: ALS for steering, tandem, and tridem, axles and GVW for 3-S3-S2 configuration trucks at the Headingley static weigh scale from August 14-16, 2013.

West Hawk Weigh Scale, July 2013

Location: PTH 1, 1.1 km West of Ontario border | Direction: Combined

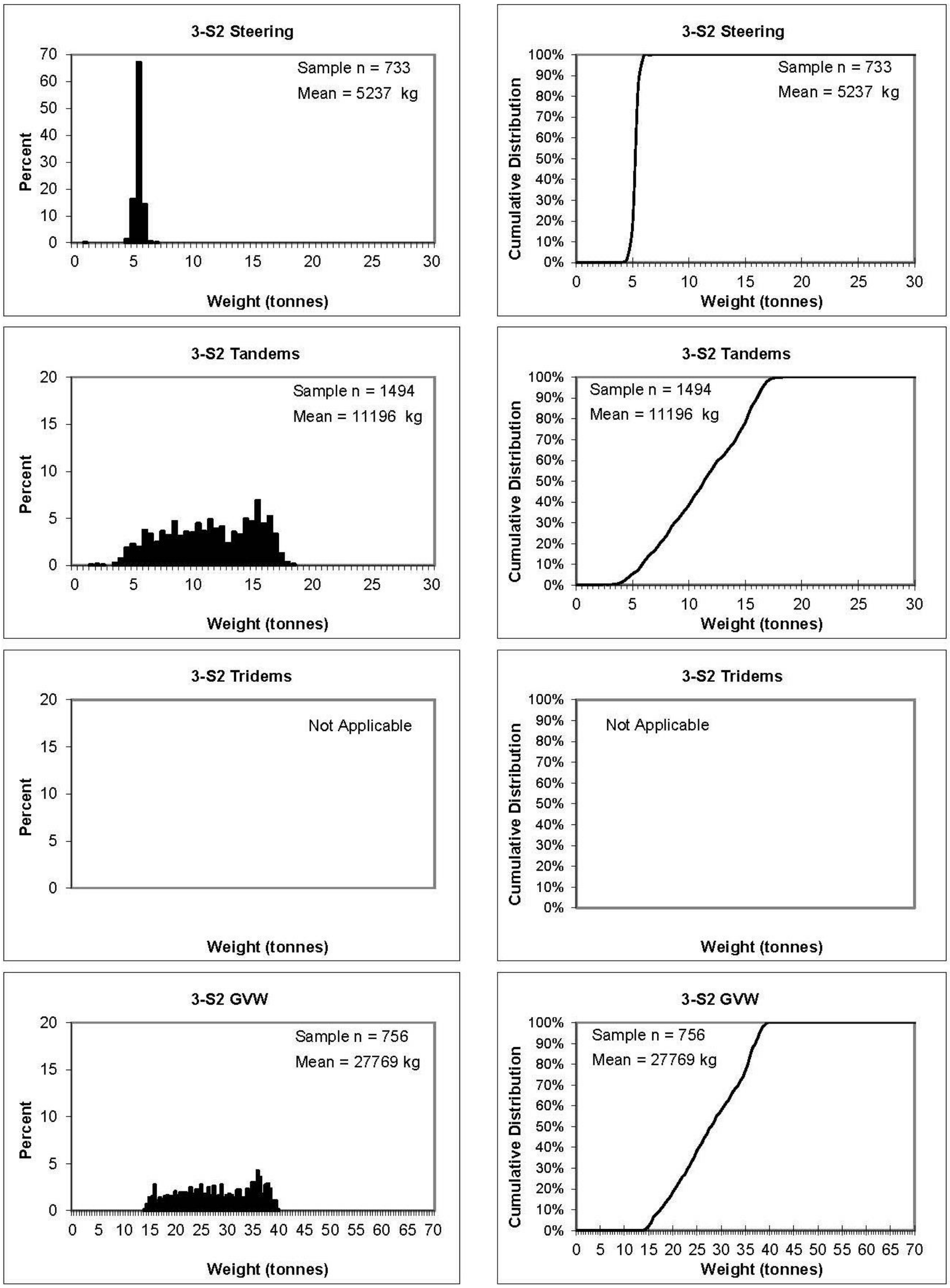

Figure 24: ALS for steering, tandem, and tridem, axles and GVW for 3-S2 configuration trucks at the West Hawk static weigh scale from July 11-12, 2013.

West Hawk Weigh Scale, July 2013

Location: PTH 1, 1.1 km West of Ontario border

Direction: Combined

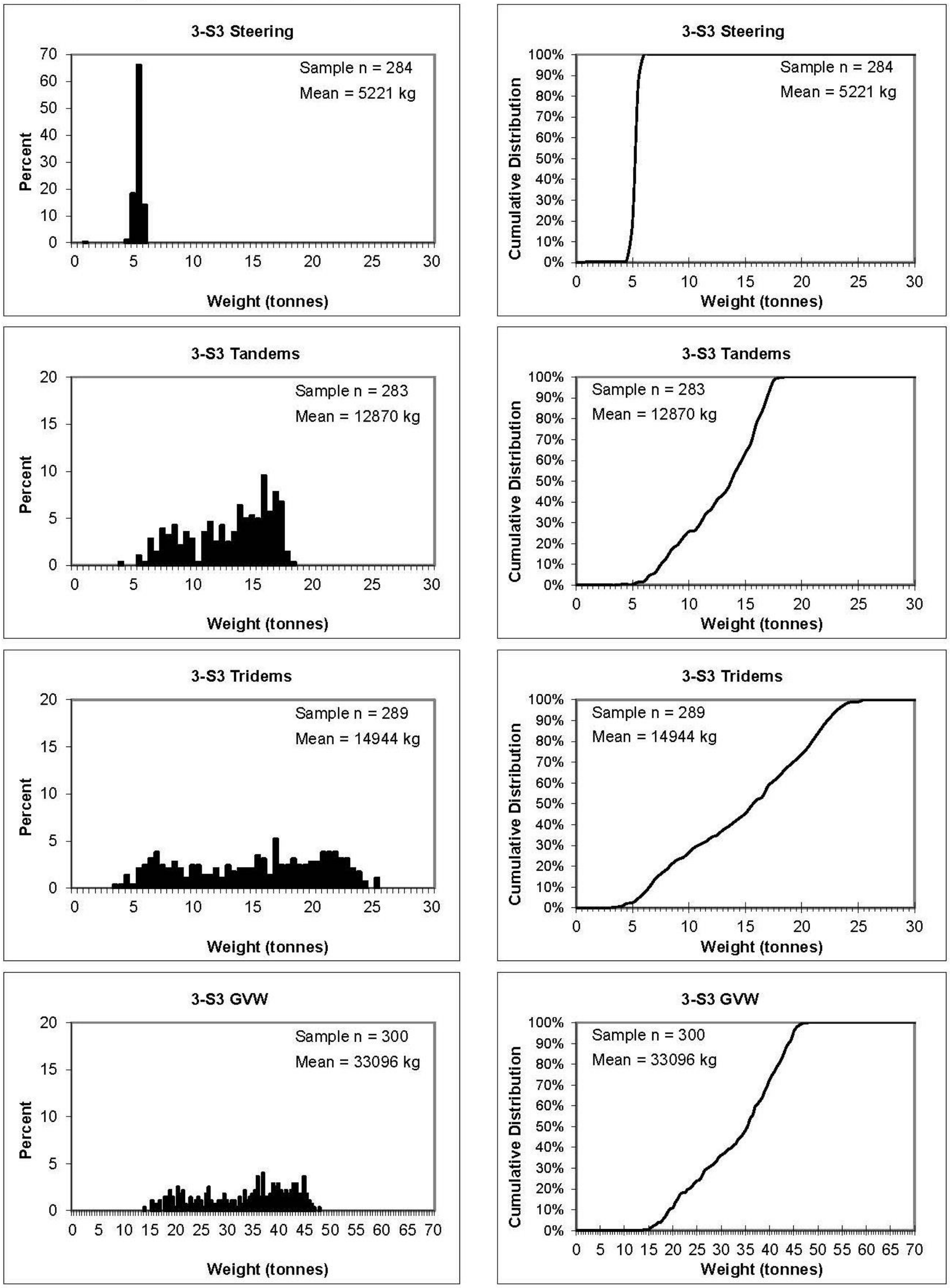

Figure 25: ALS for steering, tandem, and tridem, axles and GVW for 3-S3 configuration trucks at the West Hawk static weigh scale from July 11-12, 2013.

West Hawk Weigh Scale, July 2013

Location: PTH 1, 1.1 km West of Ontario border — Direction: Combined

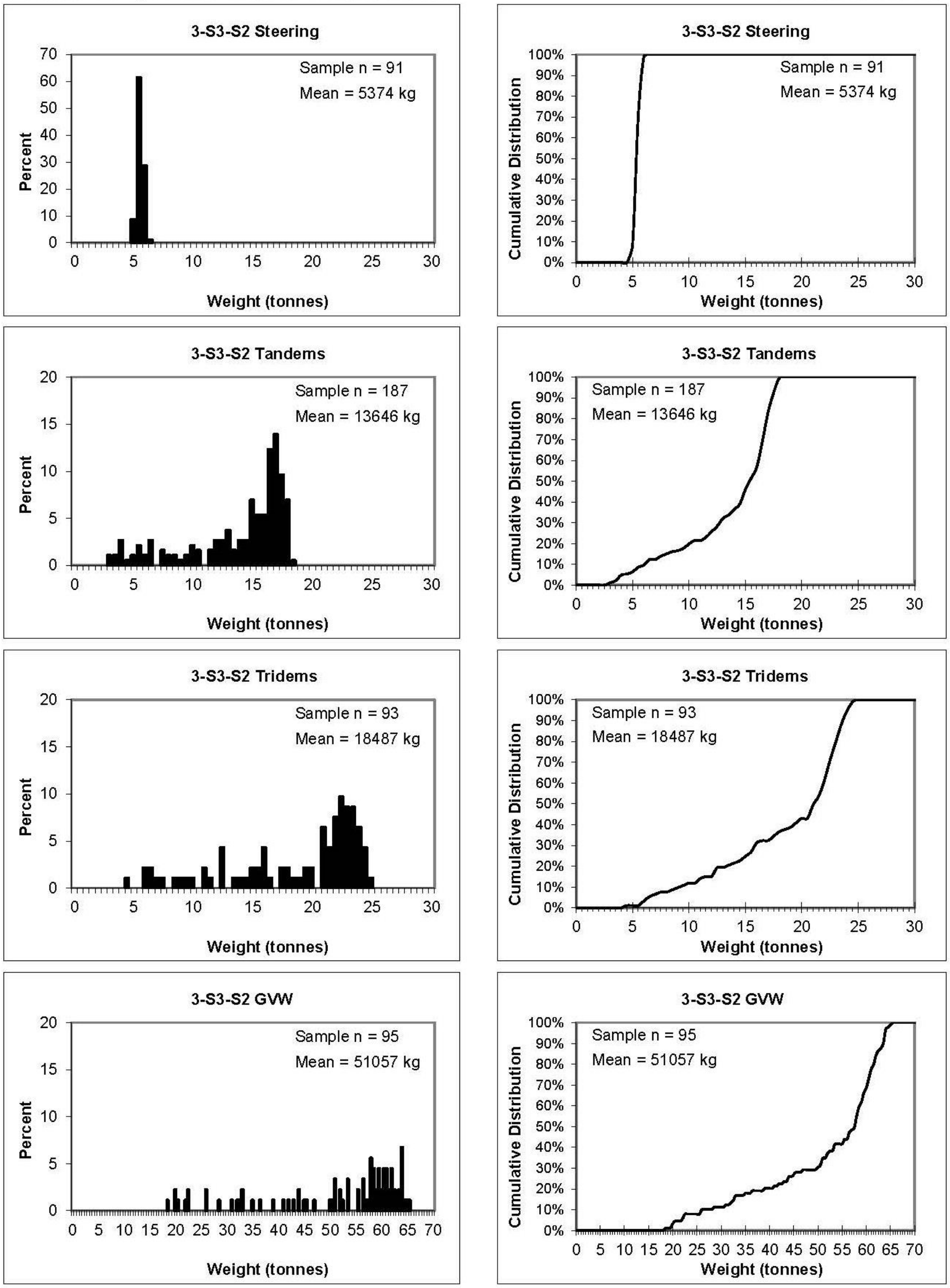

Figure 26: ALS for steering, tandem, and tridem, axles and GVW for 3-S3-S2 configuration trucks at the West Hawk static weigh scale from July 11-12, 2013.

Emerson Weigh Scale, August 2013

Location: PTH 75, 1.8 km North of U.S. border Direction: NB

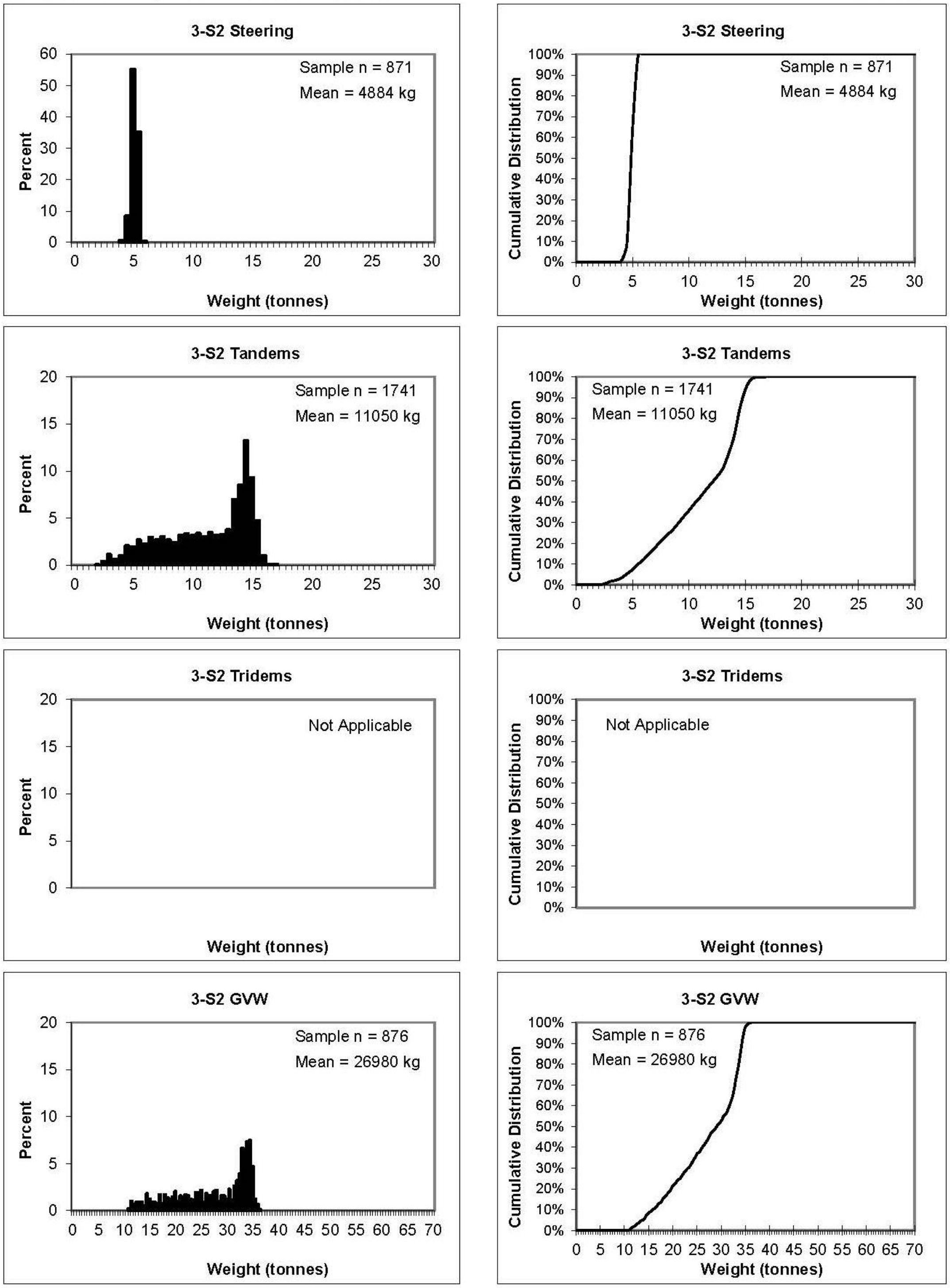

Figure 27: ALS for steering, tandem, and tridem, axles and GVW for 3-S2 configuration trucks at the Emerson static weigh scale from August 12-14, 2013.

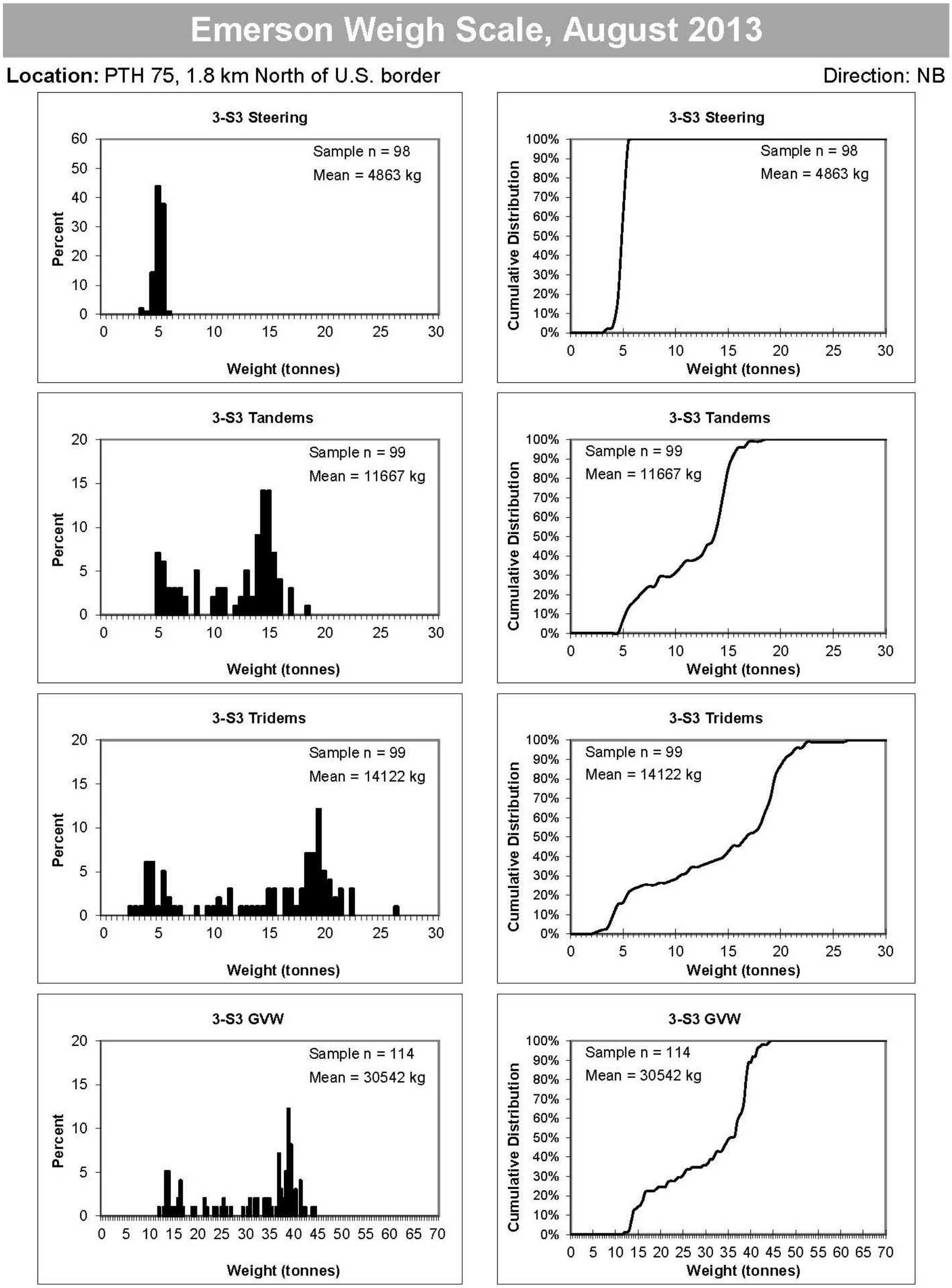

Figure 28: ALS for steering, tandem, and tridem, axles and GVW for 3-S3 configuration trucks at the Emerson static weigh scale from August 12-14, 2013.

Table 34: Summary of ALS from 2013 UMTIG surveys at Headignley, West Hawk, and Emerson static weigh scales.

Configuration/Axle Group		Headingley, August 14-16, 2013		West Hawk, July 11-12, 2013		Emerson, August 12-14, 2013	
		Avg. Load (kg)	Distribution Shape	Avg. Load (kg)	Distribution Shape	Avg. Load (kg)	Distribution Shape
3-S2	Tandem	10082	B	11196	U	11050	L
	GVW	25229	B	27769	U	26980	L
3-S3	Tandem	11052	BU	12870	UL	11667	BL
	Tridem	12041	BU	14944	U	14122	BL
	GVW	28148	BU	33096	U	30542	BL
3-S3-S2	Tandem	12445	BL	13646	L	-	-
	Tridem	16527	BL	18487	L	-	-
	GVW	46661	BL	51057	L	-	-

* Note: The following acronyms in this table apply to distribution shapes:

B = Approximate bimodal distribution.

BU = Bimodal distribution with unloaded bias.

BL = Bimodal distribution with loaded bias.

U = Approximate uniform distribution.

UL = Uniform distribution with loaded bias.

L = Uniform distribution with significant loaded bias.

APPENDIX F: ALGORITHMS TO CONFIRM VEHICLE CONFIGURATION

The following algorithm was used to define and screen for specific truck configurations, as per the (Manitoba Infrastructure, 2016). Table 35 defines the fields of interest in the raw WIM data records:

Table 35: Vehicle characteristics associated with data fields in WIM databases.

Data Field	Vehicle Characteristic
NoAxles	Number of axles in vehicle
Class	Vehicle classification as per FHWA 13-Class vehicle scheme (see Appendix A)
Sep1-2	Centre-to-centre spacing between first and second axles in configuration (cm)
Sep2-3	Centre-to-centre spacing between second and third axles in configuration (cm)
Sep3-4	Centre-to-centre spacing between third and fourth axles in configuration (cm)
Sep4-5	Centre-to-centre spacing between fourth and fifth axles in configuration (cm)
Sep5-6	Centre-to-centre spacing between fifth and sixth axles in configuration (cm)
Sep6-7	Centre-to-centre spacing between sixth and seventh axles in configuration (cm)
Sep7-8	Centre-to-centre spacing between seventh and eigth axles in configuration (cm)

3-S2 Configuration Trucks (FHWA Class 9):

- NoAxles = 5
- Class = 09
- Sep1-2 ≥ 300
- 100 ≤ Sep2-3 ≤ 185
- Sep3-4 ≥ 500
- 100 ≤ Sep4-5 ≤ 185

3-S3 Configuration Trucks (FHWA Class 10):

- NoAxles = 6
- Class = 10
- Sep1-2 ≥ 300
- 100 ≤ Sep2-3 ≤ 185
- Sep3-4 ≥ 500
- 240 ≤ (Sep4-5 + Sep5-6) ≤ 370

3-S3-S2 Configuration Trucks (FHWA Class 13 8-Axle B-Trains):

- NoAxles = 8
- Class = 13
- Sep1-2 ≥ 300
- 100 ≤ Sep2-3 ≤ 185
- Sep3-4 ≥ 550
- 240 ≤ (Sep4-5 + Sep5-6) ≤ 370
- Sep6-7 ≥ 550
- 100 ≤ Sep7-8 ≤ 185
- Wheelbase 1 Criteria: (Sep1-2 + (Sep2-3)/2) ≤ 620
- Wheelbase 2 Criteria: ((Sep2-3/2) + Sep3-4 + Sep4-5) ≥ 625
- Wheelbase 3 Criteria: (Sep5-6 + Sep6-7 + Sep7-8) ≥ 625