GEORGIA DOT RESEARCH PROJECT 18-36

FINAL REPORT

DEVELOPMENT OF WEIGH-IN-MOTION DATA QUALITY CONTROL ALGORITHMS AND PROCEDURES

Georgia Department of Transportation

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16. Abstract: This report recommends a Weigh-In-Motion (WIM) data quality control (QC) process that will assist in delivering higher quality WIM data and continuously improving WIM program performance as its user base grows within the Georgia Department of Transportation (GDOT). Specifically, this research study serves to establish a procedure for off-site office QC checks by analyzing WIM data from six permanent sites. The Office of Transportation Data (OTD) anticipates rapid growth in the volume of data seized from an increasing number of WIM sites over the next couple of years. The goal of this study is to assist GDOT's OTD with effectively managing and improving WIM data quality by providing a summary of findings that have practical implications (e.g., identifying lane numbers and site IDs needing a calibration or attention). The results indicate that a significant portion of invalid weight records exist in the 2018 data and that there are three critical steps to improve data quality: 1) replace Brass Linguini (BL) sensors with quartz sensors as soon as possible, and conduct calibration upon installation; 2) conduct an annual WIM device calibration observed by a third party, and 3) investigate means of enforcing the legal speed limit at WIM locations. Since the reliability of WIM data vastly depends on QC requirements, a thorough investigation of additional data and field validations of parameters contained in the data are necessary. A comparison data set (CDS) needs to be established immediately after a calibration for each WIM site. Additionally, such calibration should be conducted annually at three to five randomly selected sites. During a calibration, axle spacings should also be validated in association with the decision-making process employed by the vehicle classifier. Lastly, the study team recommends that calibration and maintenance logs be made available to the party conducting data QC checks.

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Final Report

DEVELOPMENT OF WEIGH-IN-MOTION DATA QUALITY CONTROL ALGORITHMS AND PROCEDURES

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EXECUTIVE SUMMARY

This study develops a Weigh-In-Motion (WIM) data quality control (QC) process that will assist in delivering higher quality WIM data and continuously improving WIM program performance as its user base grows within the Georgia Department of Transportation (GDOT). At present, end users are expected to undertake a data-driven decision-making analysis of transportation assets, including roads and bridges.

Specifically, this research study serves to establish a procedure for off-site office QC checks by analyzing WIM data from six permanent sites, all instrumented with newly installed piezoelectric quartz sensors. GDOT's Office of Transportation Data (OTD) anticipates rapid growth in the volume of data seized from an increasing number of WIM sites over the next couple of years. The goal of this study is to assist OTD with effectively managing and improving WIM data quality by providing a summary of findings that have practical implications (e.g., identifying lane numbers and site IDs needing a calibration or attention).

This study investigates a total of six data sets from six sites collected over a period of one year (January 2018–December 2018). The raw data are analyzed for each site including all parameters contained in the data. RStudio 3.2 and Python 3.7—leading data analytics tools widely used for processing big data sets—are employed for this study. The results indicate a significant number of invalid weight records in the 2018 data and three critical steps to improve data quality: 1) Brass Linguini (BL) sensors should be replaced with quartz sensors as soon as possible, and a calibration needs to be conducted upon installation; 2) WIM device calibration observed by a third party should be conducted annually, and 3) GDOT needs to investigate means of enforcing the legal speed limit at WIM locations.

Notably, significant percentages of vehicles with zero weight were discovered at three of the six sites. The WIM data collection vendor explained that both BL and quartz sensors existed at these six sites and some lanes had been instrumented for obtaining class-only information. The vendor indicated that the study team should ignore the weight data from lanes with BL sensors as they are not expected to be accurate.

Results confirm that vehicle weights from quartz sensors are more reasonable in terms of magnitude, although their accuracy needs to be field validated, whereas weights from BL sensors can extend well above the allowed limit of 80,000 lbs. In some cases, the weights are significantly low, which indicates that the sensors may be recording noises. Additionally, for a significant percentage of vehicles (>3%), a passing speed well above 80 mph was recorded. The weight data for these vehicles should not be considered valid as the vendor is not responsible for calibrating load sensors for that speed range (i.e., according to the American Society for Testing and Materials (ASTM) 1318-09 (2017) standard).

Since the reliability of WIM data greatly depends on QC requirements, a thorough investigation of additional data and field validations of parameters contained in the data are necessary. Specifically, through an active Quality Assurance (QA) program requiring WIM device calibration, a comparison data set (CDS) can be established immediately after calibration for each WIM site, and this dataset can be used to detect monthly and annual weight shifts. During the calibration process, axle spacings must also be validated in association with the decision-making process employed by the vehicle classifier. Some states perform WIM device calibration as often as twice per year although annual calibration is most common. In addition, a third-party observation of WIM device calibration is strongly recommended, a practice currently employed by Florida DOT. Finally, the study team recommends that calibration and maintenance logs be made available to the party conducting data QC checks.

This study involves the first attempt to establish a third-party QC process; therefore, the recommendations and findings presented in this report should not be construed as final recommendations. In a subsequent study supported by OTD, the research team plans to analyze the 2019, 2020, and 2021 WIM data; conduct a field observation of WIM device calibration; and, enhance the QC process developed in this report. The following electronic files are submitted with this report to support the implementation of findings:

- PDF files including numerical and graphical summaries from the data analysis for each of the six WIM sites.
- A Microsoft word file including a draft 'Weigh-In-Motion (WIM) Data Quality Control Guide.' See Appendix B.
- R and Python scripts used to develop the proposed data QC process. These replace SQL scripts. See Section 4 for more detail.

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Special thanks also to the project managers, Mr. David Jared (retired) and Sunil Thapa, who advised the research team in successfully performing the study and assisted in the coordination of project meetings with the GDOT OTD. Finally, the team would like to express thank for continuous support from Supriya Kamatkar and her leadership in the Performance-based Management and Research Office.

1. INTRODUCTION

1.1 Background

Weigh-In-Motion (WIM) devices are installed in roadways to record gross weights, axle weights, and axle spacings as vehicles drive over measurement sites without having to divert traffic to static weigh stations. The Georgia Department of Transportation (GDOT)'s Office of Transportation Data (OTD) currently manages WIM data collected from more than 18 permanent sites in Georgia. In Figure 1, GDOT's Traffic Analysis and Data Application (TADA) shows active WIM locations on a map as of November 2019. For this report, the study team has enhanced the map by clearly identifying the WIM site IDs and locations.

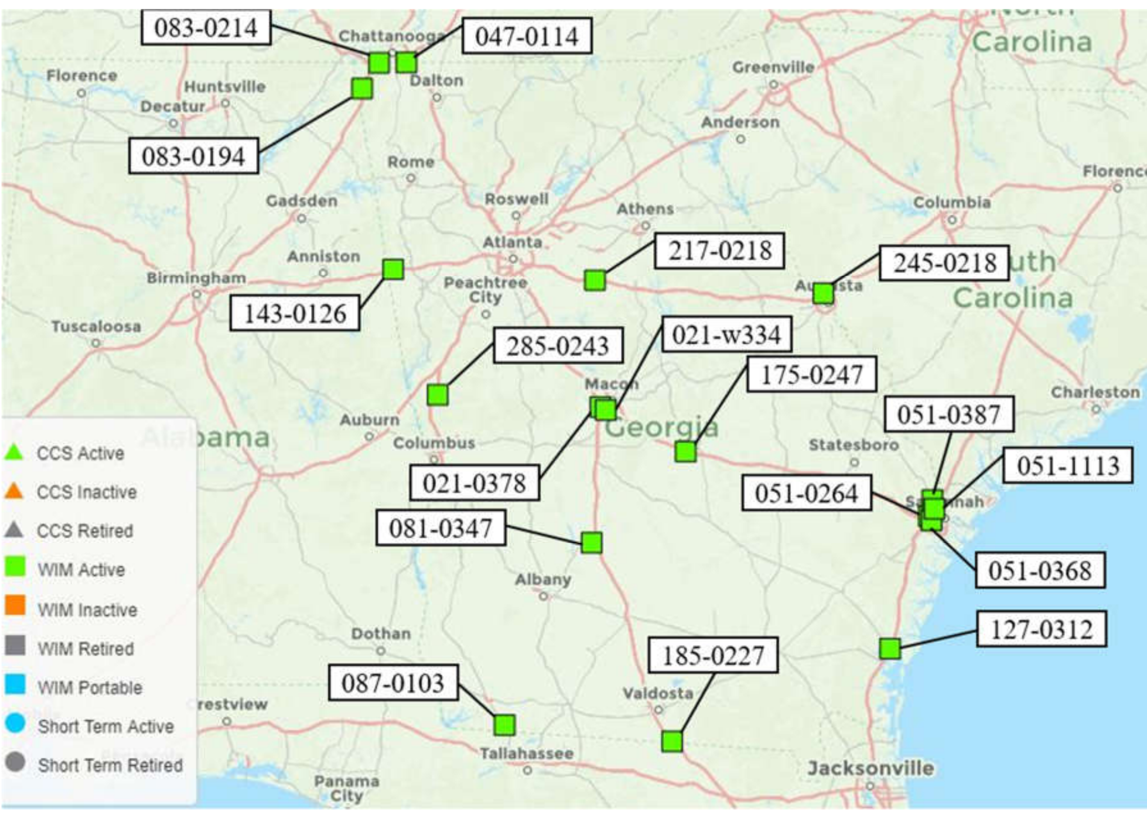


Figure 1 – Active WIM Site Locations (GDOT, 2019) with IDs Shown.

GDOT currently runs a WIM project through the Innovative Delivery program. Some WIM devices have a license plate reader system and a side-view camera capable of capturing a photo of passing vehicles (GDOT, 2018). When this project commenced in 2018, OTD managed 12 active WIM sites; by 2019, this number has grown to 18. The installation of additional permanent WIM systems is anticipated over the next couple of years. Nationwide, the ongoing growth in the volume of data collected from WIM sites is unprecedented, and the management of data quality presents a major challenge to states, particularly those managing upwards of 40–50 sites. The Long Term Pavement Performance (LTPP) program's Traffic Analysis Software (LTAS) for traffic data QC and processing was released after Federal Highway Administration (FHWA)'s pooled fund pavement study was completed in 2016 (Selezneva et al., 2016). Due to limited support through LTPP, however, state DOTs have been developing their own QC processes and algorithms. Further, Bridge Weigh-In-Motion (B-WIM) systems and data collection sensors are being studied by another FHWA's pooled fund study (LTBPP, 2018), though installing and maintaining B-WIM systems is considered expensive and overly complex (Al-Qadi et al., 2016). While portable WIM systems also exist, Selezneva and Von Quintus (2014) have concluded that they do not yield reliable data in Georgia. Therefore, permanent WIM systems installed in roadways present the most viable option at this time.

When it comes to identifying future WIM site placement, the key for success is to recognize the detailed nature (e.g., traffic volume, the number of lanes instrumented, sensor types, and vehicle classifier types) of the WIM data collected from existing permanent sites and the rich data new sites will produce. Various uses of WIM data include, but are not limited to, pavement, bridge, and geometric design, as well as pavement/bridge maintenance, design of traffic control systems, vehicle weight enforcement, and freight transportation planning. In addition to understanding the end use of WIM data, data quality needs to be ensured as an analysis will only be as good as the data on which it is based. Therefore, QC and quality assurance (QA) of WIM data are critically important for end users of WIM data.

1.2 Definitions Used in This Report

1.2.1 Quality Assurance and Quality Control

QA generally involves both field measurement data checks and in-office data analysis. While field data checks are used to support both the field validation and calibration of WIM systems (Selezneva and Wolf, 2017), this study focuses on the latter, an off-site office check. Therefore, recommended QC procedures from this study should be used to remotely monitor and evaluate WIM system performance over time and identify changes in WIM data parameters that may indicate calibration drift in a WIM device and/or a malfunction, if any.

In this project, QC represents the part of GDOT's WIM data management aimed at meeting the proposed quality requirements presented in this document. Meanwhile, QA represents the part of WIM data management focused on providing confidence that the proposed WIM data quality requirements will be met. For example, as part of a QA process, the OTD may implement a QC manual or conduct QC compliance studies at randomly selected WIM locations. Another example of a QA process is conducting a third-party QC observation during a WIM sensor calibration.

This study is intended to recommend WIM sites where field data QC may be performed and to start developing a process for field validations based on off-site data QC outcomes. During an off-site office QC check, if the effect of dynamic loading (i.e., moving vehicles) appears to be inaccurately or inconsistently reflected in the WIM data, the study team will recommend validating the WIM data. WIM data collection validation generally involves visually observing vehicle classes and comparing vehicle axle spacings and weights reported by a WIM system with known vehicle classes and static weights. Such process identifies errors between known static and dynamic WIM weight measurements. Typically, test trucks representing the most frequently observed heavy vehicles (e.g., Class 9 trucks) are used for WIM data field validations.

1.2.2 Precision and Accuracy

Precision generally describes the variation evident in WIM data when the same vehicle is weighed repeatedly by the same WIM sensor. Accuracy describes the difference between the vehicle weight measurement and the vehicle's actual weight. With reference to vehicle classification, precision describes the variation in vehicle classification (or axle spacing) when the same vehicle class is weighed repeatedly with the same WIM data acquisition system, and accuracy describes the difference between the vehicle class identified by the system and the vehicle's actual class. Since this Phase-I study is limited to an off-site office analysis, discussing the precision and accuracy of vehicle weights and spacing measurements is not appropriate. Rather, this study aims to capture anomalies and describe the spread in the (parameter) observations. Thus this study's findings should point to specific windows of time, lanes, and sites requiring the calibration of and/or attention to a WIM device.

1.2.3 Definition of Usable Data in this Report

In this report, "usable data" indicates a data set that meets the needs of different end users. The end users in this report are those who care about transportation asset design and/or evaluation and ultimately undertake a data-driven analysis of transportation assets including roads and bridges that are most likely to be impacted by axle spacing and vehicle weight. Usable data should contain a complete set of parameters required by end users; thus, usability is maximized when no parameters are missing from the WIM data. Since OTD is expanding the user-base beyond research and pavement/bridge design, the specific list of parameters selected in this study are defined in Section 3. Primary parameters determining the un-usability of the data include invalid axle weight/spacing and vehicle class as the main function of WIM systems is not only to provide vehicle counts but also capture axle weights and spacings, which are associated with vehicle classification and axle load configurations. When referring to "usable data" beyond this report, the definition is subject to change as new users and/or needs are determined. A row of data contains a series of parameters for each vehicle, and thus usable entries are interchangeably used in this report as each vehicle record is described in the data entry logged by a WIM device.

1.2.4 Definition of Comparison Data Set in this Report

In this report, comparison data set (CDS) indicates the data set acquired during the month immediately after the calibration of a WIM device. Two sets of CDSs are generated for each site: month-long and year-long sets (often referred to as month-based and year-based data sets). The year-long CDS is acquired in the first January for a period of one year following a calibration.

1.2.5 Definition of Vehicles Requiring an Oversize Permit

The overall legal dimensions are listed below, and any dimensions exceeding the legal limits require a permit (GDOT, 2020).

- Weight exceeding 80,000 lbs. gross weight
- Width 8.5 ft.
- Height 13.5 ft.
- Length 100 ft. (including overhang)

1.3 Significance and Potential Stakeholders

Although the WIM data has been collected for a while, GDOT-OTD has not had major customers requesting and consuming the data, particularly axle weight and spacing information. However, OTD anticipates more future use of the data. For example, Mechanistic-Empirical Pavement Design Guide (MEPDG) users require a WIM device that meets the American Society for Testing and Materials (ASTM) E1318 standards. At present, as a part of Research Project (RP) 18-04, truck factors and MEPDG traffic inputs using WIM data are investigated. Additionally, WIM data is beneficial for bridge load/sufficiency rating analyses.

A recent synthesis report (Hazlett et al., 2020) indicated that DOT employees who could use WIM data “do not know the extent and accuracy of the data available to them.” In turn, OTD will not be able to fully understand the utility of WIM data without input from others in the agency. At the same time, the precision and accuracy of the data required by users are expected to vary. Hazlett et al. (2020) concluded that more research is needed to bridge the gap between user requirements and help various areas and internal divisions at DOTs understand how WIM data could be useful to inform better decisions. To address this gap in the literature, this report recommends a visualization technique to help GDOT employees across the agency and other stakeholders understand the data quality. Similarly, Lawson (2016) conducted a pilot study and produced a web-based visualization and analytics tool to communicate useful information derived from data analysis with DOT planners and designers.

This project involves the first attempt to establish a third-party off-site QC process. Thus, this study aims to develop specific QC procedures that will ultimately lead to higher quality WIM data and yield continuous improvement of WIM program performance for the following, but not limited to, potential stakeholders:

- The Office of Bridge Design and Maintenance for determining bridge load ratings and maintenance needs
- The Office of Materials and Testing for generating MEPDG traffic inputs
- The Office of Traffic Operations for conducting safety related analyses
- The Office of Maintenance for managing assets
- The Georgia Department of Public Safety for issuing permits for oversize vehicles (GDOT, 2020).

GDOT utilizes a vendor who installs, maintains, and calibrates WIM systems as part of its contract to operate all GDOT traffic counters and WIM sites. This service has been outsourced to Southern Traffic Services Inc. (hereafter referred to as "the vendor"). Its subcontractor, Drakewell Limited, provides data-hosting services through TADA. As the user base increases within GDOT, OTD intends to work with a third party on implementing QA measures including an office QC check on the data and a field QC to validate vehicle classes and weights. The study team has neither former acquaintance with the vendor nor any conflict of interest (e.g., financial relationships) with the vendor.

1.4 Recent Improvement Made to Respond to the Latest Needs

With the growing need for analyzing WIM data for transportation assets such as bridges and pavements, accuracy in weight measurements is critical. The errors for a WIM system utilizing piezoelectric quartz sensors should be within the 10% Gross Vehicle Weight (GVW) tolerance specified in ASTM E1318 for Type I WIM systems. Brass Linguini (BL) piezoelectric polymer traffic sensors have been primarily used in Georgia; however, to increase weight measurement accuracy, the vendor has been replacing these (i.e., BL) sensors with piezoelectric quartz (i.e., Kistler) sensors to better serve the growing need for accurate vehicle weight measurements and to utilize the latest technology available.

1.5 Description of Current WIM Sites

In Georgia, WIM sensors are primarily installed in concrete pavement. Those installed in concrete appear to last longer and perform better than those installed in asphalt, observations consistent with those noted by another DOT (ADOT, 2017). Although the life expectancy of WIM sensors has increased overall, some sensors have become non-functional due to asphalt pavement failures (e.g., rutting and other local failures) after approximately two years, while the sensors installed in concrete pavement are still functional. The maintenance limitation and the decreased return on investment for sensors installed in asphalt pavement explain why Georgia's WIM sensors have been installed in concrete. If more WIM sensors are needed for asphalt pavement designs, a segment of asphalt sites must be adequately prepared in consultation with the WIM vendor. Other factors influencing WIM site selection include, but are not limited to, traffic volume and the frequency of stopping vehicles.

1.6 Specific Goals and Forward Approach

Monitoring traffic through extensive data collection is crucial for improving safety and efficiency in transportation asset management. This study focuses on identifying off-site office QC measures for six selected WIM sites. The six sites are selected because Kistler's quartz sensors have been installed there, and these sensors are expected to increase the accuracy of recorded vehicle weights and classes. Kistler claims its piezoelectric quartz sensors keep precise track of quasi-static and highly dynamic force processes (Kistler, 2020), and their claim has been validated by multiple transportation agencies based on a DOT survey conducted by ADOT (2017). Since more WIM piezo-polymer sensors are expected to be replaced with Kistler's quartz sensors and the old sensors do not provide as much accuracy as the new sensors, particularly in terms of axle weight, this study focuses on reviewing the 2018 WIM data from the six sites with newly replaced/installed quartz sensors. This approach allows for a more meaningful analysis from data generating a reasonable range of weights and weight distributions (e.g., tandem axle weights).

Although the weight accuracy of piezo-polymer sensors is unknown, it is expected to range between 10% and 30% (ADOT, 2017) for this sensor type. Additionally, the temperature sensitivity of piezo-polymer sensors, despite an auto-calibration feature, is a well-known issue (ADOT, 2017). These two factors make the WIM data from these sensors unsuitable for reviewing vehicle weights. Additionally, their weight tolerance is likely to exceed the ASTM E1318-09 (2017) specification requirements for Type I WIM systems: steering axle weights (20%), tandem axle weights (15%), and GVW (10%). Meanwhile, other state DOTs' experience with Kistler's quartz sensors indicate the GVW accuracy is well within 10% (ADOT, 2017) when the sensors are successfully installed and calibrated.

Observing anomalies in WIM data is expected. Anomalies result from limitations in WIM devices and/or system errors. They can also occur due to behavioral changes of drivers such as acceleration, deceleration, and breaking when approaching a WIM sensor. Accordingly, WIM data needs to be effectively reviewed so that the quality of the data can be improved. The objective of this research project is to provide GDOT with a well-organized QC process to continuously review WIM data and improve data quality in partnership with its WIM vendor.

1.7 Acknowledgement of Challenges in Weight Data Collection

The study team understands that WIM systems are susceptible to producing inaccurate weight data (Moses, 2019) and acknowledges problems and challenges faced by WIM vendors nationwide, particularly for field staff installing, maintaining, and calibrating WIM equipment. Obtaining reliable weight measurements for dynamic loads and identifying calibration factors when calibrating a highly sensitive load cell are extremely challenging even in a controlled laboratory environment. The study team also understands that weight measurement errors in the field come from a variety of sources including dynamic factors like vehicle speed, vibrations in vehicle suspension systems, and pavement profiles (Moses, 2019), as well as the WIM sensor and data logger types. The results of this analysis can inform the field staff of potential weight shifts and measurement errors, if any. These inconsistencies and errors may not otherwise be detected until a similar QC check is reported in real time to GDOT and its WIM vendor. Finally, the study team understands that the findings from the 2018 WIM data QC checks may not be immediately useful or provide an acceptable level of quality. Rather, this study establishes a QC process that may serve as an example to inform how the 2019 and future data are handled and enhance QC procedures moving forward. In the subsequent phase, the research team will be able to start from the QC measures identified through this process and use the 2019 and future data as a CDS, if suitable, for analysis of all WIM data.

2. LITERATURE REVIEW

There are numerous publications on the use of WIM data and QC procedures. This section presents selected references that the study team finds most useful and thus pertinent to the study. This literature review focuses on WIM data QC practices among DOTs in the United States.

2.1 NCHRP Synthesis 546

The recently published National Cooperative Highway Research Program (NCHRP) synthesis report (Hazlett et al., 2020) offers insights on the use of WIM data collected nationwide. While this report mainly describes the use of WIM data to support decision making for transportation asset management, bridge load rating, pavement design, weight enforcement, and freight logistics, it also reports on a survey of WIM data QC practices. The use of WIM data and QC procedures are described in the following subsections. As shown in Figure 2, approximately 88% of state DOTs conduct QC on WIM data (Hazlett et al., 2020).

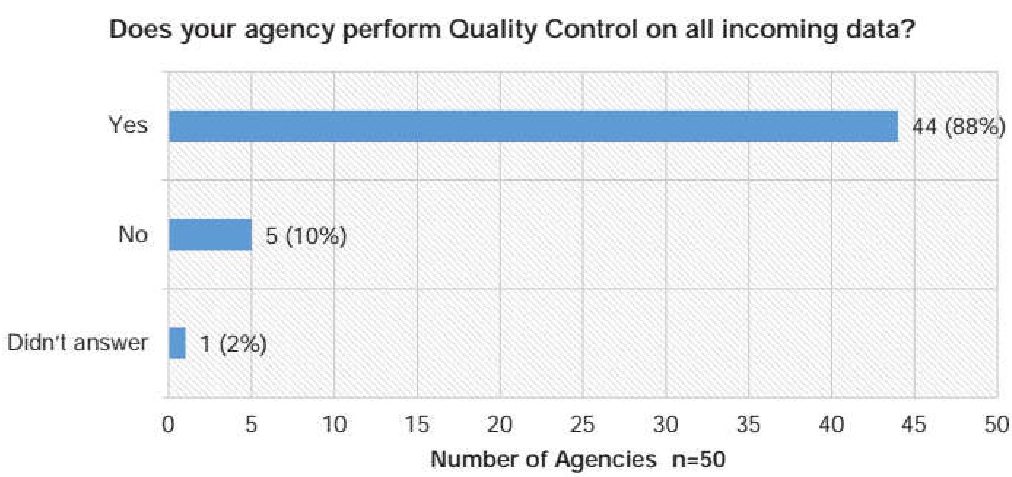


Figure 2 – Frequency of WIM Data QC (Hazlett et al., 2020).

2.1.1 WIM Data Use

2.1.1.1 Pavement Performance and Design

In 1996, the FHWA's LTPP program revealed major problems with WIM data, including issues with accuracy, calibration, and missing data (ADOT, 2017). Monitoring pavement performance relies on understanding how traffic degrades pavement performance, and WIM data plays a key role in this assessment. By 2015, LTPP-led studies (Pierce, 2015; Hallenbeck et al., 2014; FHWA, 2015) resulted in an LTPP vehicle classification table and traffic inputs for the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) and AASHTOWare Pavement ME Design software (Standing Committee, 2017). Additional studies on the use of WIM data are published by FHWA (2016; 2018; Selezneva and Wolf, 2018).

2.1.1.2 Bridge Design

Bridges in the United States are designed according to the AASHTO Load and Resistance Factor Design (LRFD) method. This method uses live load factors derived from truck data recorded in Ontario, Canada, in 1975. These live load factors are considered conservative because they represent live loads for bridge design across the United States (Hazlett et al., 2020). The LRFD process also allows for the use of site-specific live load factors based on actual traffic conditions calculated using WIM data (Kwon et al., 2011). These factors represent the actual traffic load spectrum and thus are more tailored for traffic on a specific group of bridges. Using WIM data to determine these (reduced) live load factors can thus lead to significant cost savings for signature bridges and provide adequate justification for the cost of acquiring WIM data (Hazlett et al., 2020). Illinois DOT, for instance, has recently evaluated state-specific live load factors for LRFD using its WIM data (Chi, 2019).

2.1.1.3 Asset Management and Bridge Load Rating

AASHTO's Load and Resistance Factor Rating (LRFR) is a program that requires in-service bridges to be load-rated every other year. The LRFR allows the use of standard load factors or site-specific load factors using WIM data. The New York DOT has funded research to develop site-specific load factors for the state of New York (Ghosn et al., 2011).

The New York DOT has also used WIM data to estimate the number of overweight trucks on roads and bridges and, in turn, assess the damage they cause (Lou et al., 2016). The department has found that 18% of trucks are overweight, with 6% illegally overweight (Ghosn et al., 2015). In damages to roads and bridges from illegal overweight trucks, the New York DOT estimated an amount of 100 million dollars (Ghosn et al., 2015).

2.1.2 WIM Quality Control Procedure

The NCHRP report (Hazlett et al., 2020) also highlights the necessity WIM data QC and presents statistics about how state DOTs address WIM data with QC issues. As shown in Figure 3, approximately 76% of DOTs indicate that data are flagged and reviewed for inclusion or exclusion. About 28% of DOTs simply remove the data that do not meet their quality requirements.

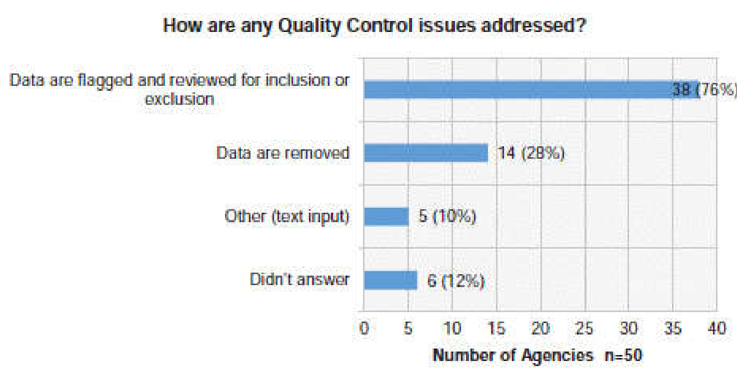


Figure 3 – Methodology for Addressing WIM Data with QC Issues (Hazlett et al., 2020).

In Figure 3, the agencies that answered "Other" conduct on-site observations to check hardware or pavement condition problems, investigate possible recalibration, and discontinue the use of suspected "bad WIM data" in end-use applications until the reason for the bad data can be corrected. Figure 4 illustrates how often state DOTs calibrate WIM systems. In general, they are calibrated upon installation and annually thereafter, though some DOTs calibrate as often as twice a year (ADOT, 2017). The item, "Other", is not specified in the report (Hazlett et al., 2020). Fifty seven participants including 50 U.S. state DOTs, New York City Department of Transportation (NYCDOT), and 6 Canadian provincial DOTs were invited to answer the questions in Figures 3 and 4. Agencies were able to select multiple items to answer the questions.

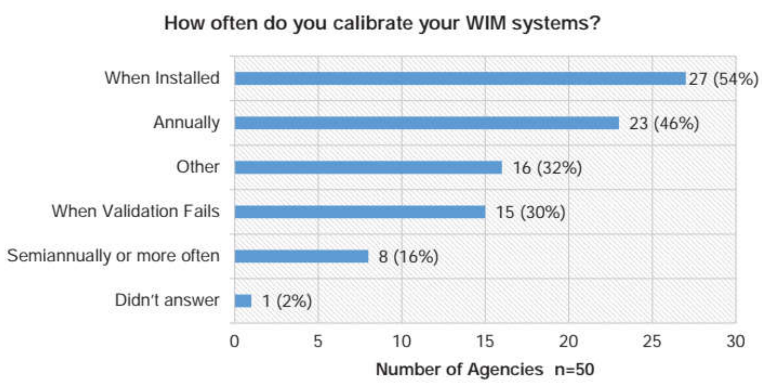


Figure 4 – Frequency of WIM System Calibration (Hazlett et al., 2020).

2.2 FHWA WIM DATA Quality Control Procedure

The FHWA's WIM Data Analyst's Manual (Quinley, 2010) includes a list of QC checks recommended to identify incomplete and inconsistent data. A WIM data QC check is particularly recommended to determine whether the WIM data is suitable for its intended use and to detect any system malfunctions as a result of improper system settings—calibrations and traffic conditions, for instance—as well as environmental conditions

(Quinley, 2010). To comply with the requirements of ASTM E 1318-09 (2017) for a Type I WIM system, the system needs to be calibrated yearly.

2.3 Georgia's Traffic Monitoring Guide 2018

Georgia's Traffic Monitoring Guide (GDOT, 2018) includes the current procedures and practices of GDOT's traffic monitoring system. This document describes OTD's current management of and practices employed in the traffic data collection program, which includes the collection of traffic data, QC and QA, data processing and statistics, and reporting. According to the guide, WIM data is transmitted electronically from the permanent sites each day. Currently, TADA (GDOT, 2019) publishes vehicle counts, axle and gross weight, and vehicle classification data. GDOT and data customers use WIM data for pavement and capacity studies, enforcement, inspection purposes, and analyses of truck transport practices. This guide also articulates one of OTD's main goals—to provide an "accurate portrayal of statewide traffic data and trends"—and discusses OTD's efforts toward developing procedures for WIM data QC and QA programs (GDOT, 2018).

2.4 GDOT WIM Data Study in 2014

Applied Research Associates Inc. (Selezneva and Von Quintus, 2014) completed an analysis of Georgia's WIM data in 2014 (RP 10-09) and concluded that the WIM data from two permanent WIM sites were of acceptable quality for pavement design, particularly for MEPDG; however, the other WIM samples collected from portable WIM devices were unacceptable. Portable WIM data was collected over a 48-hour sampling period for sites with high Class 9 volume; yet, the data sample was excluded due to higher-than-expected percentages of overloaded trucks. The study concluded that the WIM data from permanent sites must be accurate and reliable. In addition, this study recommended that GDOT establish a reliable WIM data QC process and that "QC should be viewed as an essential part of WIM data processing" (Selezneva and Von Quintus, 2014).

2.5 NCDOT Quality Control Procedure

The North Carolina DOT has a QC process involving separate assessments for weight and vehicle class cards (Ramachandran et al., 2011). This document is somewhat outdated; however, the QC process including the checks shown in Table 1 is consistent with other DOT and FHWA QC procedures (Quinley, 2010) and provides specific checks on both weight and class.

Table 1 – NCDOT QC Rules on Weight and Class (Ramachandran et al., 2011).

QC Checks on Weight	QC Checks on Class
Any field with a null value	Any field with a null value
Invalid hour	Invalid hour
Invalid month	Invalid month
Invalid vehicle class code	Total lane volume exceeds max. limit of 3000
Invalid Federal Information Processing Standard (FIPS) Code	Invalid FIPS Code
Invalid station ID	Invalid station ID
Invalid direction for station	Invalid direction for station
Invalid lane number for station	Invalid lane number for station
Invalid year	Invalid year
Invalid day	Invalid day
Hour without any weight records. A full day of data may not be available for all lanes	A full day of data unavailable for a day for all lanes
Axle count inconsistent with number of axle spacings	Class volume exceeds maximum limit
Axle count inconsistent with number of axle weights	a.m. total lane volume exceeds 1:00 p.m. total lane volume
GVW inconsistent with sum of axle weights	Static total lane volume for four consecutive hours
Axle weight out of acceptable range	Review class distribution by month for unusual patterns
Axle spacing out of acceptable range	Review class % distributions for unusual patterns
Sum of axle spacing exceeds maximum wheelbase of 98.2 ft	DOW volumes by month
Review average Day of Week (DOW) volumes by month for unusual patterns	
Review GVW plots by class by month for unusual patents	

2.6 PennDOT Quality Control Process

The Pennsylvania DOT (2017), following an assessment of reasonable and consistent WIM data, uses LTPP's data processing software due to its active participation in the LTPP data collection effort (FHWA, 2018).

2.7 MDOT Quality Control Process

The Montana DOT (Stephens et al., 2017) has a well-documented Automated Traffic Recorder (ATR)/WIM data QC process. ATR data is compared to WIM data to evaluate the reasonableness of traffic volume, such as average daily truck volume, and is used in some cases for a comparison of vehicle classes.

2.8 ADOT Quality Control Recommendations

The Arizona DOT (2017), after surveying other DOTs' QC procedures, has developed the most extensive QC process among those employed by DOTs across the United States. This comprehensive procedure includes the following checks:

- Data file size checks
- Polling error checks including a review of the number of error vehicles, status-clear vehicles, and good-weight
- Site identification, lane, direction, date, time, and location description checks
- Volume, class, and speed errors based on site-specific traffic volume, class, and speed averages
- Invalid weight counts
- Right- and left-wheel weight comparison on front-axle data for Class 9 vehicles

- Average Class 9 front-axle weights against a minimum weight and CDS weight
- Minimum/maximum axle weight for Class 9 vehicles
- Minimum/maximum axle spacing for Class 9 vehicles
- Total wheelbase based on vehicle class
- Average Class 9 hourly or daily volume checks
- Average Class 9 loaded/unloaded peak loads
- Vehicles per day against ATR data
- Average Class 9 GVW against historical data
- Average Class 9 front-axle weights against historical data
- Average percentage of overweight vehicles against historical data
- Average tandem axle spacing of Class 9 vehicles against historical data

ADOT (2017) has also planned to establish 60 new WIM sites statewide after conducting a survey on available types of WIM sensors nationwide. The project team found that the piezoelectric quartz sensors perform much better than the piezo-polymer sensors due to their consistent reliability, reduced calibration requirements, and relative temperature insensitivity. The report's authors concluded that with proper installation, piezoelectric quartz WIM sensors should provide accurate axle and truck weight measurements in Arizona. They also recommended piezo-polymer sensors for vehicle classification, traffic volume, and speed studies and piezoelectric quartz sensors for weight data collection because they are insensitive to temperature (ADOT, 2017).

2.9 FDOT Traffic Monitoring Handbook

The Florida DOT's Traffic Monitoring Handbook (FDOT, 2018) describes the end-to-end process of traffic monitoring at FDOT. Accordingly, the handbook discusses devices, including WIM systems, used for collecting traffic and data QC plans, comprising monthly average daily traffic (ADT) and average annual daily traffic (ADTT) computations and annual statistics. Additionally, FDOT (Donaldson, 2012) performed a study on the installation of a Virtual Bypass System (VBS) which includes the design, furnishing, and installation of WIM equipment; integration; testing; and, a four-year operations and maintenance (O&M) period. The VBS was intended to automatically identify possible overweight vehicles traveling on a bypass route at a capacity of 1200 counts per hour. The study also considered the dynamic testing procedures of WIM sensors. Lastly, Moses (2019) has recently conducted a study on measuring WIM device accuracy, among numerous studies his team has conducted over the years, and published his latest findings and recommendations. He evaluated four WIM systems and concluded that different levels of accuracy were achieved by them.

2.10 INDOT Quality Control Recommendations

The Indiana DOT (INDOT) used an outlier analysis and data mining techniques to identify sensors out-of-range and create a data-driven protocol for WIM maintenance (Bunnell et al., 2018). INDOT has more than 40 WIM sites, which enable the validation of vehicle classification by image processing (Li et al., 2010). Eric Conklin with GDOT-OTD connected the study team with Tommy Nantung at INDOT, and he shared his experience with WIM data QC for MEPDG (Jiang et al., 2008), emphasizing the importance of obtaining the raw data for WIM data QC checks.

2.11 Other Attributes Considered for a WIM Data Quality Control Check

WIM malfunctions and system errors are generally captured during a WIM data QC process. The temperature/moisture sensitivity of WIM devices is a well-known cause of erroneous WIM outputs (Quinley, 2010) although newer devices (e.g., piezoelectric quartz sensors) appear to reduce such problems (ADOT, 2017). Some WIM sensors performed very well in a controlled space, yet they experienced some level of failure when installed on a highway (Szary and Maher, 2009).

Finally, the latest literature review conducted by the team for FHWA's pooled fund study (Al-Qadi et al., 2016) indicates that road surface roughness and installation workmanship could also affect the accuracy of WIM data measurements. ADOT (2017) recommends that WIM calibrations include test truck runs at the widest possible speed range. The ASTM E1318-09 (2017) standard states, "WIM system shall be designed for installation in one or more lanes at a traffic data-collection site and shall be capable of accommodating highway vehicles moving at speeds from 10 to 80 mph (16 to 130 km/h), inclusive." Additionally, the standard requires that the system produce **all data**: Wheel Load, Axle Load, Axle-Group Load, Gross-Vehicle Weight, Speed, Center-to-Center Spacing Between Axles, Vehicle Class (via axle arrangement), Site Identification Code, Lane and Direction of Travel, Date and Time of Passage, Sequential Vehicle Record Number, Wheelbase (front-most to rear-most axle), Equivalent Single-Axle Loads, and Violation Code.

3. DESCRIPTION OF WIM SITES AND DATA

3.1 Description of WIM Sites and Data

Table 2 lists the 6 sites studied in this report. Figure 5 shows the six selected WIM site locations highlighted by red boxes. The active sites produce large WIM data sets, each of which provides the date and timestamp of every passing vehicle at each sensor. The WIM systems record the number of axles, single axle weight, GVW, axle spacing, lane, vehicle class, length of vehicle, gap between vehicles, speed, and/or temperature of the site.

Table 2 – Site ID and Description of 6 WIM Sites.

Site ID	Location	Latitude	Longitude	Orientation
021-7334	I-75 N of I-475 Split Dr, Macon	32.77959	-83.68055	NE
051-0368	I-16 East of Dean Forest Exit	32.06899	-81.19281	E
127-0312	I-95 N of US-25/US-341/SR-27	31.23438	-81.5093	NE
143-0126	I-20 btwn Alabama State Line & SR100 Veterans M. Hwy	33.68077	-85.30221	E
185-0227	I-75/SR401 @FLA SL, Lake Park, Lowndes Co	30.62671	-83.76155	NW
245-0218	I-20 E of I-520 @SC State Line, Augusta	33.52746	-82.01906	NE

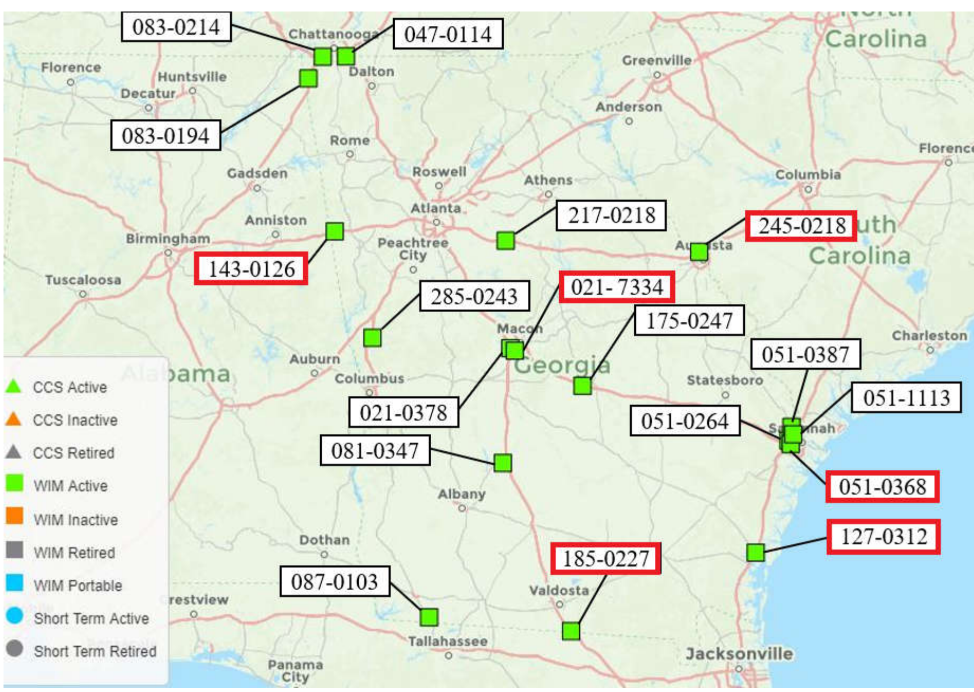


Figure 5 – Six WIM Site Locations with Kistler Sensors.

3.2 Data Collection Device

3.2.2 WIM Sensor Models

Two load sensor models are primarily used by the vendor: Kistler Lineas quartz sensors (hereafter referred to as quartz sensors) and Roadtrax BL Class 1 sensors (hereafter referred to as BL sensors). In Georgia, both sensors exist in the state's current WIM systems, and they are often compared for their performance. Lanes instrumented with quartz sensors and inductive loops are considered to provide information on both vehicle weight and class, whereas lanes with BL sensors are only useful for obtaining vehicle class information. Although BL sensors record vehicle weight information, the vendor considers the weight data from quartz sensors more accurate and thus more reliable.

3.2.2 Data Logger

The HI-TRAC® EMU3 by Q-Free data logger is used by the vendor. The manufacturer's data sheet shows that the unit incorporates interfaces to two types of sensors: inductive loop sensors and a road-installed temperature probe. The TDC HI-TRAC® EMU3 data logger can be powered by a solar panel and/or accompanying battery. Detection options include WIM and classification.

3.2.3 Device Setup

Section 3.3 shows the setup of the sensors and field equipment at the six sites. The sites feature two main WIM system layouts:

(1) Quartz-loop-quartz array or BL-loop-BL array, installed sequentially and polled by one roadside data logger, the Hi-TRAC EMU3.

(2) Two loops with a single quartz or BL sensor, installed and polled by one roadside data logger, the Hi-TRAC EMU3.

3.3 Lane Numbering Convention and Site Instrumentation Layouts

The WIM site sketches are provided by the vendor, and the lane naming convention shown in Table 3 is used in conjunction with lane numbers in presenting the methodology and results in Sections 4 and 5. The sensor type is color coordinated. When this study commenced in 2018, the vendor identified the six sites where quartz sensors had been installed. As of May 2020, three instrumentation types have been identified by the vendor:

(1) Quartz* load sensors and loops – Both weight and class data are available

(2) BL** load sensors and loops – Ignore weight and use class only

(3) Class only instrumentation

Table 3 – Lane Designation of WIM Sites.

Site ID	Lane Number								Speed Limit (mph)
	1	2	3	4	5	6	7	8	
021-7334	Ln1 NB*	Ln1 SB*							65
051-0368	Ln1 EB* Slow	Ln2 EB* Fast	Ln3 WB* Slow	Ln4 WB* Fast					65
127-0312	Ln1 NB* Slow	Ln2 NB* RT Ctr	Ln3 NB LT Ctr	Ln4 NB Fast	Ln1 SB Slow	Ln2 SB RT Ctr	Ln3 SB LT Ctr	Ln4 SB Fast	70
143-0126	Ln1 EB* Slow	Ln2 EB Fast	LN3 WB* Slow	Ln4 WB Fast					70
185-0227	Ln1 NB* Slow	Ln 2 NB Center	Ln 3 SB Fast	Ln1 SB* Slow	Ln 2 SB Center	Ln 3 SB Fast			70
245-0218	Ln1 EB* Slow	Ln 2 EB Fast	Ln 1 WB Rest Area to I-20	Ln 2 WB Slow**	Ln 3 WB Ctr**	Ln 4 WB Fast			65
021-0378	Ln1 NB Slow**	Ln 2 NB Center**	Ln 3 NB Fast**	Ln 4 SB Slow**	Ln 5 SB Center**	Ln 6 SB Fast**			65
047-0114	Ln 1 NB Slow**	Ln 2 NB Center**	Ln 3 NB Fast**	Ln 1 SB Slow**	Ln 2 SB Center**	Ln 3 SB Fast**			65
051-0264	Ln 1 EB Slow**	Ln 2 EB Fast	Ln 1 WB Slow**	Ln 2 WB Slow					50
051-0700	Ln 1 NB Slow**	Ln 2 NB Fast**	Ln 3 SB Slow**	Ln 4 SB Fast**					55
083-0194	Ln 1 NB Slow**	Ln 2 NB Fast**	Ln 3 SB Slow**	Ln 4 SB Fast**					70
083-0214	Ln 1 EB Slow**	Ln 2 EB Fast**	Ln 3 WB Slow**	Ln 4 WB Fast**					70
087-0103	Ln 1 NB Slow**	Ln 2 NB Fast	Ln 3 SB Slow**	Ln 4 SB Fast					65
245-0214	Ln 1 EB Slow	Ln 2 EB RT CTR**	Ln 3 EB LT CTR**	Ln 4 EB Fast	Ln 1 WB Slow	Ln2 WB RT CTR**	Ln3 WB LT CTR**	Ln4WB Fast	55
051-0387	Ln1 NB* Slow	Ln2 NB* Ctr	Ln 3 NB Fast	Ln1 SB* Slow	Ln2 SB* Ctr	Ln 3 SB Fast			70

The first six sites in Table 3 apply to this study, and Figures 6 through 11 show the corresponding site sketches, provided by the vendor in 2019. The instrumentation shown in Table 3 appears to be slightly different from the site sketches. In the site instrumentation layouts, load sensors are shown in all lanes; in Table 3, most lanes are set up for obtaining class-only information.

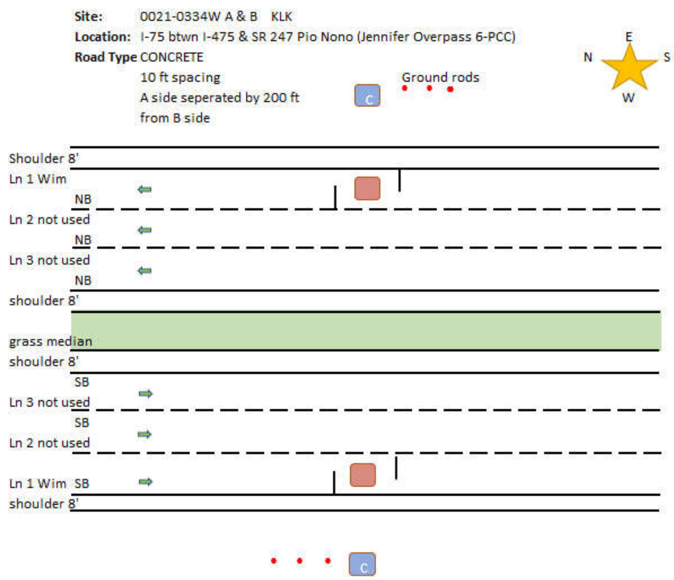


Figure 6 – Site 0217334 Sensor Layout Provided by the Vendor.

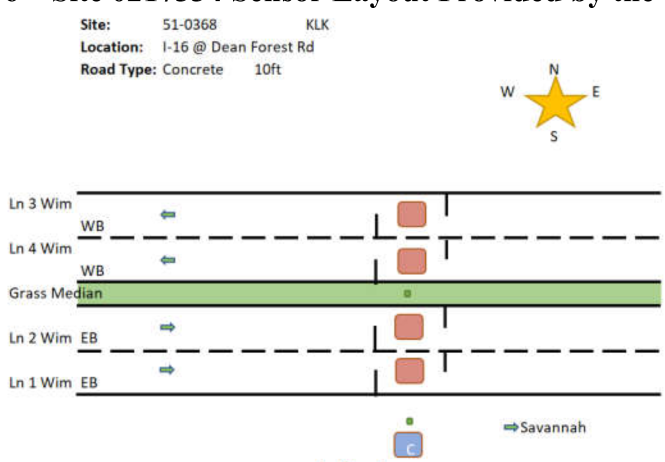


Figure 7 – Site 5100368 Sensor Layout Provided by the Vendor.

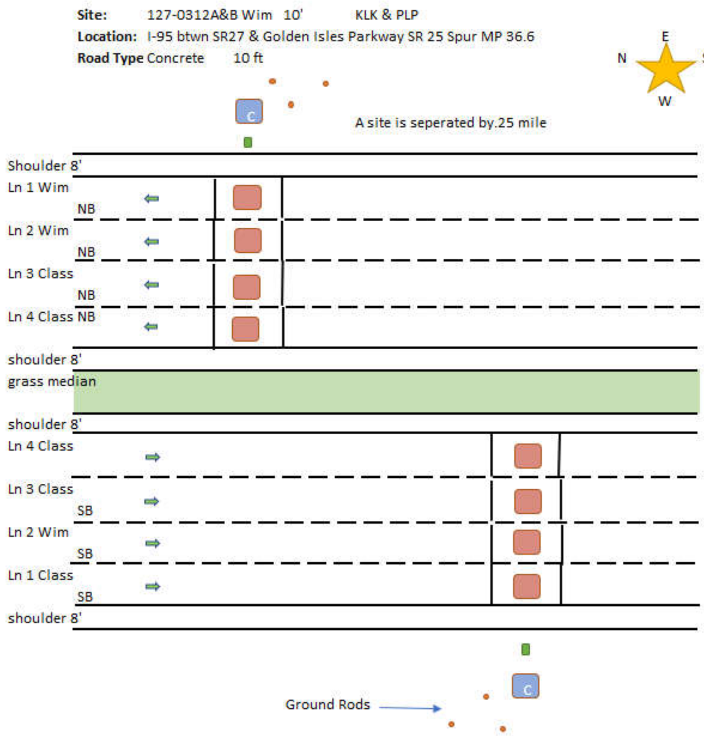


Figure 8 – Site 1270312 Sensor Layout Provided by the Vendor.

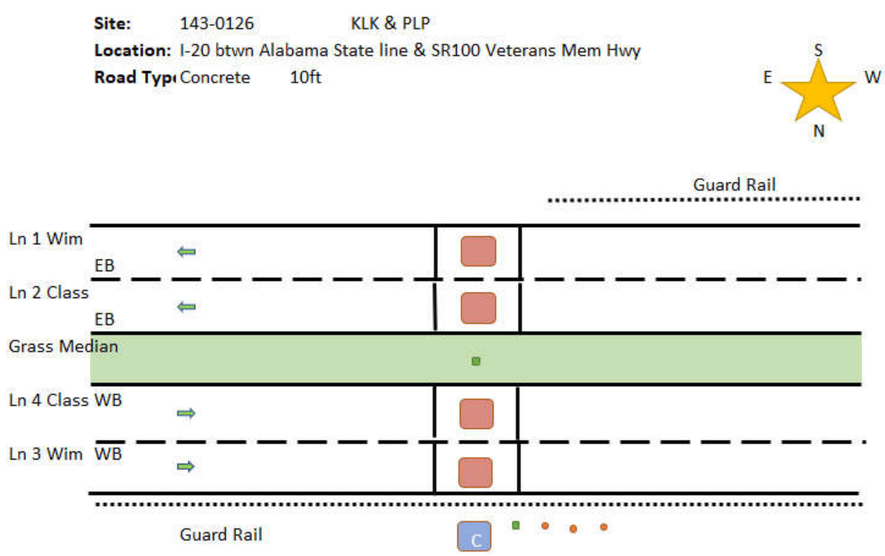


Figure 9 – Site 1430126 Sensor Layout Provided by the Vendor.

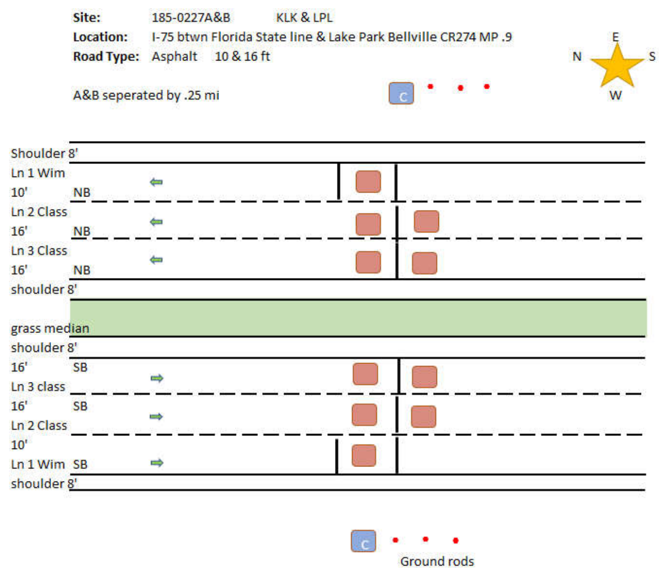


Figure 10 – Site 1850227 Sensor Layout Provided by the Vendor.

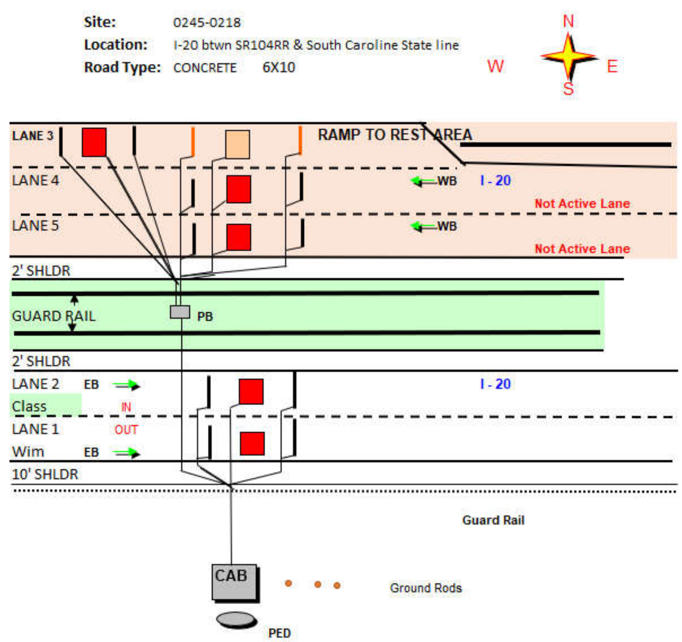


Figure 11 – Site 2450218 Sensor Layout Provided by the Vendor.

3.4 Data Exploration and Definition of Usable Data

3.4.1 Raw Data and Data Exploration

This section reports an initial data analysis conducted to explore the raw data. The goals of this preliminary analysis are to understand the contents of a WIM dataset and describe the characteristics of WIM data records from six sites in Georgia. Raw data refers to data that has not been altered or processed for use. For this analysis, the raw data was acquired from Drakewell, the data-hosting services provider. The purpose of data characterization is to obtain information about the WIM records relevant to QC. During this process, the study team considered the feasibility of reading comma-separated values (CSV) files using R and Python scripts and a Structured Query Language (SQL) database. Table 4 summarizes the file sizes, which range from 0.5 gigabyte (GB) to 3.31 GB. There are two main processes of data wrangling required for this analysis: 1) work with the separator, "|", in the axle weight and spacing columns and then split the columns or each record based on the number of axles recorded and 2) screen and/or convert the non-numerical values such as the entries "NaN" (acronym for Not a Number) and "NA" (acronym for Not Available) to zero for a numerical operation further in computer code.

Table 4 – WIM Data File Size.

Total Records & File Size \ SiteID	**021-7334**	**051-0368**	**127-0312**	**143-0126**	**185-0227**	**245-0218**
Total Number of Rows in the Raw Data	3,540,250	22,675,978	20,851,239	13,207,994	15,908,113	11,647,613
File Size (GB)	0.5 GB	2.25 GB	3.31 GB	2.08 GB	2.49 GB	1.76 GB

The following list includes the parameters (or 28 columns) included in the raw data (*.csv) files provided by Drakewell. The parameters used for this study are bolded. The values from the first row of Site ID 143-0126 data are presented in square brackets as an example to illustrate the data value after presenting the parameter name.

1. **Node [GDOT_CCS]**
2. **Cosit [000001430126]**
3. **Time [2018-01-01 00:00:07]**
4. Vehicle Number [NA]
5. **Lane [1]**
6. **Lane Name [LN 1 EB Slow]**
7. Straddle Lane [NA]
8. Straddle Lane Name [NA]
9. Reverse [NA]
10. Class Scheme [14]
11. **Class Scheme Name [FHWA15]**
12. **Class [9]**
13. Class Name [F9]
14. **Length (m) [24.18]**
15. **Headway (s) [NA]**
16. **Gap (s) [NA]**
17. **Speed (mph) [64.62]**
18. **Weight (kg) [8920]**
19. **Temperature (C) [NA]**
20. Duration (ms) [NA]
21. Validity Code [NA]

22. Chassis Code [NA]

23. Class Index [NA]

24. Loop Time (ms) [NA]

25. Chassis Profile [NA]

26. Num Axles [5]

27. Axle Weights (kg) [2230|1630|1640|1640|1780]

28. Axle Spacings (m) [5.21|1.3|10.03|1.48]

3.4.2 Usable Data

In this study, “usable data” refers to records that do not have missing or invalid parameters (see Section 1.2.3) for the analysis described in Section 4. The parameters for usable data include axle weight and axle spacing as well as lane IDs or names; specifically, data columns 5, 6, 27, and 28 presented in Section 3.4.1 are reviewed to establish a usable data set. Although other parameters such as temperature, speed, and headway are important, the parameters for pavement and bridge design and evaluation are not essential for the current study.

4. METHODOLOGY

The raw WIM data, provided in a CSV file for each site, are read with computer programs, RStudio 3.2 (2019) and Jupyter Notebooks using Anaconda Python 3.7 (Rossum, 2003). This decision was made because speeding up the QC process, particularly with limited computing resources, will enable better and faster decisions and possibly lead to a real-time QC program. Running SQL scripts would have required significantly more computing resources than running R and Python scripts. An R script is a series of commands that can be written using any text editor. This study uses RStudio's editor to write R scripts to generate—or knit— WIM data QC summaries in a PDF file. Meanwhile, a Python script is run to cross-check selected numerical summaries and provide supplemental charts to those generated by the R script. This section is organized according to the findings presented in the PDF summary file generated for each WIM site. Finally, the study team has coordinated WIM site visits to understand the equipment setup and field calibration process. Based on the team's experience, we develop a strategic approach to apply QC measures from the literature, focusing on practical measures suitable for GDOT and the improvement of WIM data quality.

4.1 Numerical and Graphical Summaries Using R Script and PDF Knitting

Each PDF file begins with a summary of findings, three to four pages in length. The summary is organized in a manner consistent with the order applied to Sections 4.2 through 4.6. The first section provides a description of the data exploration process, subsequent sections present the parameters described in Sections 4.2 through 4.5, and the last section presents the findings that result from employing the methods described in Section 4.7.

This subsection describes the methodology for presenting detailed graphical and numerical summaries. Numerical summaries featuring measurements such as a mean, a standard deviation, and a percentage proportion are presented in tabular form whenever possible. Graphs show anomalies and features (of a distribution) that are not evident from numerical summaries. Histograms and boxplots, for example, show a distribution of vehicle weights or axle spacings. The following subsections briefly describe graphical tools employed for presenting the findings.

4.1.1 Boxplot

Boxplots provide the center of the data (median) and describe variability. In a boxplot, the median is measured with the middle number in a distribution when values are ordered from smallest to largest. Variability or spread in the data is measured using interquartile range (IOR), which is the difference between the first and third quartiles. The first and third quartiles (Q1 and Q3) are equivalent to the 25^{th} and 75^{th} percentile, respectively. Figure 12 illustrates the positions of the first, second, and third quartiles and upper and lower whiskers. The upper and lower whiskers capture data that fall outside of the Q1-1.5IQR and Q3+1.5IQR. Outliers indicate extreme values with respect to the rest of the data. In Figure 12, the third quartile (75% of the data) is approximately lower than 100,000 lbs. In other words, the boxplot illustrates that the upper 25% of the GVW data exceed 100,000 lbs with outliers exceeding 200,000 lbs.

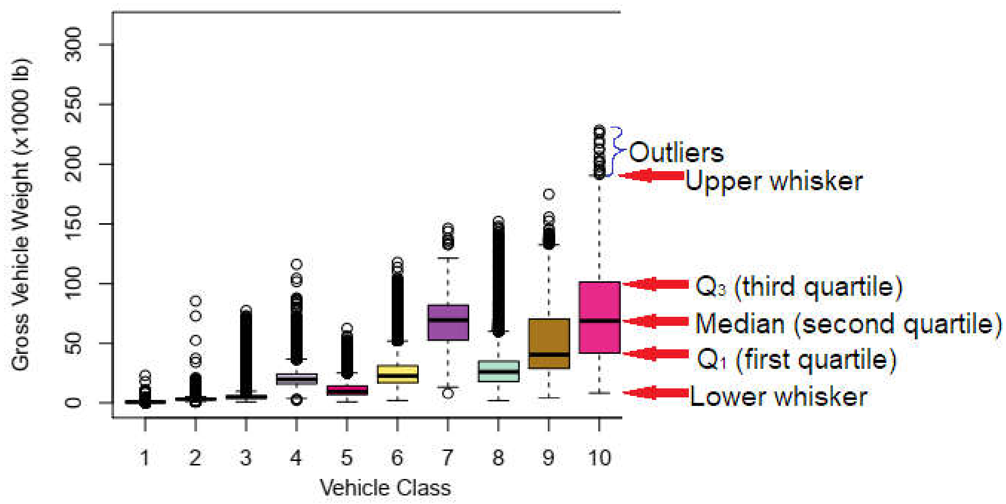


Figure 12 – Interpreting a Boxplot.

4.1.2 Bar Chart

Bar charts are used to show proportions of observations in each level for a single non-numerical or categorical variable. For example, proportions of vehicle classes in each lane are shown in a bar chart.

4.1.3 Histogram

Histograms enable a review of data density. In a histogram, observations are grouped into several bins and plotted as bars. A more frequent occurrence is indicated with a taller bar. Unlike boxplots, histograms show the shape of a distribution. For example, a distribution of single axle weights for a WIM site may have a unique shape—asymmetric with a single peak. Asymmetry is described with a right or left skew. Prominent peaks (i.e., taller bars relative to the rest of the data) in the distribution are described as uni-modal, bimodal, and multi-modal when one, two, and more than three peaks are present in the distribution.

4.1.4 Box-Histogram Plot

A box-histogram plot provides a boxplot in combination with a histogram for a more detailed data analysis. Boxplots are great to review outliers and quartiles whereas histograms provide a good snapshot of the whole distribution of observations. Thus, seeing these plots together is beneficial because each provides a different point of view.

4.1.5 Axle Load Spectra

A load spectrum provides the frequency of load occurrences. For example, axle weights and proportions are used to estimate individual axle load spectra for various axle configurations. Axle load spectra are used to measure the probability of occurrence in single or tandem axle loads. The legal load limit is 20,000 lbs and 34,000 lbs, respectively. Thus, if a 30,000 lb single axle load is observed, the spectrum may identify the observation as a rare event. Once axle load spectra are normalized with respect to the legal load level (e.g., 20,000 lbs for single axle), they are referred to as the normalized axle load spectra (NALS). The MEPDG traffic inputs (i.e., Level 1 inputs) are NALS for each truck class, axle group type, and more (Selezneva et al., 2016).

4.1.6 Scatter Plot

Scatter plots provide a review of the relationship between two numerical variables. For instance, the relationship between vehicle speed and weight may indicate an association.

4.1.7 Organization of PDF Document

The first section of the PDF summary document is titled "Data Exploration." The subsequent sections of the summary are presented according to the organization of the next section of this report with identical numerical subsection numbers presented below.

4.2 Proportions of Vehicle Class

4.2.1 Percentage Vehicle Counts by Class in Each Lane

This section provides lane designations corresponding to lane numbers and reviews if a significant variation exists among lanes. In the slow lanes, more truck traffic is expected.

4.2.2 Percentage Vehicle Counts by Class in Each Month

This section reviews if a significant variation exists from month to month for both traffic directions. During the holidays and severe winter conditions, less truck traffic is expected although the volume depends on traffic logistics and movement of goods on each route.

4.3 Average Annual Daily Traffic and Average Annual Daily Truck Traffic

This section utilizes summaries of usable data and calculates the average annual daily traffic (AADT) and the average annual daily truck traffic (AADTT) for each traffic direction. When a significant deviation in AADT and AADTT occurs from the values reported on TADA, which appears to be consistent with the traffic counts from the raw data, anomalies are observed.

4.4 Spacing between Axles

Spacings between axles vary among vehicle classes. Therefore, this section discusses the number of axles observed in selected vehicle classes and describes the spread in the axle-spacing observations.

4.5 Axle Weight Including Single-Axle and Tandem-Axle Load Spectra

This section presents the percentage of vehicles with a total axle weight (or GVW) exceeding the 80,000 lb legal limit as well as the number of vehicles with a total length greater than 100 ft. Additionally, a single axle load spectrum is created in 1000 lb load increments and a tandem axle load spectrum is presented in 2000 lb load increments.

4.6 Summary of Findings

In this last section, the 3–4 page summary closes with major findings followed by an important note for reviewing the graphical and numerical summaries in the subsequent section.

4.7 Detailed Graphical and Numerical Summaries

A series of graphical plots are presented followed by a numerical summary, if applicable, mainly utilizing usable data.

4.7.1 Graphical Summary – Proportions of Vehicle Class and Traffic Counts

This subsection provides proportions of vehicle classes in a bar chart for each traffic direction and displays traffic counts from analyzing usable data. Finally, it shows a comparison between ADT and AADT counts as well as truck traffic counts by plotting a histogram of daily traffic and truck traffic, including the ADTT and AADTT, respectively.

4.7.2 Numerical Summary – Vehicle Class Counts and Proportions

This section provides the most important numerical summary, listing the total number of vehicle entries, the number of missing parameters such as weight and classification, the percentage of usable data, the number of days/hours/seconds recorded vs. included in the usable data, and the vehicle counts by class in a tabular format.

4.7.3 Graphical Summary – Vehicle Class Proportions by Lane

In addition to the number of vehicle counts by traffic direction, the percentage of vehicle classes by lane is reviewed in a series of bar charts.

4.7.4 Numerical Summary – Vehicle Class Proportions in Each Lane

The number of vehicles by class in each lane is summarized in a table.

4.7.5 Graphical Summary – Vehicle Class Proportions by Month

In this section, bar charts are used to convey monthly class proportions as well as the proportions by traffic direction and lane presented in Sections 4.7.1 through 4.7.4. Monthly traffic and truck traffic counts are also presented to capture anomalies, if any.

4.7.6 Numerical Summary – Vehicle Class Proportions by Month

A numerical summary of the findings graphically described in Section 4.7.5 is provided in this section.

4.7.7 Graphical Summary – Axle Weight and Spacing Distributions by Class

This section starts with a boxplot of the number of axles recorded in each vehicle class and continues with boxplots of axle weights and the distance between axles for each vehicle class.

4.7.8 Graphical Summary – Gross Vehicle Weight and Length

This section provides a distribution of GVW as well as vehicle length and distance between the first and last axle in both SI and US customary units.

4.7.9 Numerical Summary – Percent Vehicle Counts with Gross Vehicle Weight and Length Exceeding a Threshold

This section provides the percentage of vehicles that exceed their weight limits: GVW, single axle weight, and tandem axle weight limits (80,000 lbs, 20,000 lbs, and 34,000 lbs, respectively). Additionally, the percentage of vehicles longer than 100 ft is reported.

4.7.10 Graphical and Numerical Summary – Gross Vehicle Weight Distribution for Each Class

This section compares GVW data spreads in each lane and presents the GVW distributions by class.

4.7.11 Graphical Summary – Axle Spacings for Class 9

Here, box-histogram plots show the center and spread of the data as well as the distribution. Distances between two axles are plotted to review the consistency with the definition used for Class 9 in the classifier.

4.7.12 Graphical Summary – (Annual) Single Axle Spectra for Class 9

This section presents a single axle load spectrum for each traffic direction for the entire year's data.

4.7.13 Graphical Summary – (Annual) Tandem Axle Spectra for Class 9

An annual tandem axle load spectrum is created for each traffic direction for the entire year's data.

4.7.14 Numerical Summary – Proportions of Axle Spacing Entries Qualifying as Single Axle (Class 9 Only)

This section gives a numerical summary of the proportion of vehicle counts with three cases: the second and third axles are considered a tandem load, the third axle is considered a single axle, and the third and fourth axles are considered tandem. The percentage of occurrence is reported. For example, such cases occur 98% of the time in Class 9 vehicles at Site ID 127-0312.

4.7.16 Graphical Summary – Headway (or Gap) between Vehicles for Class 9

Headway parameter data in seconds are not always available. With the available data, the headway parameter is plotted against vehicle class in a boxplot. For example, such boxplot may indicate that median headway values increase as vehicle class changes from 1 to 13.

4.7.17 Numerical Summary of the WIM Data

This section provides a numerical summary of the data entries without any modification (i.e., as provided by Drakewell). The subsequent subsections provide a numerical summary of the usable data after removing entries with missing vehicle class and traffic directions for each traffic direction.

4.7.18 Cross-Validation of Selected Items Using Python Scripts

This section provides both graphical and numerical summaries from an analysis of the raw data from each site. By writing an independent script, selected results are generated to cross-check the results produced using the methods described in Sections 4.7.1 through 4.7.17, and additional supplementary plots, such as Class 9 single axle load spectra by month in each lane, are presented.

4.7.19 Analysis of Entries with Zero Weight

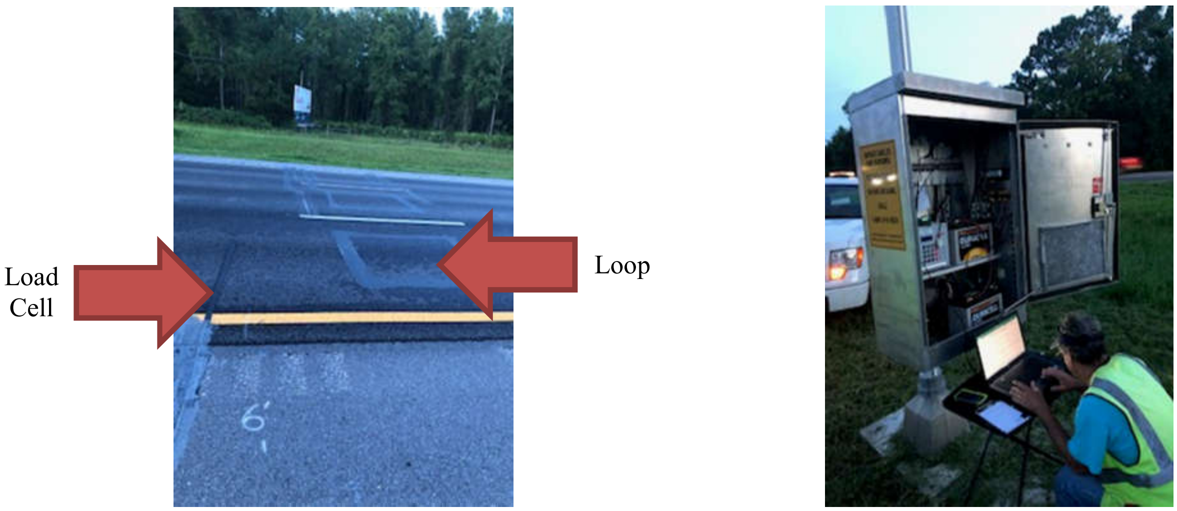
Due to a significant number of entries with zero weight, an analysis of these entries is necessary. Based on a discussion with the vendor, entries with zero weight may result from BL sensors and class-only instrumentation. This section summarizes the number of (traffic) occurrences by lane and month and date of the zero-weight data and plots the following parameters against lanes: month, vehicle class, speed, headway, and temperature, if available.

4.8 Observation of FDOT's WIM Load Sensor Calibration Process

The first site visit was made to Site ID 021-7334 near Macon, Georgia, to gain a better understanding of how WIM systems work. During the visit, the study team met Southern Traffic Services, Inc. representatives and learned about a typical site setup and coordinated a site visit to observe FDOT's WIM sensor calibration process. The WIM vendor has extensive experience working with FDOT from installing, maintaining, and calibrating WIM devices in Florida, and its crew also calibrates Georgia's WIM equipment. Thus, in the subsequent trip, the study team observed a WIM sensor calibration process in Gainesville, Florida, located on Interstate 75. The entire calibration process takes a couple of days to prepare and execute; however, the team only viewed the site for a couple of hours and gathered as much information as possible from conversations with the field staff. The team performing the calibration process was Southern Traffic Services, Inc., and the research team learned that a third-party was present to observe the calibration process which was required by FDOT's policy, although the research team has not been able to find a written policy on its website.

Three trucks of known weights were utilized and repeatedly driven over the WIM sensors gathering their weight data. This process was repeated multiple times to obtain an accurate result. The averaged weight value for each truck was then compared to each truck's actual known weight. From this comparison, a calibration factor was then calculated and applied to all vehicles passing over WIM sensors to establish an accurate record for axle weight. At first, recorded weights for passing vehicles varied each time by hundreds or sometimes thousands of pounds. The field team iterated the process until each weight value was within the tolerance established by FDOT, allowing the WIM system to provide an accurate estimate of a vehicle's true weight.

Georgia and Florida have a similar WIM system setup. The system has one load cell and two loops within a traffic lane and the sensor. One of the two loops is shown in Figure 13. The two loops are box-shaped and record axle spacings. The transverse load cell (quartz sensor) reads the weight of each axle. When a single vehicle passes over a quartz sensor, the data acquisition system, in a control panel, logs the data (see Figure 13). The data do not have to be retrieved on site as they are sent directly to Drakewell's server.



(a) WIM System Street View (b) WIM Control Panel

Figure 13 – Observation of FDOT WIM Sensor Calibration Process.

Figure 14 – One of Two Calibration Trucks Used in Florida (Moses, 2019).

In a recent WIM calibration study, a similar process was used with two trucks of known weights. Figure 14 shows one of the calibration trucks used. Tables 5 and 6 show how FDOT's research team (Moses, 2019) documented the trucks' actual weights and spacings used for the calibration of multiple WIM devices as well as descriptive statistics of weight differences during calibration. GDOT does not currently employ a third-party observation for its WIM system calibration process; rather, WIM calibration is conducted by the vendor alone.

Table 5 – Actual Weight and Axle Spacing Used for Calibration (Moses, 2019).

TRUCK #1							
ACTUAL WEIGHTS (pounds)				ACTUAL AXLE SPACINGS (feet)			
GVW	STEER AXLE	DRIVE AXLE	TRAILER AXLE	AXLE 1-2	AXLE 2-3	AXLE 3-4	AXLE 4-5
77,240	11,040	31,900	34,300	15.7	4.5	21.08	4.4
TRUCK #2							
ACTUAL WEIGHTS (pounds)				ACTUAL AXLE SPACINGS (feet)			
GVW	STEER AXLE	DRIVE AXLE	TRAILER AXLE	AXLE 1-2	AXLE 2-3	AXLE 3-4	AXLE 4-5
77,700	11,100	31,920	34,680	15.7	4.5	20.75	4.4

Table 6 – Descriptive Statistics of Weight Differences (Moses, 2019).

Equipment	Count	Mean	StDev	CoefVar	Minimum	Maximum	Skewness	Kurtosis
	EMU3 (West) - iSINC (East)							
EMU3	30	+1.35	1.75	1.30	-2.01	5.27	0.19	-0.52
iSINC	30	-1.56	1.88	-1.20	-4.71	2.45	-0.07	-0.78
	EMU3 (East) - iSINC (West)							
EMU3	31	1.56	2.19	1.40	-3.50	5.15	-0.37	-0.27
iSINC	31	1.03	2.35	2.28	-5.53	4.35	-0.91	0.54

5 RESULTS AND SYNTHESIS

5.1 Summary of Results from Analyzing Data from Six WIM Sites

Given the sheer amount of data, reviewing every line of the output from Section 4 and deducing practical information to enhance WIM data collection and maintenance processes is not feasible. Instead, this section offers a summary of findings from an analysis of the 2018 WIM data. Table 7 shows the major findings with practical implications for QC.

Table 7 – Summary of 2018 WIM Data QC.

QC Measures \ Site ID	**021-7334**	**051-0368**	**127-0312**	**143-0126**	**185-0227**	**245-0218**
Total Number of Entries in the Raw Data	3,540,250	22,675,978	20,851,239	13,207,994	15,908,113	11,647,613
No. of Usable* Entries	3,516,409	22,635,959	15,515,825	13,177,956	10,590,883	8,665,992
No. of Unusable Entries (% of the Raw Data)	23,841 (0.7%)	40,019 (0.2%)	5,335,414 (25.6%)	30,038 (0.2%)	5,317,230 (33.4%)	2,981,621 (25.6%)
*# of Zero/Invalid Weight ***	26	0	5,308,595	0	5,301,698	2,958,722
# of Unidentified Class (% of the Usable Data)	23,669 (0.7%)	28,595 (0.1%)	36,372 (0.2%)	26,853 (0.2%)	19,559 (0.1%)	33,404 (0.3%)
# of Class 9 Vehicles (% of the Usable Data)	261,466 (7.4%)	3,368,158 (7.4%)	2,670,470 (14.1%)	3,186,907 (24.1%)	2,889,993 (24.3%)	824,848 (8.1%)
# of Missing Classification	38	10,460	1,623	2,162	1,294,311	0
# of Missing Axle Spacing	22	128	429	15	996,212	113
No. of Entries >80 mph (% of the Usable Data)	261,335 (7.4%)	867,264 (3.8%)	867,264 (3.8%)	2,053,167 (18.3%)	2,053,167 (19.4%)	221034 (2.6%)
No. of Missing Speed	0	0	0	0	1,077	0
# of Gross Weight >80,000 lbs (% SB/EB Usable Data)	2,974 (0.2%)	68,227 (0.6%)	15329 (0.1%)	206,944 (3.2%)	14896 (<0.2%)	78 (<0.1%)
# of Gross Weight >80,000 lbs (% NB/WB Usable Data)	28,294 (1.5%)	66,707 (0.6%)	79,990 (1.7%)	310,597 (4.6%)	78,059 (2.3%)	452,265 (7.3%)
No. of Vehicle Length >100 ft (% Usable Data–SB/EB)	504 (<0.1%)	36,689 (0.8%)	775 (<0.1%)	2,043 (<0.1%)	811 (<0.1%)	18,991 (16.5%)
No. of Vehicle Length >100 ft (% Usable Data–NB/WB)	166 (<0.1%)	67,117 (1.4%)	2,596 (<0.1%)	615 (<0.1%)	429 (<0.1%)	624 (<0.1%)
# of Missing Headway	168,104	347,686	710,512	350,739	528,550	312,292
# of Missing Temperature (% Usable Data)	3,540,250 (100.0%)	22,675,978 (100.0%)	273,869 (1.8%)	13,207,994 (100.0%)	15,908,113 (100%)	11,647,613 (100%)
No. of Days Recorded	317	365	365	365	365	200
No. of Days in the Usable Data (%)	317 (100.0%)	365 (100.0%)	365 (100.0%)	365 (100.0%)	331 (90.6%)	200 (100%)
Unique Hours Recorded	7592	8759	8759	8759	8,747	4790
No. of Hours in the Usable Data (%)	7592 (100.0%)	8759 (100.0%)	8759 (100.0%)	8759 (100.0%)	7,922 (90.6%)	4790 (100%)
Unique Seconds Recorded	3,368,158	14,952,312	13,752,728	10,218,499	11,543,536	7,807,441
No. of Seconds in the Usable Data (%)	3,368,005 (100.0%)	14,950,184 (100.0%)	11,228,553 (81.6%)	10,216,614 (100.0%)	8,321,862 (72.1%)	6,491,912 (83.2%)

* The parameters used to determine the "Usable" entries are provided in Section 3.4.2.
** See Section 5.2 for an analysis of entries with zero weight.

In Table 7 and the following tables, the red text formatting is used to indicate parameters that are either anomalous or need further review. Table 8 provides a summary of anomalies in the usable data, identified from reviewing PDF summaries created using the procedures described in Section 4. This table presents most noticeable anomalies in light of the fact that the WIM sites under investigation are not fully instrumented with quartz sensors. If a WIM data set contains weight information, it is processed as part of the QC analysis regardless of sensor/instrumentation type.

Table 8 – Summary of Anomalies and/or Possible Corrective Action Needed.

Anomalies \ Site ID	021-7334	051-0368	127-0312	143-0126	185-0227	245-0218
Instrumentation of quartz sensors described by the vendor.	1 lane in each traffic direction has a quartz sensor.	2 lanes in each traffic direction have quartz sensors.	2 out of 4 lanes in NB lanes have a quartz sensor.	1 (slow) out of 2 lanes in each traffic direction has a quartz sensor.	1 (slow) out of 3 lanes in each traffic direction has a quartz sensor.	1 of 3 NB lanes, including Ln 1 WB Rest Area, has a quartz sensor.
Other notable instrumentation Layouts.			4 SB lanes are for class only.			2 SB lanes have BL sensors.
Total number of quartz sensors.	2	4	2	2	2	1
% quartz sensor instrumentation (# of lanes with a quartz sensor/# of available lanes).	100% NB 100% SB	100% EB 100% WB	50% NB 0% SB	50% EB 50% WB	33% NB 33% SB	33% NB 0% SB
Classes requiring a review of the definition in the data logger classifier.	Class 6: the number of axles Class 9 – 13: distance between axles					
Monthly shifts in single axle weight – Lanes with a quartz sensor only.	Weight shifts in the June and July data.	Single axle weight shifts in all lanes. The shifts in WB lanes are greater.	The two NB lanes with quartz sensors show monthly weight shifts.	Weight shifts in Jan. and Feb. data.	Shift in Jan. data.	Scattered, not clearly defined pattern like other sites.
Tandem axle load spectra.	High % of vehicles with tandem axle load exceeding 34,000 lbs.	Both lanes high % greater than 34,000 lbs. WB right skewed.	NB vs. SB mismatch % greater than 34,000 lbs.	Tandem axle weight for the WB traffic is relatively high.	NB vs. SB mismatch % greater than 34,000 lbs.	Excessive weight WB lanes.
Other missing/Invalid parameters in the Usable Data (Note: weight anomalies occur because some lanes have class-only instrumentation.	Data starts in February.	Nothing more observed.	Zero weight data come from different lanes throughout the year.	Greater than 18% over 80 MPH.	No weight data for more than 30 days.	Data starts in June. No weight data for Lane 2.

5.1.1 Proportions (%) of Vehicle Class

Table 9 summarizes proportions of vehicle classes by traffic directions and lanes. The usable data is intentionally used to capture anomalies, if any, in the summary table. Anomalies are indicated in red font and discussed in Section 5.6 along with graphical summaries.

Table 9 – Summary of Proportions (%) of Vehicle Class.

Site ID	Bound\Class	1	2	3	4	5	6	7	8	9	10	11	12	13	15§
021-7334	NB	1.3	64.6	19.2	0.9	3.4	0.9	0.1	1.1	6.5	0.2	0.1	0.1	0.1	1.4
	SB	0.8	63.6	20.7	0.9	3.2	1.1	0.0	1.2	8.1	0.1	0.1	0.1	0.0	0.0
143-0126	EB	0.2	52.5	14.6	0.8	2.5	0.6	0.0	1.8	24.3	0.1	1.3	0.8	0.0	0.3
	WB	0.2	54.8	13.9	0.7	1.9	0.6	0.0	1.7	24.0	0.1	1.3	0.8	0.0	0.1
	EB (Slow)	0.2	35.8	12.3	1.2	3.1	0.8	0.0	2.5	39.6	0.2	2.3	1.4	0.0	0.6
	EB (Fast)	0.1	70.4	17.0	0.3	1.9	0.4	0.0	1.1	8.0	0.1	0.3	0.2	0.0	0.1
	WB (Slow)	0.2	42.0	11.8	1.0	2.1	0.8	0.0	2.3	36.3	0.2	2.1	1.3	0.0	0.1
	WB (Fast)	0.2	71.3	16.6	0.3	1.6	0.3	0.0	0.9	8.2	0.0	0.2	0.2	0.0	0.1
051-0368	EB	0.1	75.4	18.2	0.2	1.4	0.6	0.0	0.5	3.3	0.1	0.1	0.0	0.0	0.1
	WB	0.2	73.7	18.8	0.2	1.5	0.8	0.0	0.6	3.8	0.1	0.1	0.1	0.0	0.2
	EB (Slow)	0.1	72.5	17.8	0.2	1.9	1.1	0.0	0.7	5.4	0.1	0.1	0.1	0.0	0.1
	EB (Fast)	0.2	78.3	18.7	0.1	0.9	0.2	0.0	0.4	1.2	0.0	0.0	0.0	0.0	0.1
	WB (Slow)	0.1	70.2	19.3	0.3	2.1	1.2	0.0	0.7	5.6	0.1	0.1	0.1	0.0	0.1
	WB (Fast)	0.4	78.0	18.2	0.1	0.7	0.2	0.0	0.5	1.5	0.0	0.0	0.0	0.0	0.3
127-0312	NB	0.6	62.6	17.5	0.6	2.1	0.4	0.0	1.5	13.5	0.1	0.4	0.3	0.0	0.2
	SB	0.8	61.9	15.1	0.7	2.7	0.5	0.0	1.9	15.2	0.2	0.5	0.4	0.0	0.1
	NB (Slow)	0.8	64.9	28.9	0.6	2.7	0.3	0.0	0.5	1.3	0.0	0.0	0.0	0.0	0.0
	NB (CenterR)	0.7	37.4	12.5	1.1	2.8	1.1	0.1	3.4	37.3	0.4	1.4	1.0	0.2	0.6
	NB (CenterL)	0.8	63.6	18.3	0.6	2.4	0.3	0.0	1.3	12.1	0.1	0.2	0.2	0.0	0.1
	NB (Fast)	0.3	85.3	13.2	0.0	0.6	0.0	0.0	0.4	0.1	0.0	0.0	0.0	0.0	0.1
	SB (Slow)	1.1	70.5	22.5	0.6	3.2	0.5	0.0	0.4	1.1	0.0	0.0	0.0	0.0	0.0
	SB (CenterR)	0.9	50.1	13.7	1.0	3.0	0.8	0.0	3.0	25.4	0.2	1.0	0.6	0.0	0.2
	SB (CenterL)	0.7	69.9	14.6	0.7	2.4	0.3	0.0	1.1	9.9	0.1	0.2	0.2	0.0	0.0
	SB (Fast)	0.4	80.9	16.2	0.1	1.9	0.0	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.0
185-0227	NB	0.5	55.6	18.1	0.4	1.7	0.5	0.0	2.0	19.3	0.1	1.0	0.7	0.0	0.1
	SB	1.0	40.8	13.0	0.7	2.0	0.7	0.0	3.5	34.8	0.1	2.0	1.2	0.0	0.1
	NB (Slow)	1.1	29.9	12.9	0.7	2.3	1.0	0.0	4.1	43.3	0.2	2.7	1.8	0.0	0.2
	NB (Center)	0.2	63.6	19.9	0.4	1.7	0.4	0.0	1.2	11.7	0.1	0.4	0.4	0.0	0.1
	NB (Fast)	0.2	76.4	21.7	0.0	1.0	0.0	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.1
	SB (Slow)	1.3	27.6	10.3	0.7	1.9	0.9	0.0	4.5	47.8	0.2	2.9	1.7	0.0	0.1
	SB (Center)	0.3	61.6	17.3	1.1	2.3	0.4	0.0	2.3	13.7	0.1	0.4	0.4	0.0	0.0
	SB (Fast)	0.3	76.7	19.9	0.1	2.2	0.0	0.0	0.4	0.3	0.0	0.0	0.0	0.0	0.0
245-0218	EB	0.0	66.4	21.0	0.0	1.2	0.8	0.1	0.7	9.2	0.1	0.3	0.1	0.0	0.2
	WB	0.1	69.0	19.2	0.1	0.7	0.5	0.0	1.8	7.7	0.1	0.2	0.1	0.0	0.3
	EB (Slow)	0.0	66.4	21	0.0	1.2	0.8	0.1	0.7	9.2	0.1	0.3	0.1	0.0	0.2
	EB (Fast)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	WB-RestArea	0.1	72.2	22.0	0.1	0.7	0.8	0.1	1.5	2.4	0.1	0.0	0.0	0.0	0.1
	WB (Slow)	0.1	61.8	17.4	0.2	1.2	0.7	0.0	2.9	14.8	0.3	0.3	0.2	0.1	0.2
	WB (CTR)	0.1	71.9	19.4	0.1	0.5	0.4	0.0	1.3	6.0	0.1	0.1	0.1	0.0	0.1
	WB (Fast)	0.3	77.6	19.3	0.0	0.1	0.1	0.0	0.5	0.2	0.0	0.0	0.0	0.0	1.9

§ Class 15 designation is used for unclassified vehicles.
NA – Not applicable, as no weight data is available.

5.1.2 Gross Vehicle Weight, Single Axle Weight, and Tandem Axle Weight

Table 10 quantifies the percentage of vehicles that exceed the weight limits for GVW, single axle weight, and tandem axle weight limits. Additionally, the percentage of vehicles more than 100 ft long is documented. Percentages exceeding 10% are indicated in red font.

Table 10 – % Proportions Exceeding Weight and Length Thresholds.

Site ID	Traffic Direction - Bound	Gross Vehicle and Axle Weight			All Classes - Vehicle Length >100 ft
		All Classes - GVW >80,000 lbs	Class 9 Single Axle Weight >20,000 lbs	Class 9 Tandem Axle Weight >34,000 lbs	
021-7334	North Bound (NB)	0.2%	1.5%	11.4%	0.03%
	South Bound (SB)	1.5%	0.1%	2.4%	0.01%
143-0126	East Bound (EB)	3.2%	6.0%	13.0%	0.03%
	West Bound (WB)	4.6%	13.1%	6.0%	0.01%
051-0368	EB	0.6%	0.0%	9.0%	0.75%
	WB	0.6%	2.4%	12.6%	1.42%
127-0312	NB	0.1%	0.0%	6.8%	0.07%
	SB	1.7%	0.7%	1.0%	0.05%
185-0227	NB	0.2%	0.0%	1.9%	0.01%
	SB	2.3%	2.1%	6.0%	0.01%
245-0218	EB	0.0%	0.0%	59.7%	16.51%
	WB	7.3%	66.4%	0.0%	0.01%

5.1.3 Traffic Counts in the Raw and Usable Data

Table 11 summarizes the AADT and AADTT counts and compares the results from the usable data and the counts reported in TADA. The latter should be consistent with the raw data. The truck percentage is not significantly affected by the unusable data.

Table 11 – AADT and AADTT from the Raw Data vs. Usable Data.

Site ID	Counts Reported in TADA			Counts Utilizing Usable Data		
	AADT	AADTT	Truck %	AADT	AADTT	Truck %
021-7334	10,700	1,567	14.6	11,093	1,595	14.4
143-0126	36,500	11,579	31.7	36,104	11,462	31.7
051-0368	63,700	4,359	6.8	62016	4,104	6.6
127-0312	56,600	10,535	18.6	42,509	8,515	20.0
185-0227	44,000	12,035	27.4	31,997	10,243	32.0
245-0218	60,700	6,243	10.3	43,330	5,057	11.7

5.1.4 Average Daily and Average Annual Daily Traffic and Truck Traffic Counts

Table 12 compares the ADT to the AADT and the ADTT to the AADTT from the usable data in order to capture a large spread, if any, in the traffic counts. When a large spread exists in the data, the annual average value is calculated by taking the total vehicle counts and dividing by the number of days recorded (e.g., 365 days), a method significantly different from taking a mean of daily traffic counts in the usable data. Section 5.5.4 graphically portrays the spread in the ADT distribution.

Table 12 – Average Daily and Average Annual Daily Traffic and Truck Traffic Counts by Lane.

SiteID\Lane #	Counts	1	2	3	4	5	6	7	8
	Lane Designation	Ln1 NB	Ln1 SB						
	ADT	6029	5139						
	AADT	6027	5066						
	ADTT	906	764						
021-7334	AADTT	904	691						
	Lane Designation	LN1 EB Slow	LN2 EB Fast	LN3 WB Slow	LN4 WB Fast				
	ADT	9041	8991	10497	8227				
	AADT	8458	8425	10491	8196				
	ADTT	10497	10491	4834	980				
143-0126	AADTT	8277	8196	4829	969				
	Lane Designation	Ln1 EB Slow	Ln2 EB Fast	Ln3 WB Slow	Ln4 WB Fast				
	ADT	15487	15343	17190	14075				
	AADT	15471	15334	17174	14037				
	ADTT	1576	433	1788	467				
051-0368	AADTT	1478	423	1773	429				
	Lane Designation	Ln1 NB Slow	Ln2 NB RT Ctr	Ln3 NB LT Ctr	Ln4 NB Fast	Ln1 SB Slow	Ln2 SB RT Ctr	Ln3 SB LT Ctr	Ln4 SB Fast
	ADT	4817	6885	10919	6710	1951	8776	8833	5710
	AADT	4816	6843	10912	6706	1213	6601	3291	2128
	ADTT	260	3401	1893	84	115	3097	1304	141
127-0312	AADTT	259	3358	1885	80	71	2323	486	52
	Lane Designation	Ln1 NB Slow	Ln2 NB Center	Ln3 SB Fast	Ln1 SB Slow	Ln2 SB Center	Ln3 SB Fast		
	ADT	7132	9890	5440	6910	7918	5140		
	AADT	7121	9435	5190	6858	2057	1336		
	ADTT	4004	1610	91	4205	1641	156		
185-0227	AADTT	3992	1531	84	4170	426	40		
	Lane Designation	Ln1 EB Slow	Ln2 EB Fast	Ln1 WB Rest Area to I-20	Ln2 WB Slow	Ln3 WB Ctr	Ln4 WB Fast		
	ADT	12564	0	6871	10609	11263	2603		
	AADT	12543	0	6763	10427	11081	2516		
	ADTT	1581	0	393	2203	971	74		
245-0218	AADTT	1560	0	381	2147	944	25		

5.2 Analysis of Entries with Zero Weight

The study team has discussed the findings with the vendor on lanes involving zero weight. The vendor indicated that each lane has a different instrument type (see Section 3.3). This section presents an analysis of the subset of the 2018 WIM data that contain zero weight.

5.2.1 Site ID 127-0312

Figure 15 presents the analysis results for entries with zero weight. The zero weight data mainly come from Lanes 5–8 during the months of May and December.

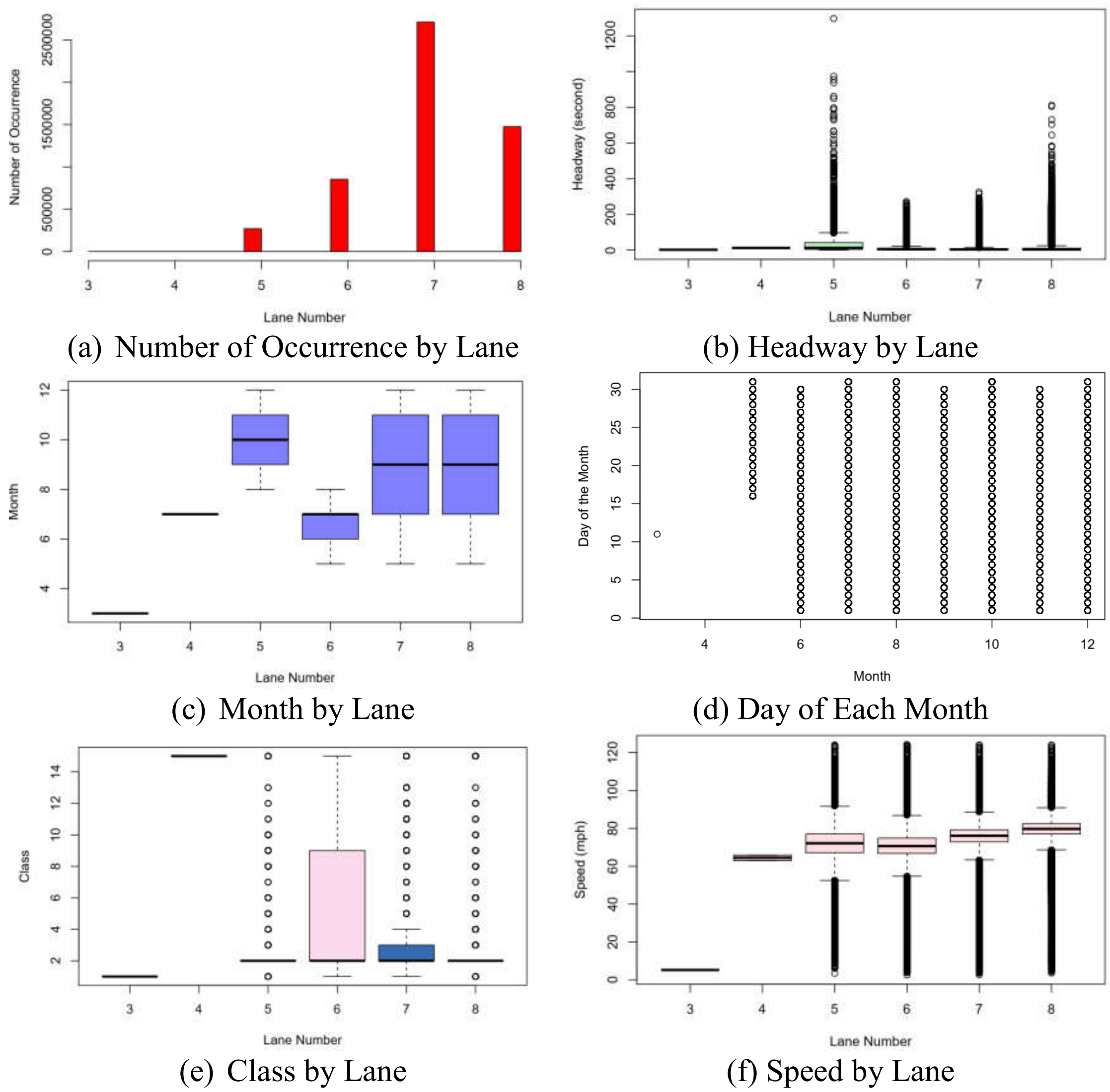


Figure 15 – Analysis of Zero Weight Data for Site ID 127-0312.

This is the only site that has available temperature data, which is shown in Figure 16. Speed, class, headway, and temperature do not appear to be associated with zero weight, although Class 2 vehicles and short durations of headway, in seconds, are most frequently observed. The WIM vendor has informed the study team that Lanes 3–8 are instrumented for reviewing vehicle classification only. While vehicle weight data exist for the SE lanes, a significant portion of entries for the weight parameter contains a zero value.

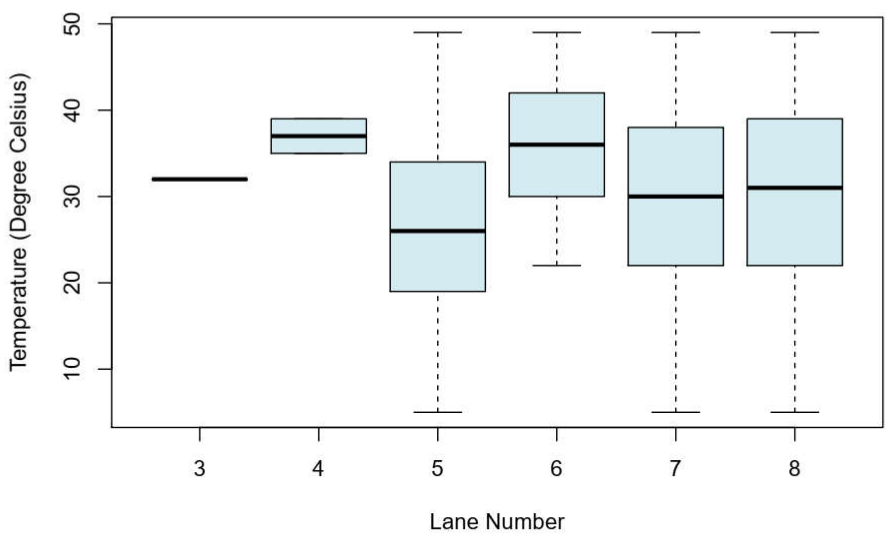
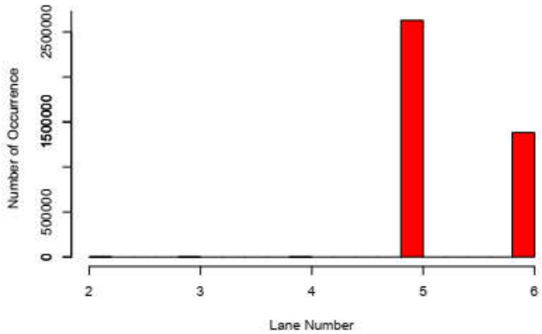


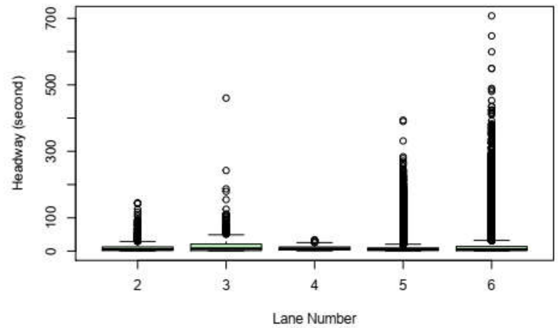
Figure 16 – Effect of Temperature on Zero Weight Entries for Site ID 127-0312.

5.2.2 Site ID 185-0227

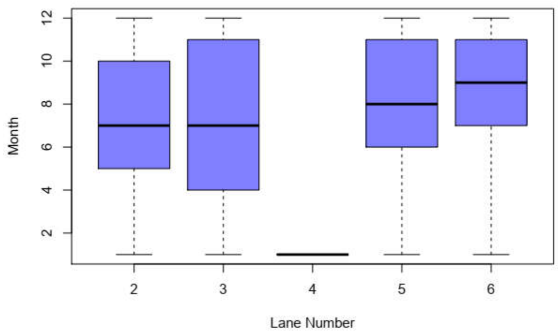
Figure 17 shows the results for the analysis of the zero weight entries. These entries mainly come from Lanes 5 and 6, which were collected from January to December in 2018. Speed, class, and headway are not associated with zero weight. The WIM vendor confirmed that Lanes 2, 3, 5, and 6 are for reviewing classification only, and, therefore, the corresponding weight data from these lanes are considered unavailable. As with the previous site, vehicle weight data exist for the lanes, but a significant portion of entries for the weight parameter has a zero value. By comparison, in the slow lane (#4) with a quartz sensor, only 200 vehicle measurements have a zero weight.



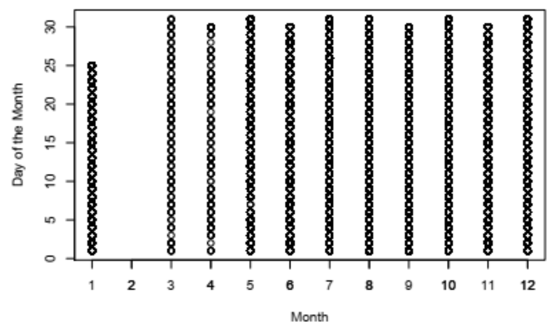
(a) Number of Occurrence by Lane



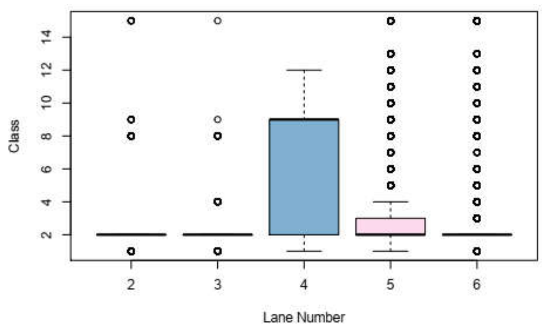
(b) Headway by Lane



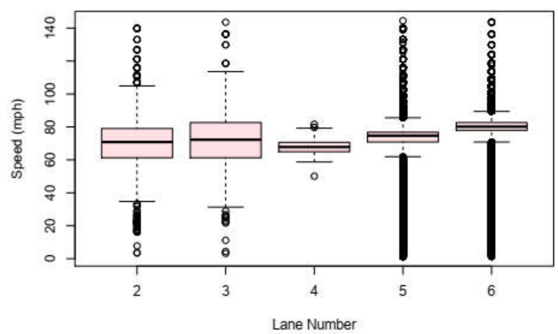
(c) Month by Lane



(d) Day of Each Month



(e) Class by Lane

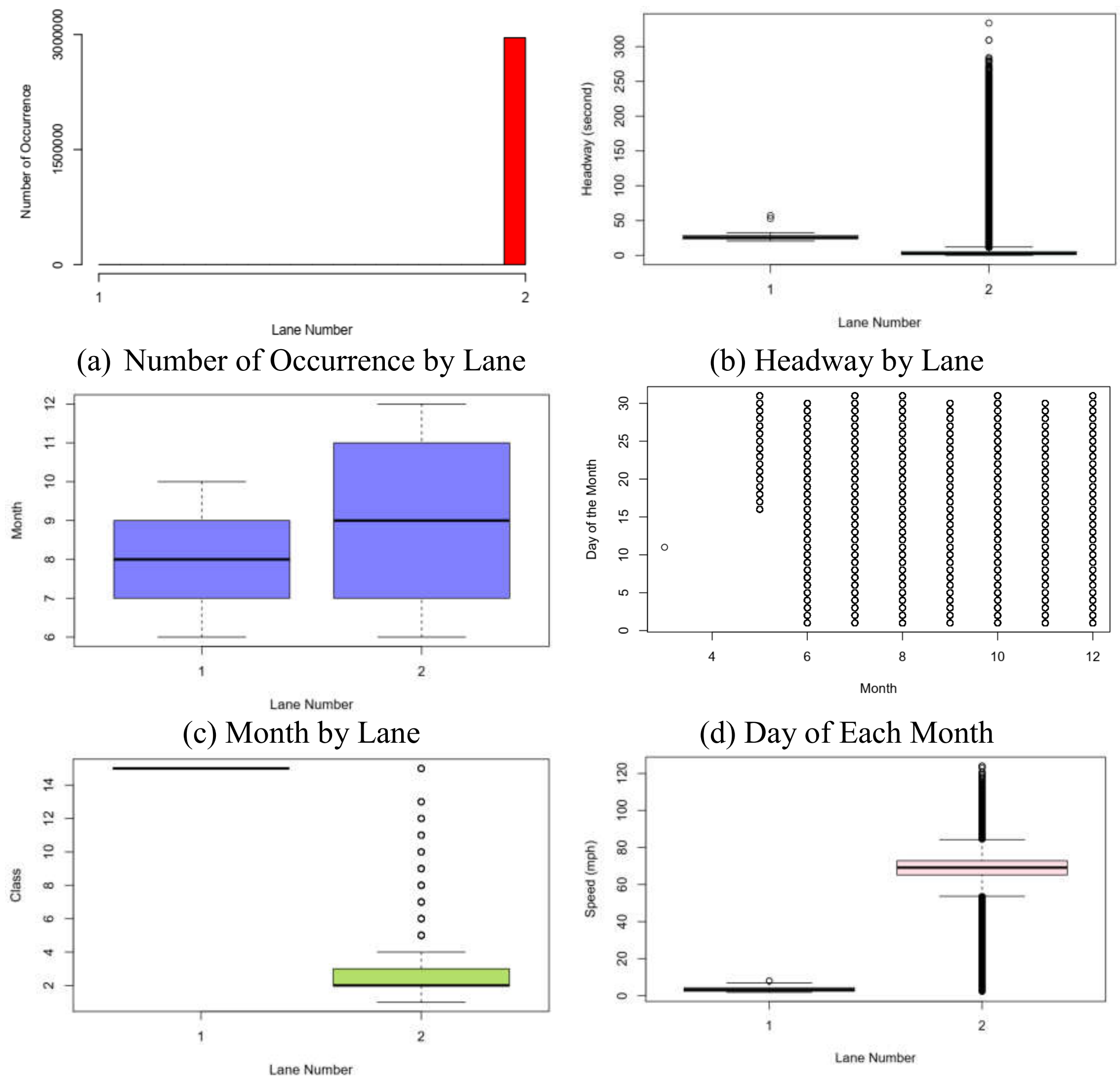


(f) Speed by Lane

Figure 17 – Analysis of Zero Weight Data for Site ID 185-0227.

5.2.3 Site ID 245-0218

Figure 18 shows the results of analyzing zero weight entries. These entries mainly belong to Lane 2 during the months of June and December. Speed, class, and headway are not associated with zero weight. The WIM vendor confirmed that Lane 2 is for reviewing class-only information, and thus the weight data are not valid. In contrast, there are only 36 vehicles with a zero weight in Lane 1, which is instrumented with a quartz sensor.



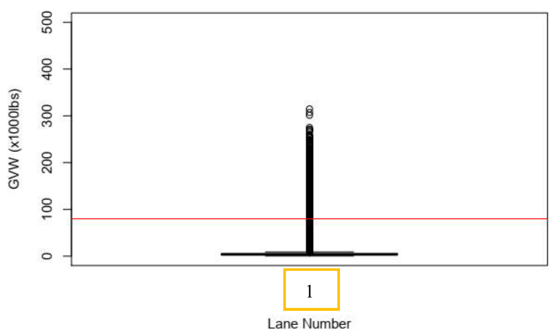
(a) Number of Occurrence by Lane
(b) Headway by Lane
(c) Month by Lane
(d) Day of Each Month
(e) Class by Lane
(f) Speed by Lane

Figure 18 – Analysis of Zero Weight Data for Site ID 245-0218.

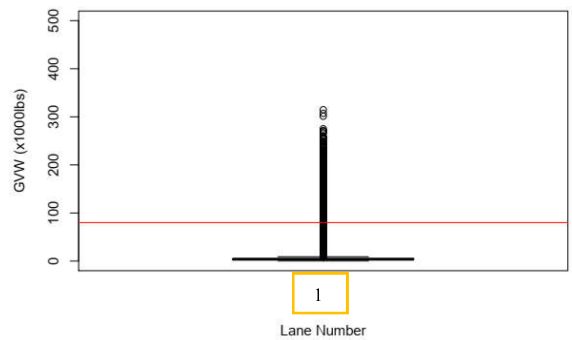
5.3 Analysis of Gross Vehicle Weight

5.3.1 Gross Vehicle Weight by Lane

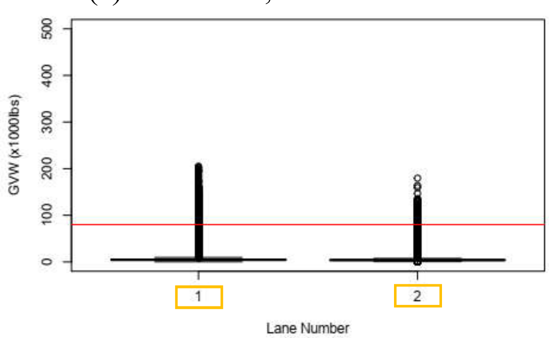
Figure 19 shows a boxplot of GVW in each traffic direction, noting that the red line indicates the 80,000 lb weight limit. Although the percentage of entries with GVS exceeding 80,000 lbs is small, two sites (185-0227 and 143-0126) recorded GVW reaching far beyond the upper whisker (Q3+1.5IQR) in their slow lanes, which have both been instrumented with quartz sensors. Lanes with a quartz sensor are boxed with a yellow line.



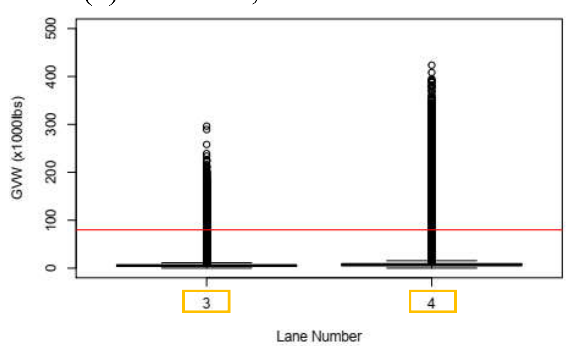
(a) NB Lanes, Site ID 021-7334



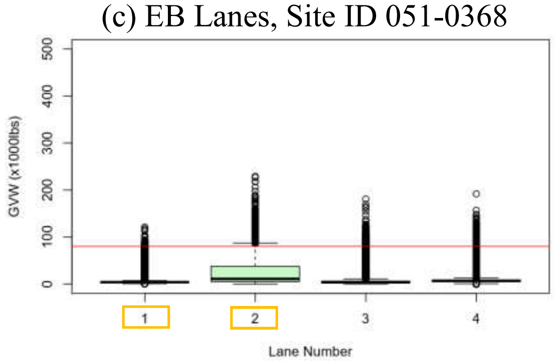
(b) SB Lanes, Site ID 021-7334



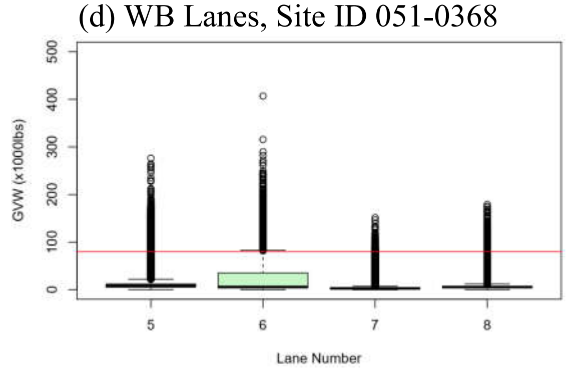
(c) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

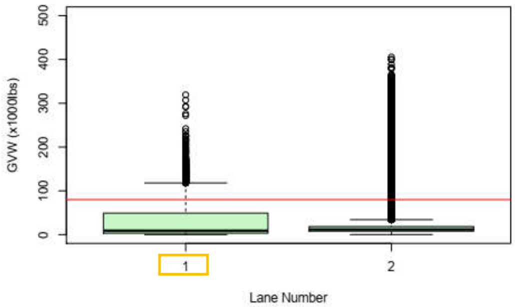


(e) NB Lanes, Site ID 127-0312

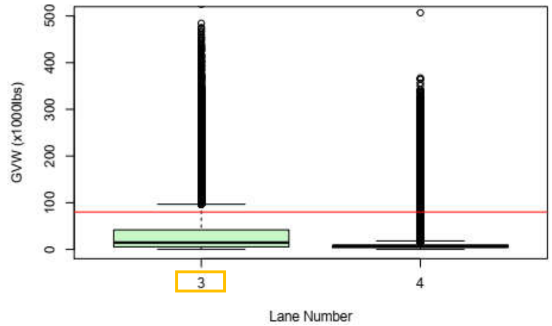


(f) SB Lanes, Site ID 127-0312

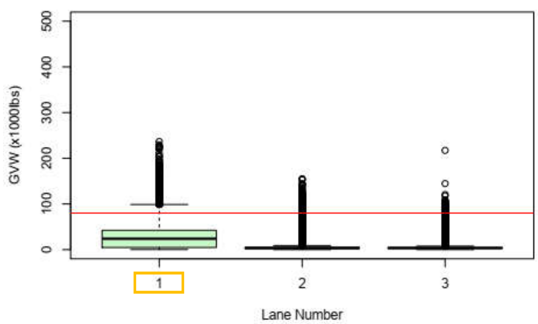
Figure 19 – Gross Vehicle Weight by Lane.



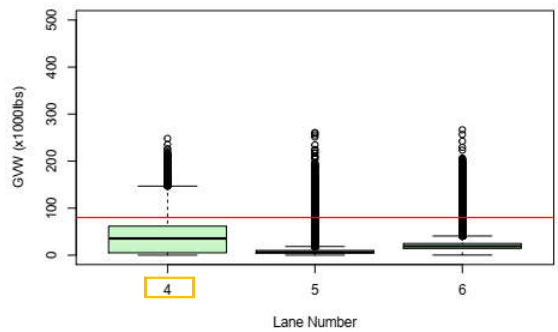
(g) EB Lanes, Site ID 143-0126



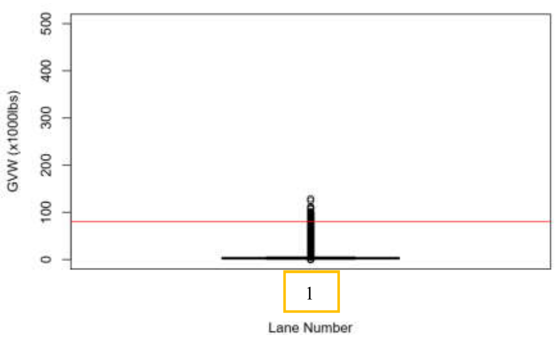
(h) WB Lanes, Site ID 143-0126



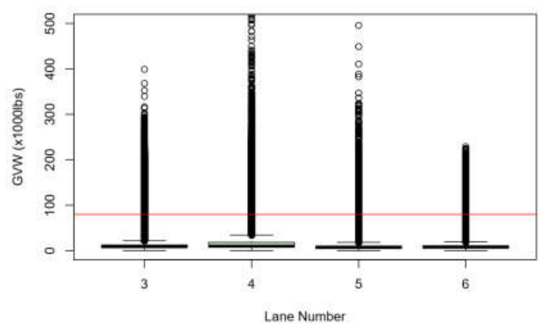
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218

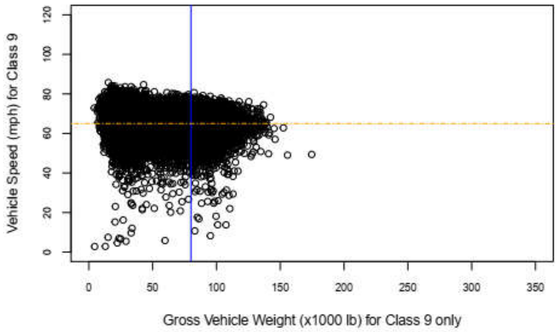


(l) WB Lanes, Site ID 245-0218

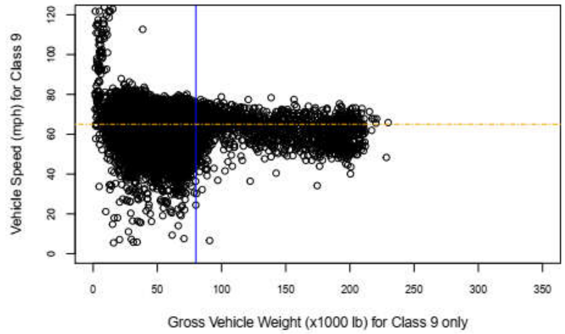
Figure 19 Continued – Gross Vehicle Weight by Lane.

5.3.2 Gross Vehicle Weight vs. Speed

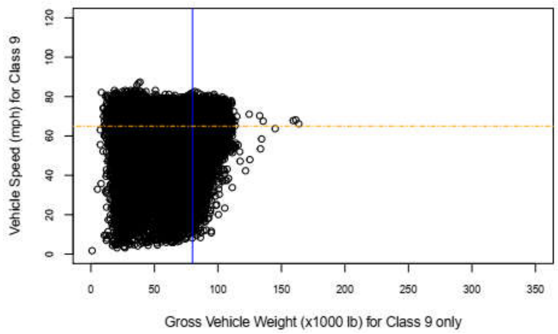
Figure 20 shows scatter plots of Class 9 GVW. The vertical blue lines indicate the 80,000 lb limit, and the dotted oranges lines indicate the legal speed limit. The vehicles in the upper right quadrant exceed the legal weight and speed limits. According to these plots, as Class 9 vehicles become heavier, the driving speed does not appear to decrease significantly. Although the number of overweight vehicles appears high in these scatter plots, the percentage of vehicles exceeding the 80,000 lb limit ranges between 0% and 7% (see Table 10).



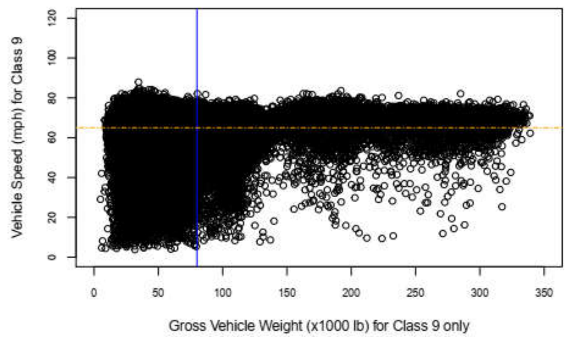
(a) NB Lanes, Site ID 021-7334



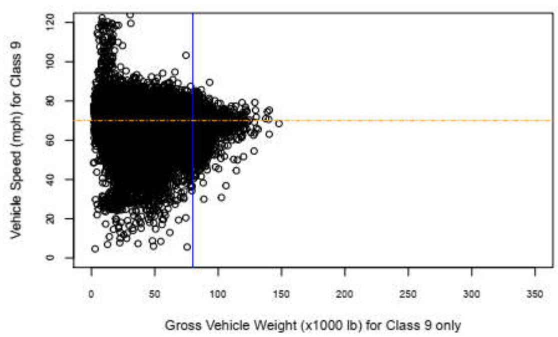
(b) SB Lanes, Site ID 021-7334



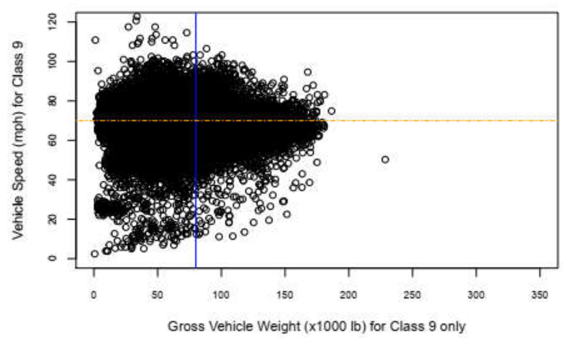
(c) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

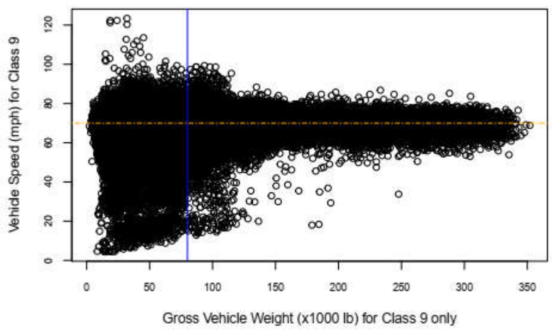


(e) NB Lanes, Site ID 127-0312

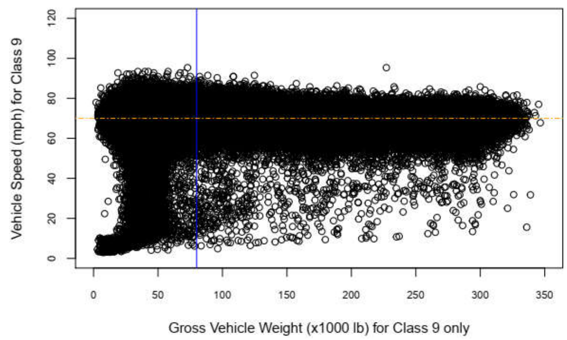


(f) SB Lanes, Site ID 127-0312

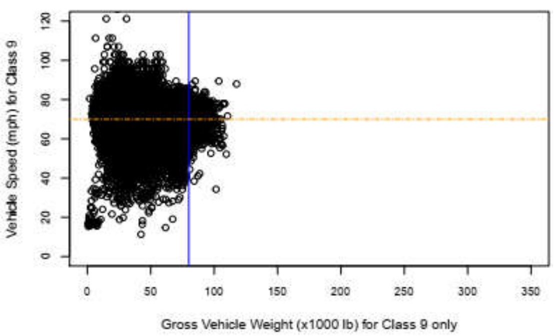
Figure 20 – Gross Vehicle Weight vs. Speed by Traffic Direction.



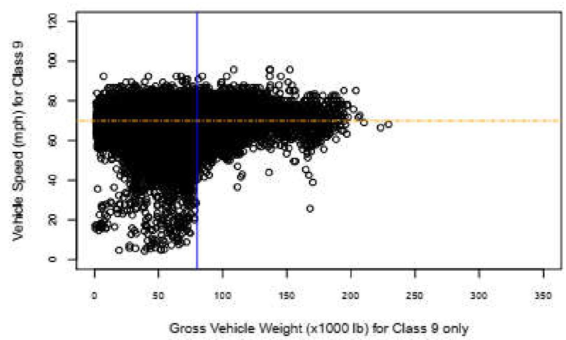
(g) EB Lanes, Site ID 143-0126



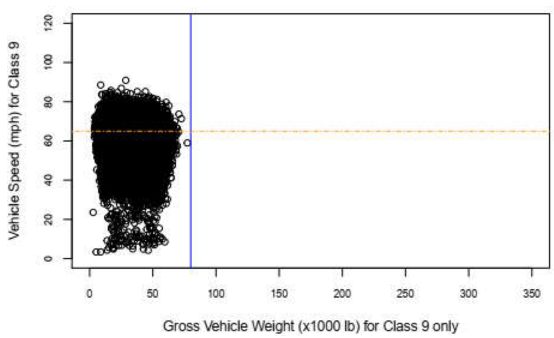
(h) WB Lanes, Site ID 143-0126



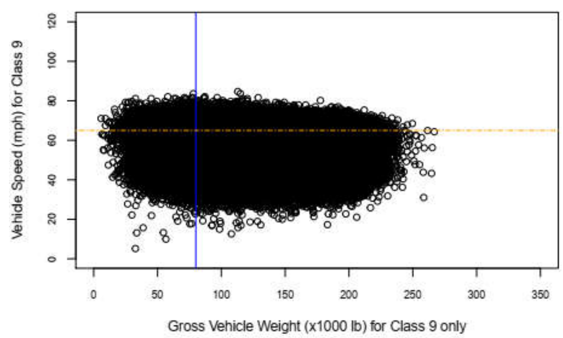
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218

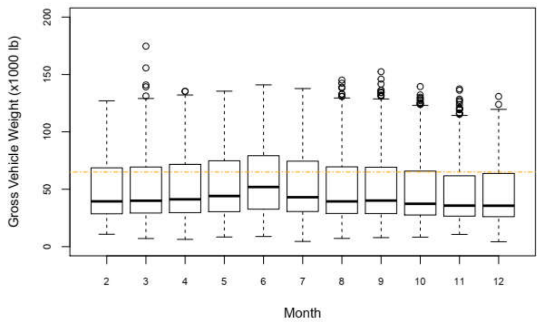


(l) WB Lanes, Site ID 245-0218

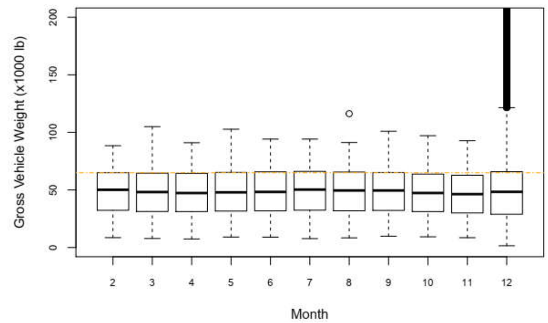
Figure 20 Continued – Gross Vehicle Weight vs. Speed by Traffic Direction.

5.3.3 Gross Vehicle Weight vs. Month

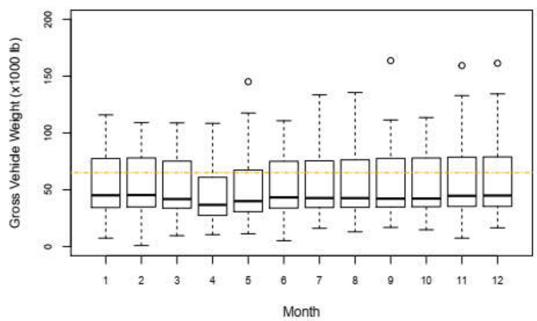
Figure 21 shows boxplots of Class 9 GVW by month. Although no significant month-to-month variation is observed, four sites appear to show a month-to-month variation. Site ID 127-0312 shows increased Class 9 GVW in June and July whereas Site ID 143-0126 shows an increase in January and February. Meanwhile, the weight decrease at Site ID 245-0218 occurs as the temperature drops. Further, at Site ID 051-0368, the median and the number of outliers increases between March and June. The monthly variation in GVW is reviewed to observe a temperature sensitivity in the absence of temperature data. The monthly variation is further reviewed for each lane in Section 5.5.1.



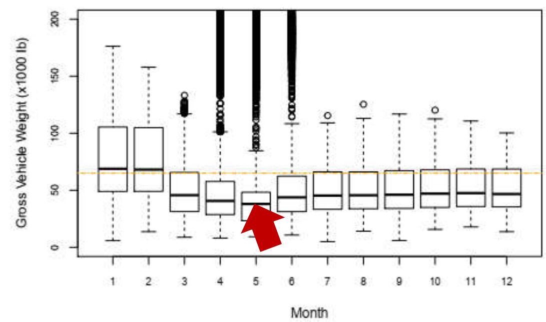
(a) NB Lanes, Site ID 021-7334



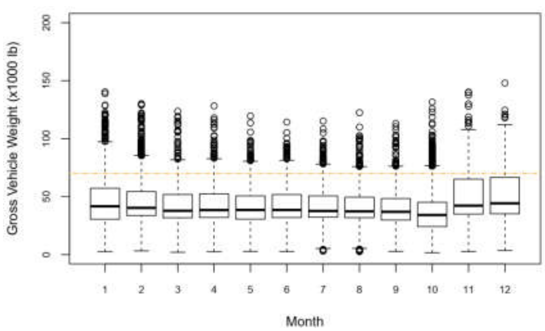
(b) SB Lanes, Site ID 021-7334



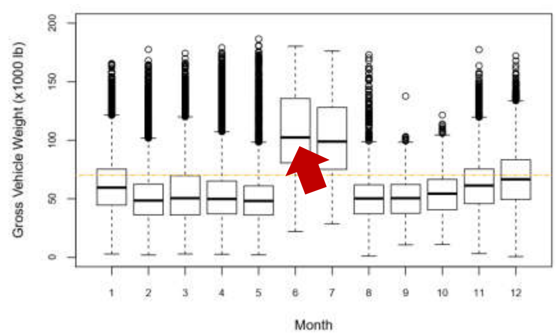
(c) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

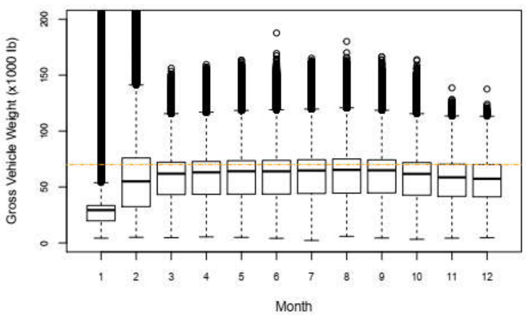


(e) NB Lanes, Site ID 127-0312

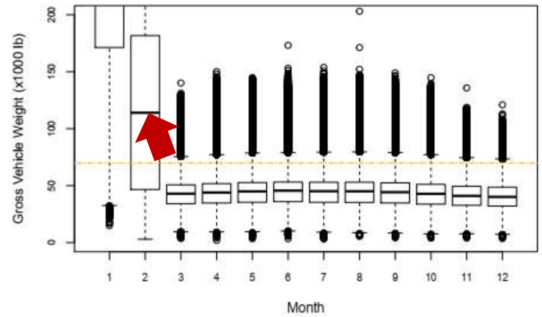


(f) SB Lanes, Site ID 127-0312

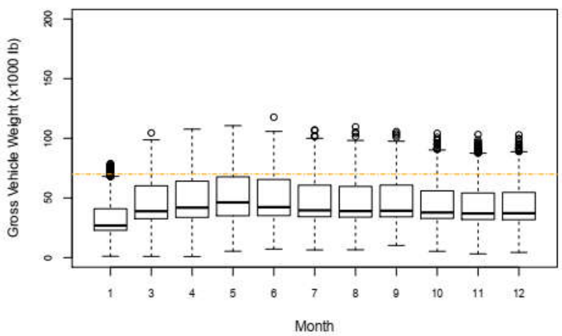
Figure 21 – Class 9 Gross Vehicle Weight by Month.



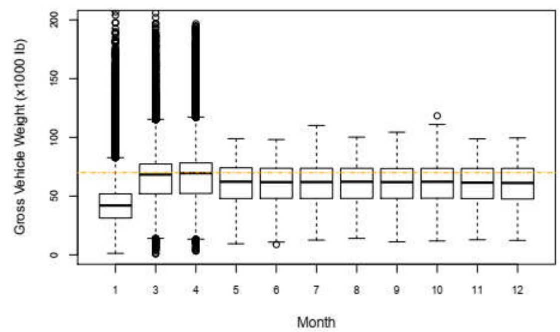
(g) EB Lanes, Site ID 143-0126



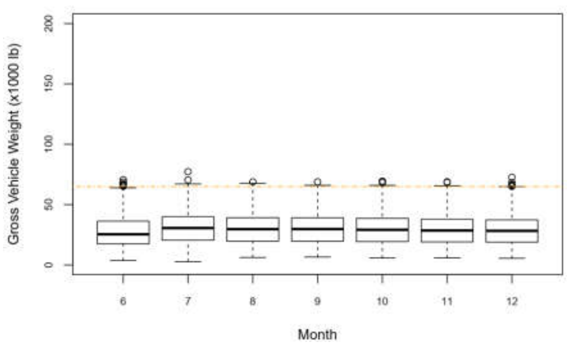
(h) WB Lanes, Site ID 143-0126



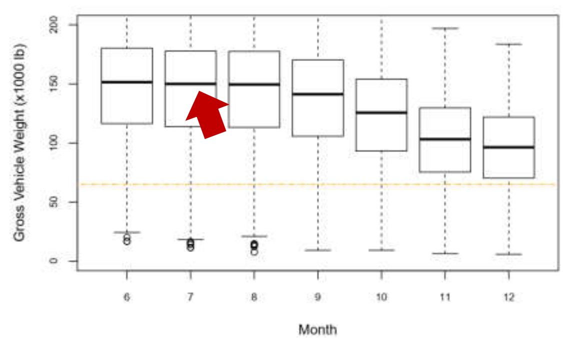
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218



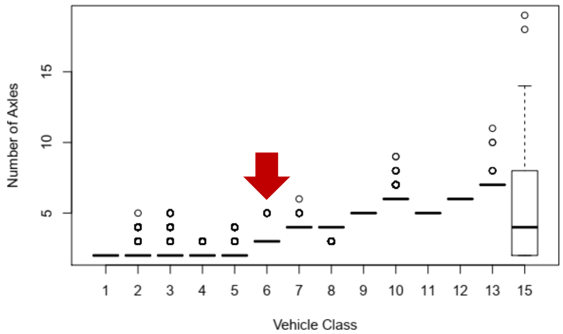
(l) WB Lanes, Site ID 245-0218

Figure 21 Continued – Class 9 Gross Vehicle Weight by Month.

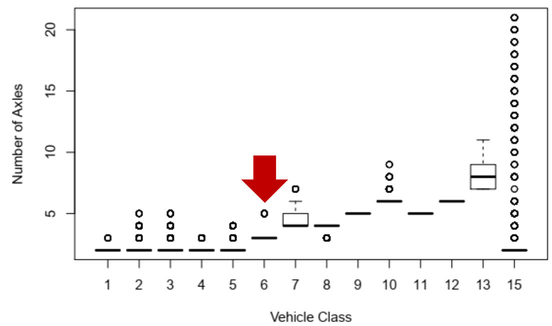
5.4 Analysis of Vehicle Class and Axle Spacing

5.4.1 Vehicle Classification and Number of Axles

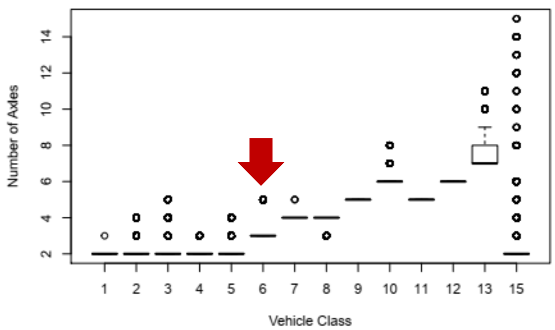
Figure 22 shows boxplots of axle counts by vehicle class. Overall, the results indicate that Class 15 has the highest median count and spread in the vehicle counts. That is, unclassified vehicles have a wide range of axle counts. Classes 2 and 3 should have as many as four axles; however, in the WIM data, fifth and sixth axles are observed. In addition, while Classes 5 and 6 should have two and three axles, respectively, third and fourth axles are observed for Class 5, and a fifth axle is observed for Class 6. Finally, Classes 7 and above appear to have the number of axles consistent with the FHWA classification (Hallenbeck et al., 2014) shown in Table 13.



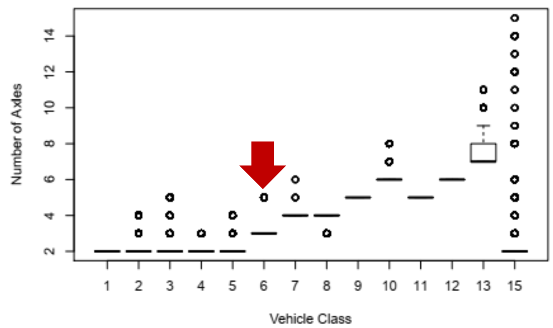
(a) NB Lanes, Site ID 021-7334



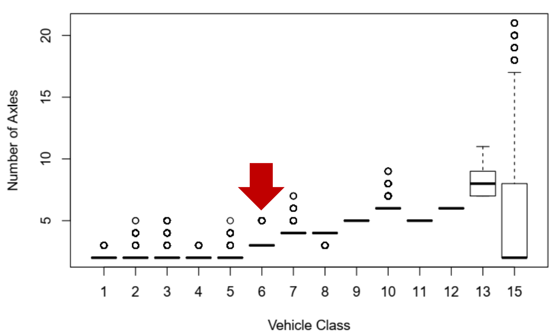
(b) SB Lanes, Site ID 021-7334



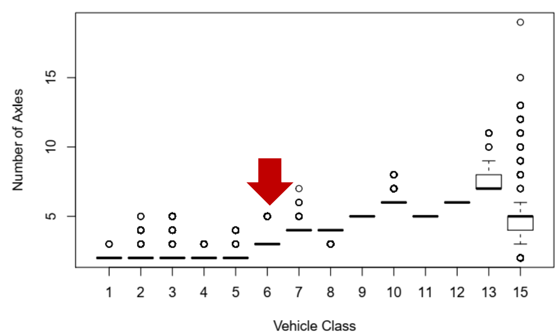
(c) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

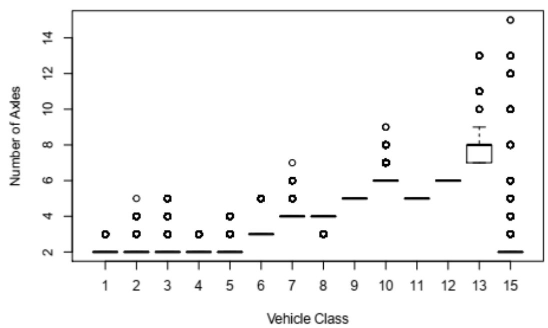


(e) NB Lanes, Site ID 127-0312

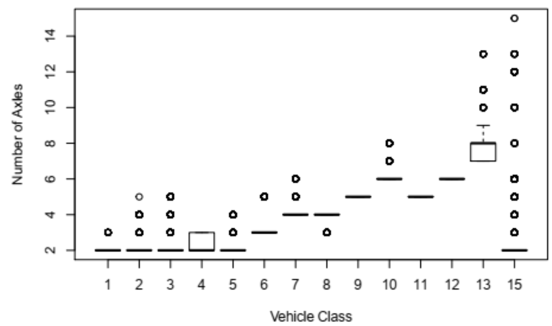


(f) SB Lanes, Site ID 127-0312

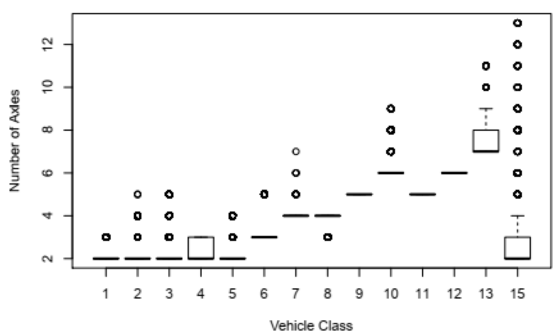
Figure 22 – Vehicle Classification and Number of Axles.



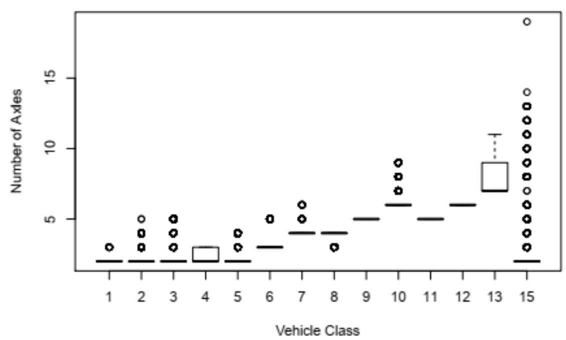
(g) EB Lanes, Site ID 143-0126



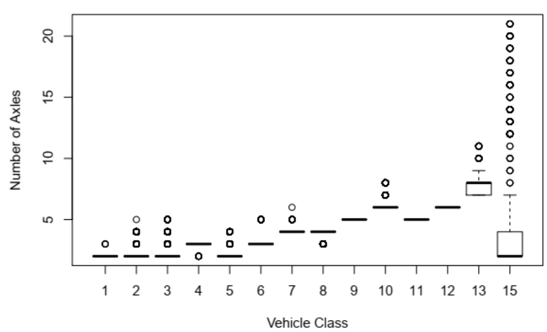
(h) WB Lanes, Site ID 143-0126



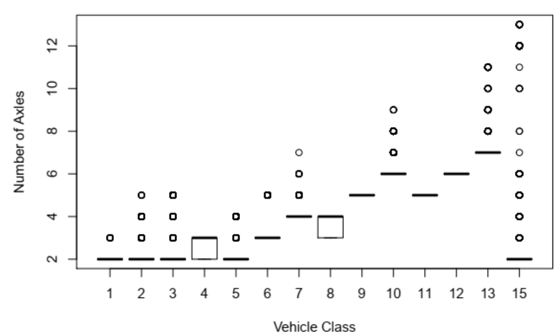
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218



(l) WB Lanes, Site ID 245-0218

Figure 22 Continued – Vehicle Classification and Number of Axles.

Table 13 – FHWA Vehicle Classification Definitions (Hallenbeck et al., 2014).

Class Group	Class Definition	Class Includes	Number of Axles
1	Motorcycles	Motorcycles	2
2	Passenger Cars	All cars Cars with one-axle trailers Cars with two-axle trailers	2, 3, or 4
3	Other Two-Axle Four-Tire Single-Unit Vehicles	Pick-ups and vans Pick-ups and vans with one- and two-axle trailers	2, 3, or 4
4	Buses	Two- and three-axle buses	2 or 3
5	Two-Axle, Six-Tire, Single-Unit Trucks	Two-axle trucks	2
6	Three-Axle Single-Unit Trucks	Three-axle trucks Three-axle tractors without trailers	3
7	Four or More Axle Single-Unit Trucks	Four-, five-, six- and seven-axle single-unit trucks	4 or more
8	Four or Fewer Axle Single-Trailer Trucks	Two-axle trucks pulling one- and two-axle trailers Two-axle tractors pulling one- and two-axle trailers Three-axle tractors pulling one-axle trailers	3 or 4
9	Five-Axle Single-Trailer Trucks	Two-axle tractors pulling three-axle trailers Three-axle tractors pulling two-axle trailers Three-axle trucks pulling two-axle trailers	5
10	Six or More Axle Single-Trailer Trucks	Multiple configurations	6 or more
11	Five or Fewer Axle Multi-Trailer Trucks	Multiple configurations	4 or 5
12	Six-Axle Multi-Trailer Trucks	Multiple configurations	6
13	Seven or More Axle Multi-Trailer Trucks	Multiple configurations	7 or more
14	Unused	----	----
15	Unclassified Vehicle	Multiple configurations	2 or more

Table 14(a) shows the default classification used in the data logging system (i.e., EMU3). Axle number is queried first, followed by a check on the axle spacing (Moses, 2019). Based on this classification scheme, the number of axles for Classes 2, 3, and 5 are acceptable; however, Class 6 vehicles should have three axles. Table 14(b) presents the classification scheme employed for Georgia's WIM program. This table was provided in May 2020.

Table 14 – Classification Scheme Implemented in EMU3.

(a) EMU Default Classification (Moses, 2019).

Class	Axles	Axle Spacing (cm)							
		SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8
1	2	10 - 183							
2	2	183 - 305							
	3	183 - 305	183 - 762						
	4	183 - 305	183 - 762	10 - 183					
3	2	305 - 405							
	3	305 - 405	183 - 762						
	4	305 - 405	183 - 762	10 - 183					
	5	305 - 405	183 - 762	10 - 183	10 - 183				
4	2	701 - 1219							
	3	701 - 1219	10 - 183						
5	2	405 - 701							
	3	405 - 701	183 - 762						
	4	405 - 701	183 - 762	10 - 183					
	5	405 - 701	183 - 762	10 - 183	10 - 183				
6	3	183 - 701	10 - 183						
7	4	183 - 701	10 - 183	10 - 183					
8	3	305 - 701	335 - 1219						
	4	305 - 701	335 - 1219	61 - 366					
	4	183 - 701	10 - 183	183 - 1341					
9	5	183 - 792	10 - 183	183 - 1402	10 - 335				
	5	183 - 792	10 - 183	183 - 701	335 - 823				
10	6	183 - 792	10 - 183	10 - 1402	10 - 335	10 - 335			
	7	183 - 509	10 - 183	405 - 1219	10 - 405	10 - 405	10 - 405		
11	5	183 - 792	335 - 792	183 - 610	335 - 792				
12	6	183 - 792	10 - 183	335 - 792	183 - 731	335 - 792			
13	8	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	
	9	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371
15	ALL OTHER VEHICLES								

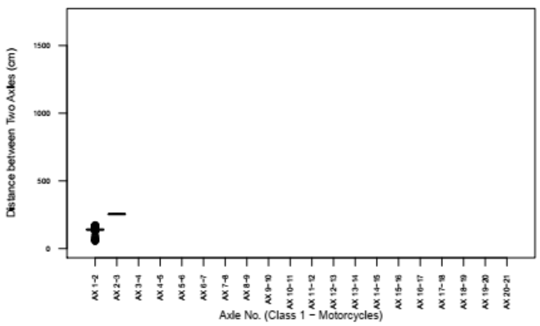
Table 14 Continued – Classification Scheme Implemented in EMU3.

(b) Vehicle Classification Used by the Vendor.

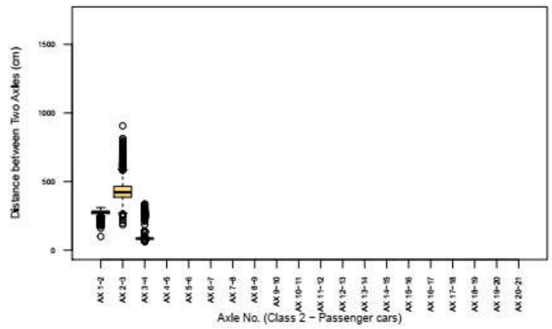
Class	Axles	GVW range	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	SP9	SP10
1	2	0 - 1000	61 - 180									
1	3	0 - 1250	61 - 180	183 - 274								
2	2		180 - 311									
2	3		180 - 311	183 - 640								
2	4		183 - 311	244 - 792	61 - 101							
2	4		183 - 311	183 - 457	168 - 366							
2	5		183 - 311	183 - 792	61 - 101	61 - 101						
3	2		311 - 448									
3	3		311 - 448	213 - 640								
3	4		311 - 448	244 - 1067	61 - 101							
3	4		311 - 448	213 - 610	168 - 448							
3	5		311 - 448	183 - 1067	61 - 101	61 - 101						
4	2		488 - 792									
4	3		579 - 975	61 - 134								
5	2		448 - 1200									
5	4		448 - 975	244 - 1067	61 - 101							
5	4		448 - 975	213 - 701	168 - 448							
5	3		406 - 702	183 - 762								
5	4		406 - 702	183 - 762	10 - 183							
5	5		406 - 702	183 - 762	10 - 183	10 - 183						
6	3		183 - 1100	61 - 274								
6	3		671 - 975	128 - 274								
6	5		183 - 975	61 - 183	244 - 1067	61 - 101						
6	5		183 - 975	61 - 183	213 - 610	168 - 448						
7	4		244 - 701	61 - 305	61 - 448							
7	4		61 - 183	305 - 914	61 - 183							
7	5		183 - 853	61 - 183	61 - 183	61 - 427						
7	6		183 - 610	61 - 183	61 - 183	61 - 183	61 - 183					
7	7		183 - 457	61 - 183	61 - 183	61 - 183	61 - 183	61 - 183				
8	3		448 - 853	274 - 1524								
8	3		183 - 448	640 - 1524								
8	4		90 - 853	305 - 1524	61 - 448							
8	4		183 - 1200	61 - 350	448 - 1524							
8	3	5443 -	305 - 702	335 - 1222								
8	4	5443 -	305 - 702	335 - 1222	50 - 366							
8	4	5443 -	183 - 702	10 - 183	183 - 1343							
9	5		183 - 914	183 - 1676	61 - 183	61 - 183						
9	5		183 - 914	61 - 183	183 - 2286	61 - 701						
10	6		183 - 914	61 - 183	61 - 183	274 - 2286	61 - 448					
10	6		183 - 914	61 - 183	244 - 914	244 - 914	61 - 183					
10	6		183 - 914	457 - 1676	61 - 183	61 - 183	61 - 183					
10	6		183 - 914	61 - 183	183 - 2286	61 - 198	61 - 448					
10	7		183 - 914	61 - 183	183 - 2286	61 - 183	61 - 183	61 - 448				
10	7		183 - 914	457 - 1676	61 - 183	61 - 183	61 - 183	61 - 448				
10	7		183 - 914	61 - 183	61 - 183	274 - 2286	61 - 183	61 - 448				
10	8		183 - 914	61 - 183	61 - 183	183 - 2286	61 - 183	61 - 183	61 - 448			
10	8		183 - 914	61 - 183	183 - 2286	61 - 183	61 - 183	61 - 183	61 - 448			
10	8		183 - 914	457 - 1676	61 - 183	61 - 183	61 - 183	61 - 183	61 - 448			
10	9		183 - 914	457 - 1676	61 - 183	61 - 183	61 - 183	61 - 183	61 - 183	61 - 448		
10	9		183 - 914	61 - 183	183 - 2286	61 - 183	61 - 183	61 - 183	61 - 183	61 - 448		
11	5		183 - 853	335 - 914	80 - 519	335 - 914						
12	6		183 - 914	61 - 183	61 - 914	183 - 549	335 - 914					
13	7		183 - 914	61 - 183	183 - 1676	61 - 183	183 - 1676	61 - 183				
13	7		183 - 914	61 - 183	335 - 1372	61 - 183	61 - 305	335 - 914				
13	7		183 - 914	61 - 183	335 - 1372	61 - 305	335 - 914	61 - 183				
13	8		183 - 914	61 - 183	335 - 1372	61 - 183	61 - 305	335 - 914	61 - 183			
13	10		183 - 914	61 - 183	61 - 183	183 - 1676	61 - 183	61 - 183	183 - 1676	61 - 183	61 - 183	
13	7		10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371				
13	8		10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371			
13	9		10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371		
13	10		10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	
13	11		10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371	10 - 1371

5.4.2 Vehicle Classification and Axle Spacing

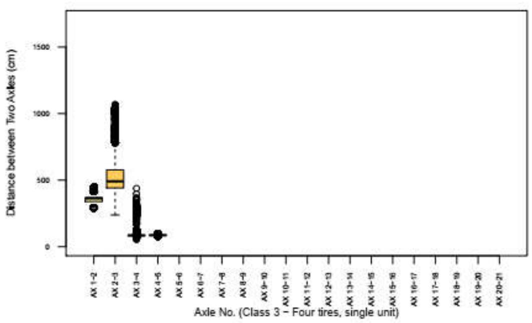
Since the axle-spacing classifier uses centimeters instead of meters in the database, Figure 23 illustrates spacings between a series of axles in centimeters for Site ID 051-0368.



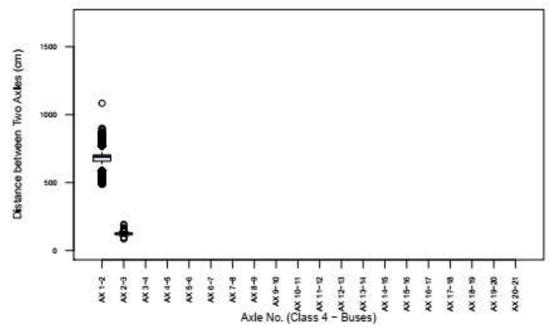
(a) Class 1 Only



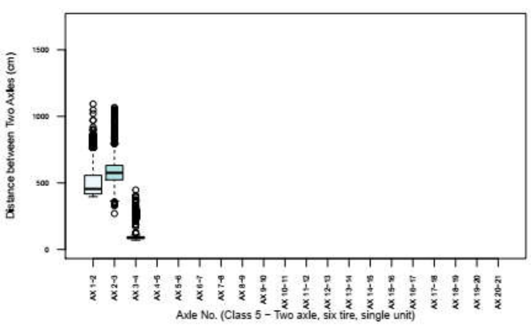
(b) Class 2 Only



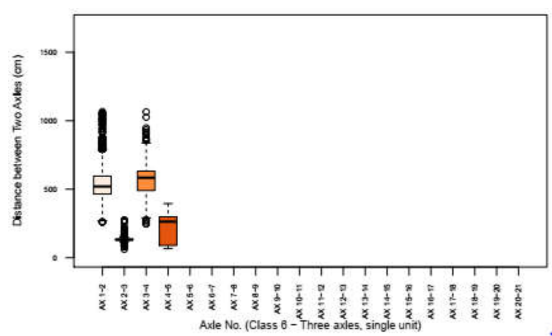
(c) Class 3 Only



(d) Class 4 Only

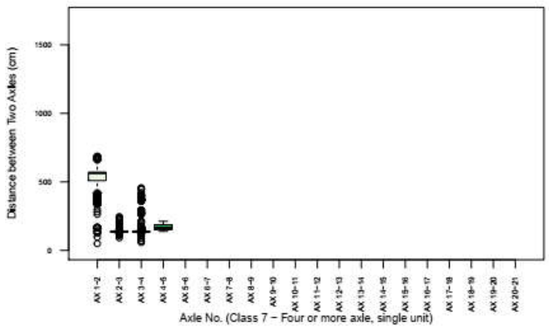


(e) Class 5 Only

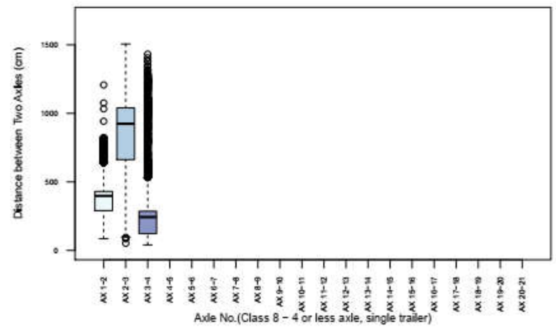


(f) Class 6 Only

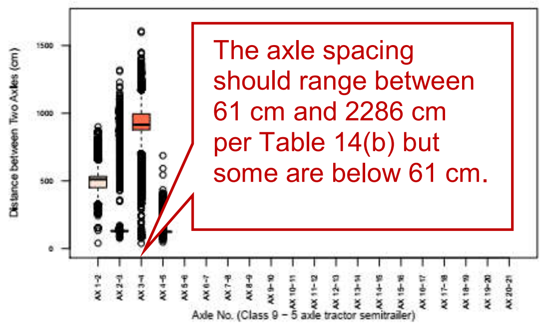
Figure 23 – Vehicle Classification and Axle Spacings for EB Lanes, Site ID 051-0368.



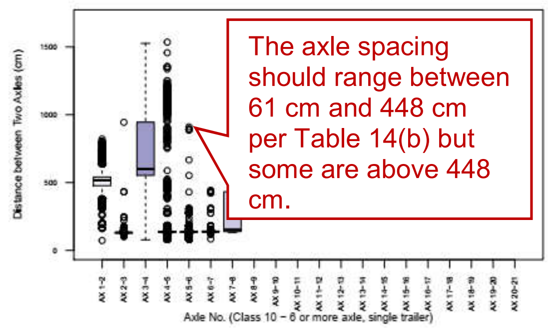
(g) Class 7 Only



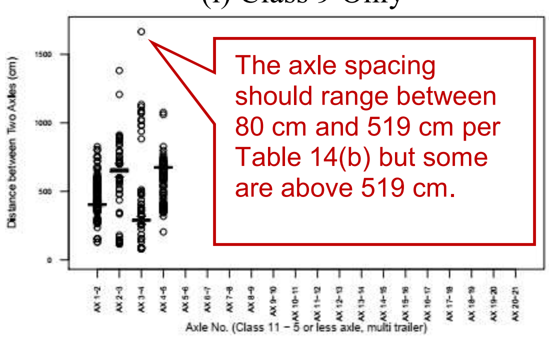
(h) Class 8 Only



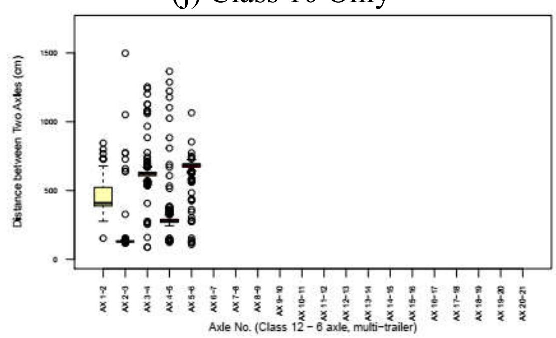
(i) Class 9 Only



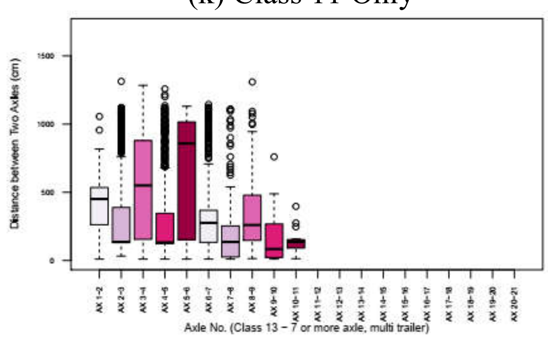
(j) Class 10 Only



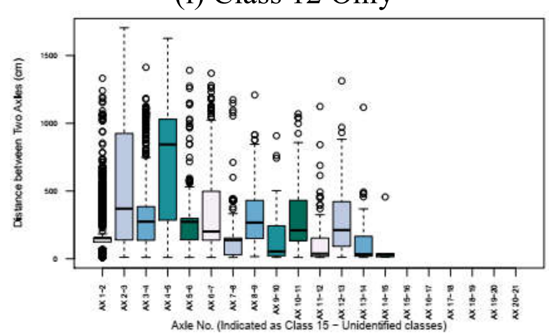
(k) Class 11 Only



(l) Class 12 Only



(m) Class 13 Only



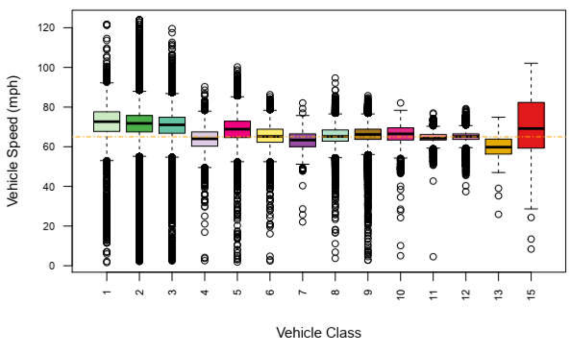
(n) Class 15 Only

Figure 23 Continued – Vehicle Classification and Axle Spacings for EB Lanes, Site ID 051-0368.

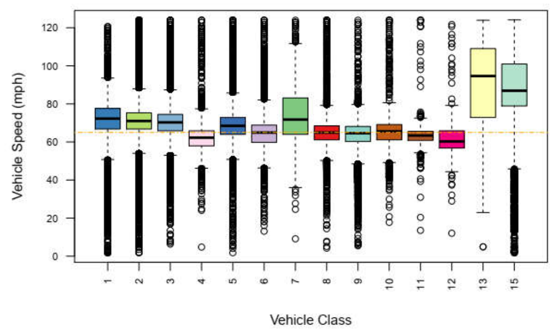
At times, observed axle spacing is neither consistent with the data logger's default classifier (see Table 14(a)) nor align with the vendor's classification scheme. For example, Class 9 vehicles' third and fourth axle distances are expected to range between 61 cm and 2286 cm per Table 14(b); however, some entries report this distance below 61 cm. Observed discrepancies, such as this one in axle spacings, should be described for each vehicle class. A similar discrepancy is observed with other classes when comparing observed axle distances to those shown in Table 14(a). In Figure 23(k), Class 11 vehicles' third and fourth axle distances range between 0 cm and 1600 cm. According to Table 14(b), however, axle spacing should range between 80 cm and 519 cm.

5.4.3 Vehicle Classification and Speed

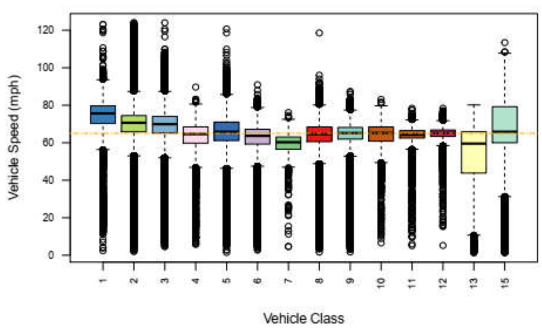
Figure 24 shows boxplots of speed by vehicle class including Class 15, unidentified vehicles. Overall, the results indicate that Class 15 has the highest median speed and a relatively high spread in the vehicle speed data. The light-orange colored dashed line indicates the legal speed limit at each site.



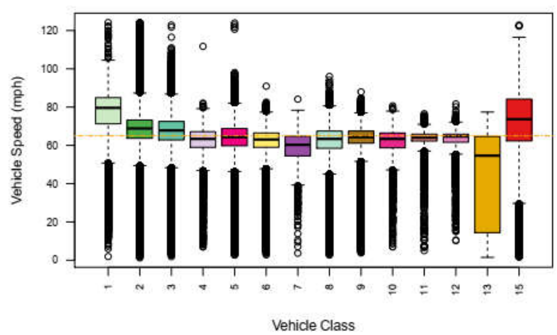
(a) NB Lanes, Site ID 021-7334



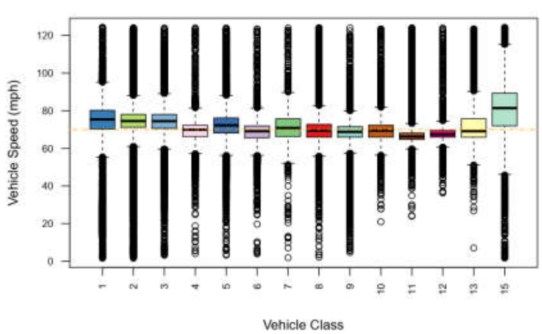
(b) SB Lanes, Site ID 021-7334



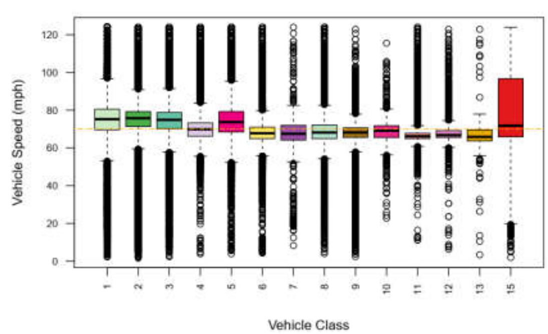
(c) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

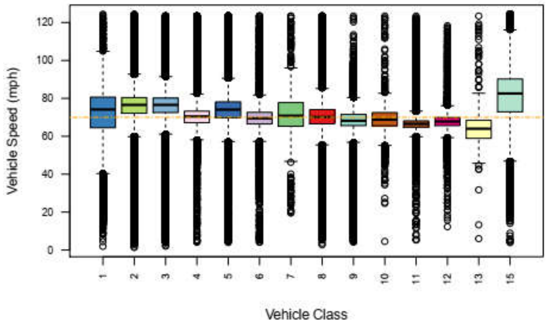


(e) NB Lanes, Site ID 127-0312

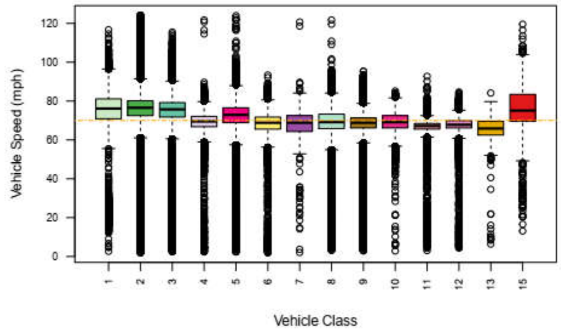


(f) SB Lanes, Site ID 127-0312

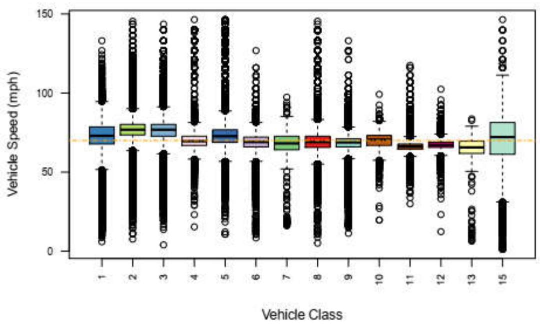
Figure 24 – Vehicle Classification and Speed.



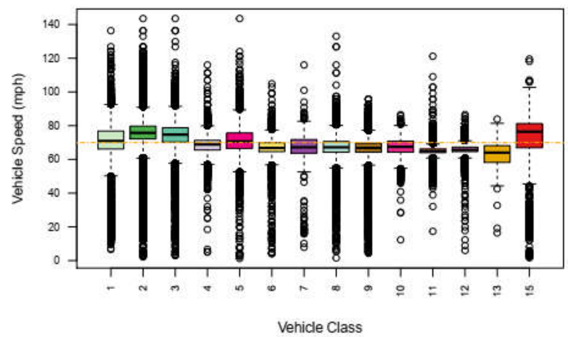
(g) EB Lanes, Site ID 143-0126



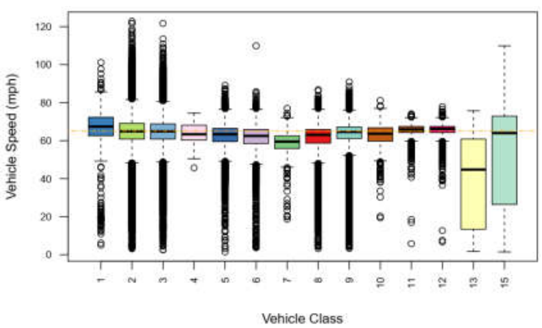
(h) WB Lanes, Site ID 143-0126



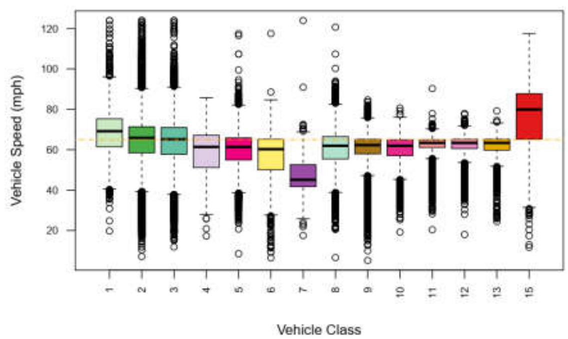
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218



(l) WB Lanes, Site ID 245-0218

Figure 24 Continued – Vehicle Classification and Speed.

5.4.4 Class 15 Vehicle Speed and Gross Vehicle Weight

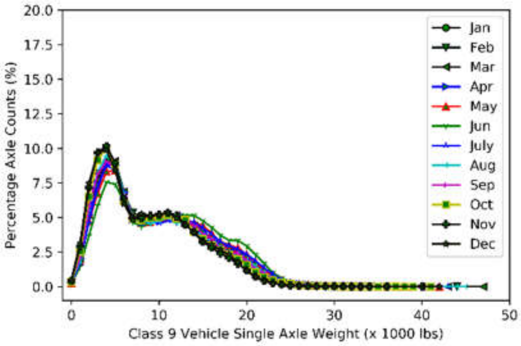
Section 5.4.3 showed that Class 15 vehicles may be associated with vehicle speed although the spread in the speed data was large. Meanwhile, Class 15 vehicles do not appear to be associated with GVW. The following section graphically reviews the weight data.

5.5 Weight Shift and Noticeable Spread

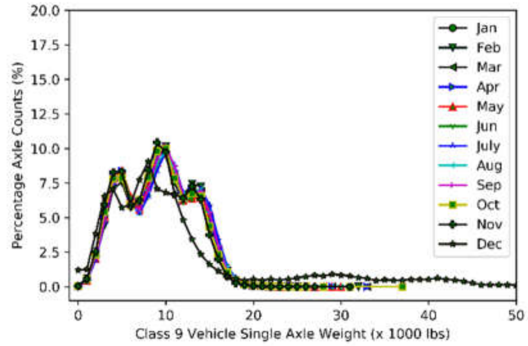
This section focuses on illustrating weight shifts observed by reviewing month-to-month variations in single axle weights. Additionally, the relationship between vehicle speed and weight is reviewed. Finally, the median and spread in axle spacings are plotted for Class 9 and Class 15 vehicles.

5.5.1 Class 9 Single Axle Load Spectrum in Each Lane and Traffic Direction

Figures 25 through 31 show the single axle load spectrum by month for each lane at the six sites. The weight shift observed in each lane can help identify sensors requiring calibration and/or maintenance and sensors that are reading consistent and reasonable vehicles weights. Single axle load distribution should generally show a single mode. Multiple modes are observed at some locations. Additionally, a significant monthly shift in single axle weight is observed at most sites. In reviewing the following figures, lanes instrumented with a quartz sensor (or sensors) are indicated with an asterisk. Lanes with a BL sensor are shown with two asterisks. Lanes without an asterisk signify that their instrumentation produces class-only information. Unreasonably large or small (e.g., noises) weights appear to come from lanes not instrumented with a quartz sensor.

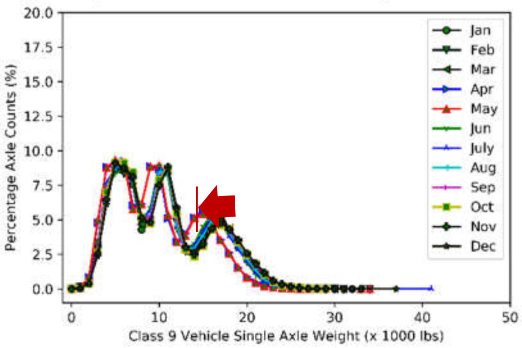


(a) Ln 1 NB *

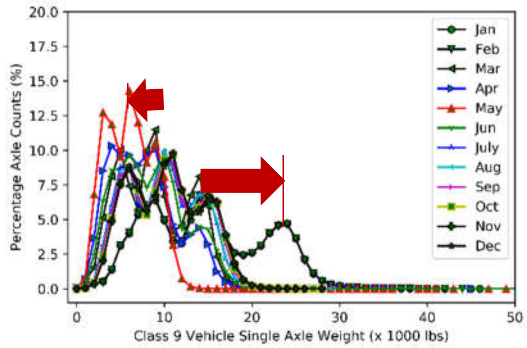


(b) Ln 1 SB *

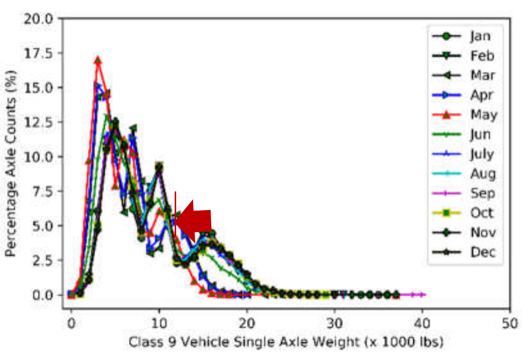
Figure 25 – Class 9 Single Axle Load in Each Lane for Site ID 021-7334.



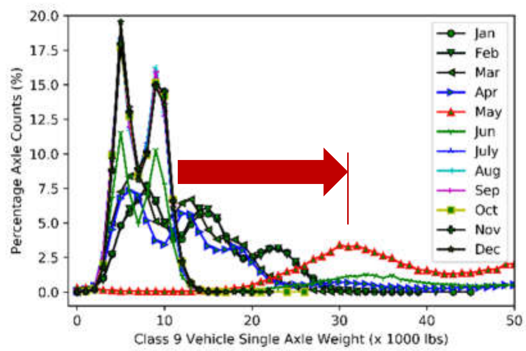
(a) Ln 1 EB Slow *



(b) Ln 1 WB Slow *

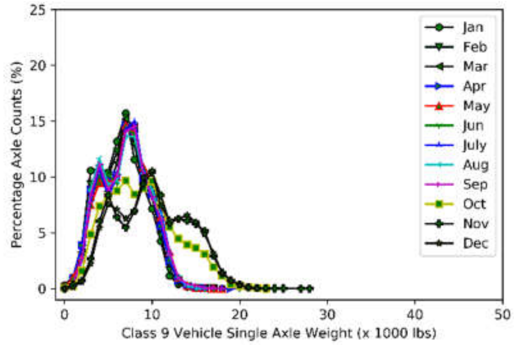


(c) Ln 2 EB Fast *

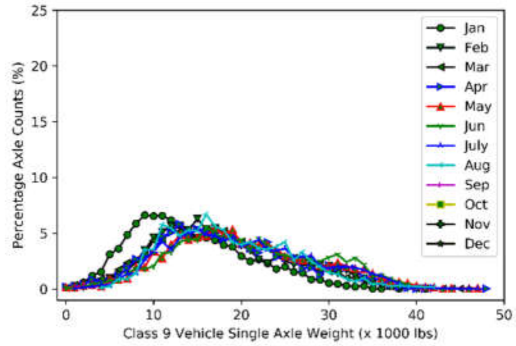


(d) Ln 2 WB Fast *

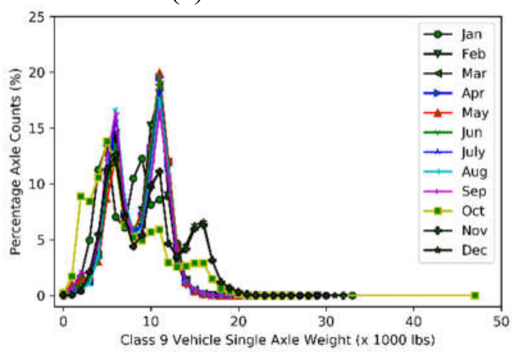
Figure 26 – Class 9 Single Axle Load in Each Lane for Site ID 051-0368.



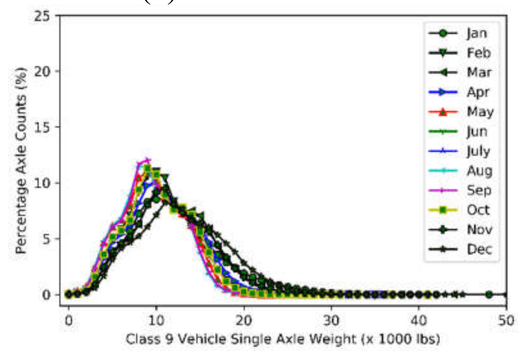
(a) Ln 1 NB Slow *



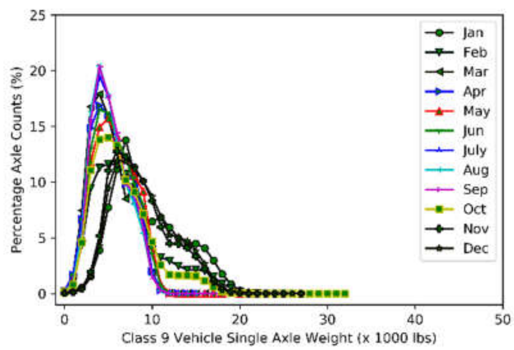
(b) Ln 1 SB Slow



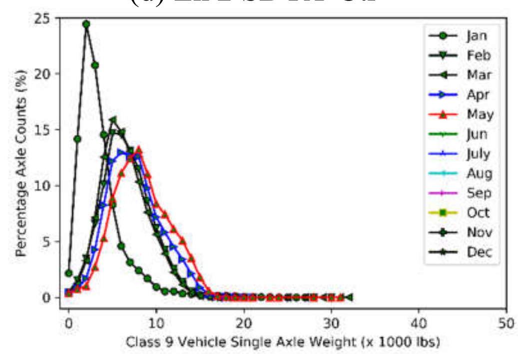
(c) Ln 2 NB RT Ctr *



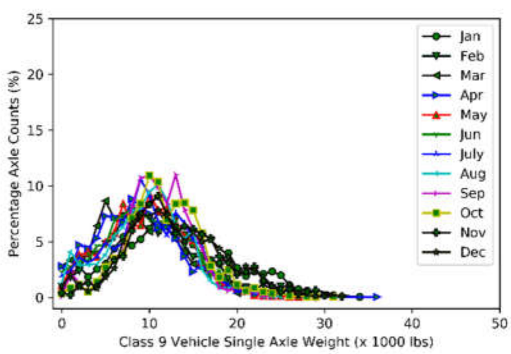
(d) Ln 2 SB RT Ctr



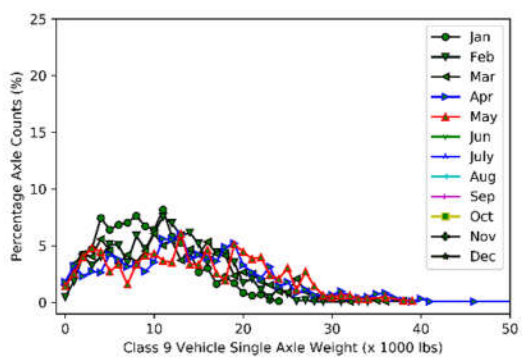
(e) Ln 3 NB LT Ctr



(f) Ln 3 SB LT Ctr

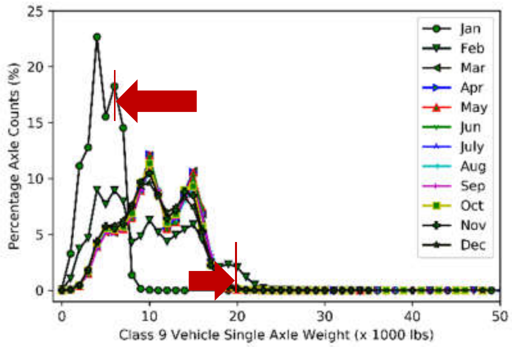


(g) Ln 4 NB Fast

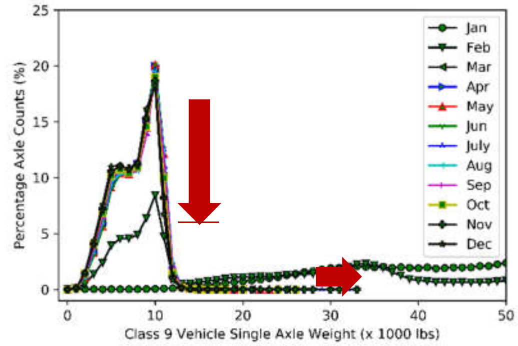


(h) Ln 4 SB Fast

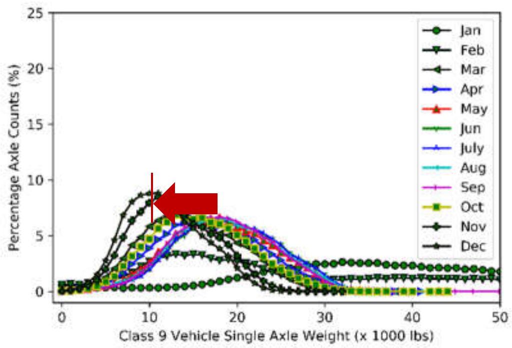
Figure 27 – Class 9 Single Axle Load in Each Lane for Site ID 127-0312.



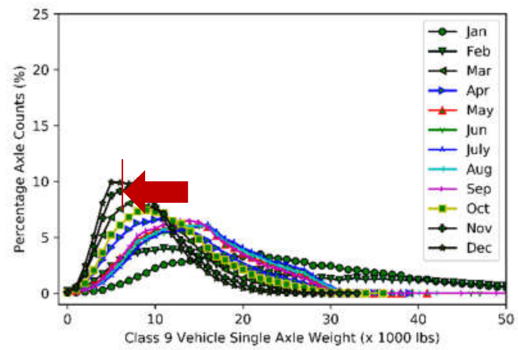
(a) Ln 1 EB Slow *



(b) Ln 1 WB Slow *

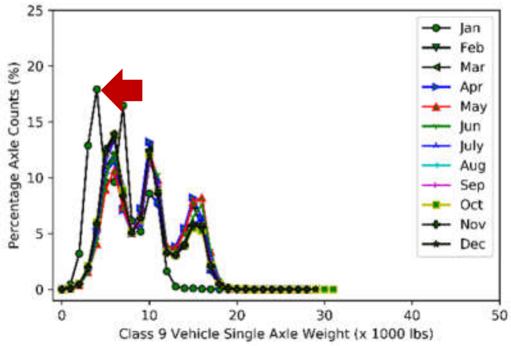


(c) Ln 2 EB Fast

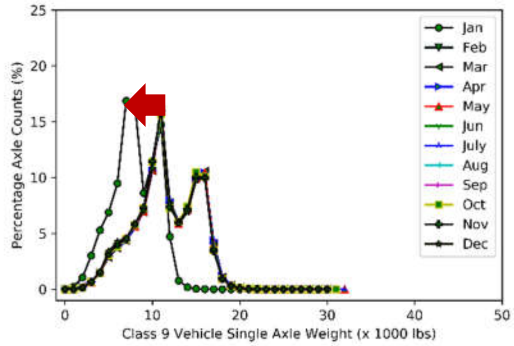


(d) Ln 2 WB Fast

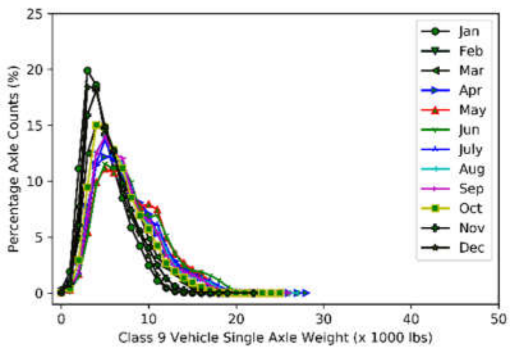
Figure 28 – Class 9 Single Axle Load in Each Lane for Site ID 143-0126.



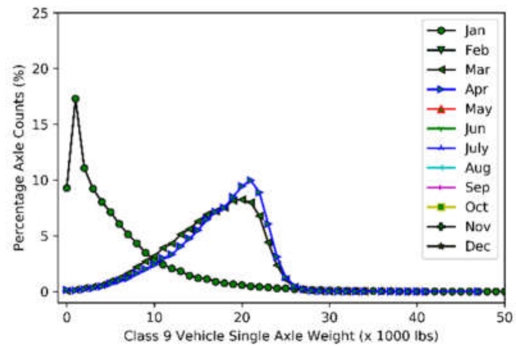
(a) Ln 1 NB Slow *



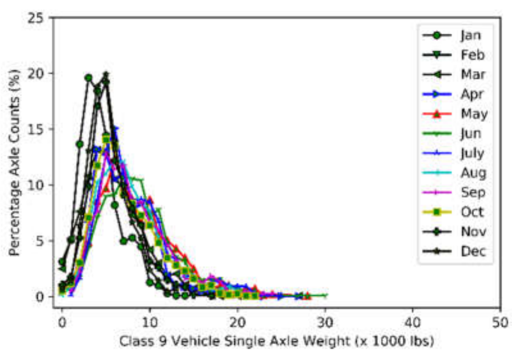
(b) Ln 1 SB Slow *



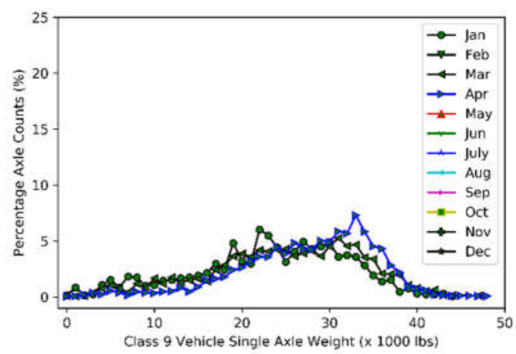
(c) Ln 2 NB Ctr



(d) Ln 2 SB Ctr

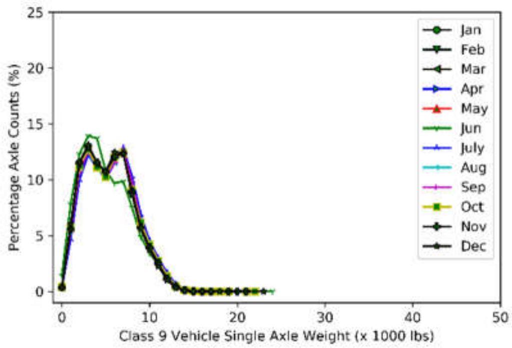


(e) Ln 3 NB Fast

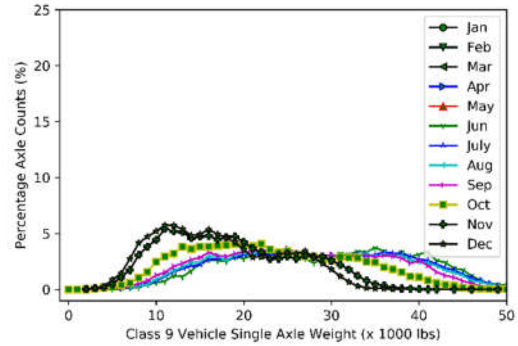


(f) Ln 3 SB Fast

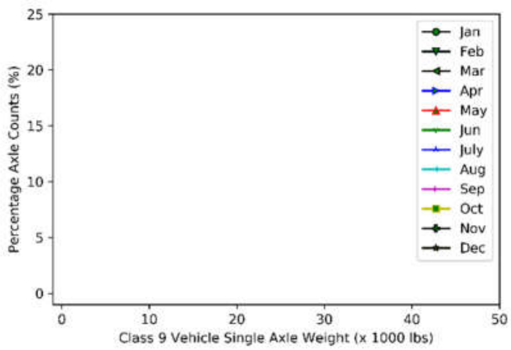
Figure 29 – Class 9 Single Axle Load in Each Lane for Site ID 185-0277.



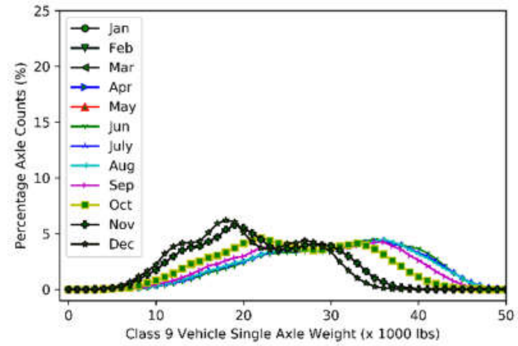
(a) Ln 1 EB Slow *



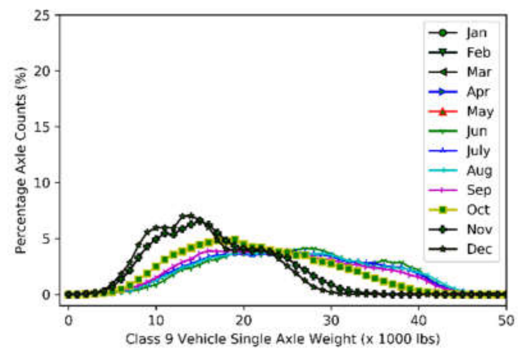
(b) Ln 1 WB Rest Area to I-20



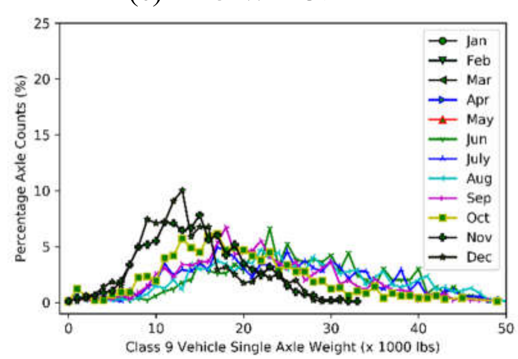
(c) Ln 2 EB Fast



(d) Ln 2 WB Slow **

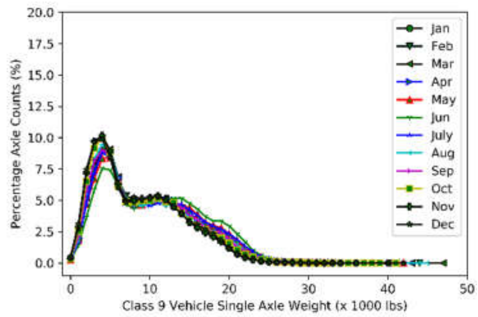


(e) Ln 3 WB Ctr **

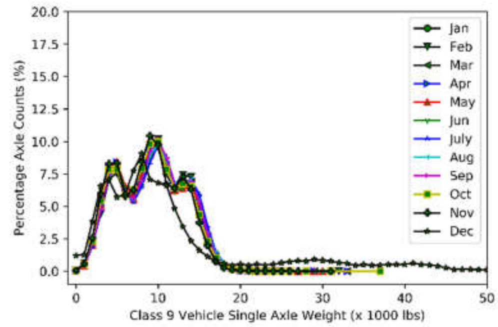


(f) Ln 4 WB Fast

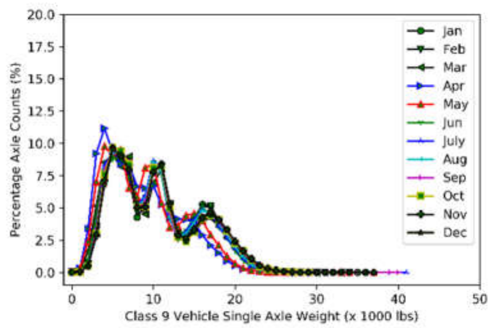
Figure 30 – Class 9 Single Axle Load in Each Lane for Site ID 245-0218.



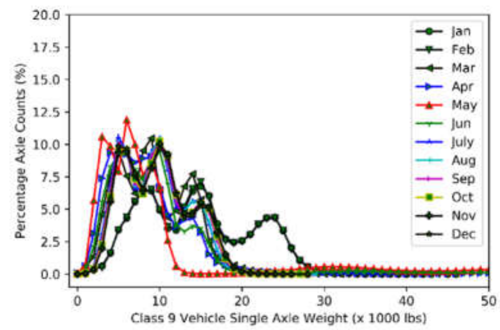
(a) NB Lanes, Site ID 021-7334



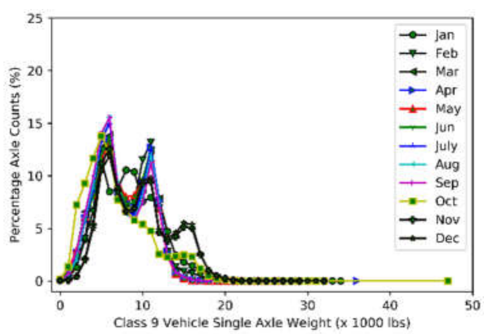
(b) SB Lanes, Site ID 021-7334



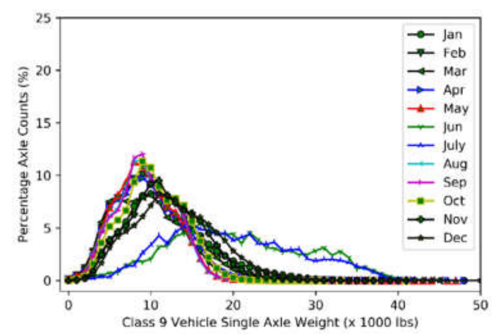
(b) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

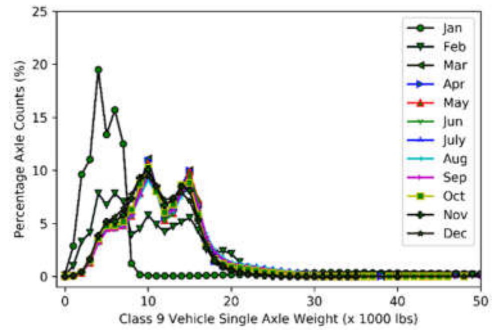


(e) NB Lanes, Site ID 127-0312

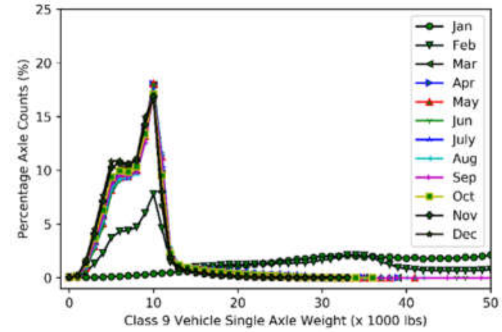


(f) SB Lanes, Site ID 127-0312

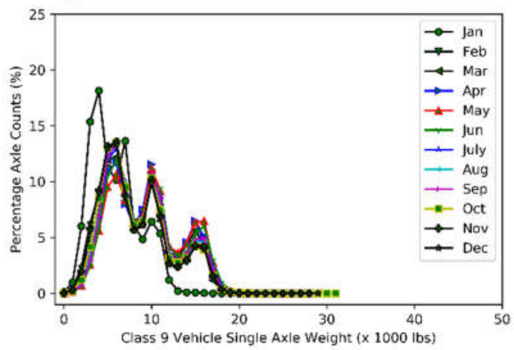
Figure 31 – Class 9 Single Axle Load by Traffic Direction.



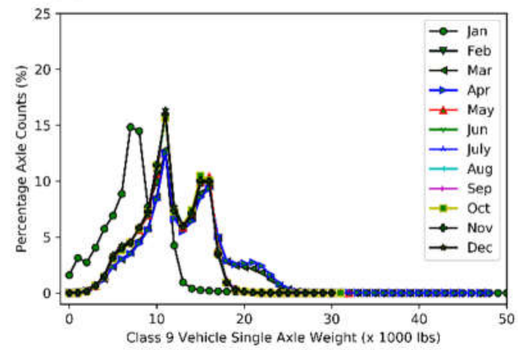
(g) EB Lanes, Site ID 143-0126



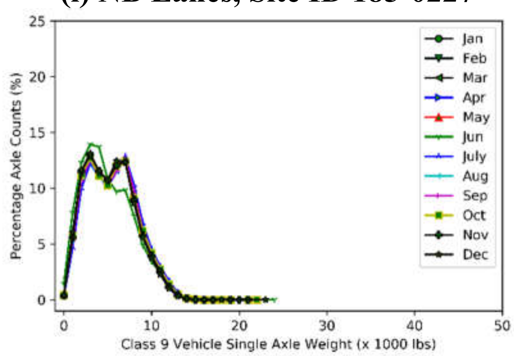
(h) WB Lanes, Site ID 143-0126



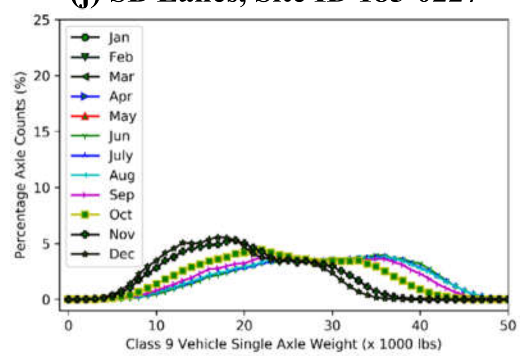
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218

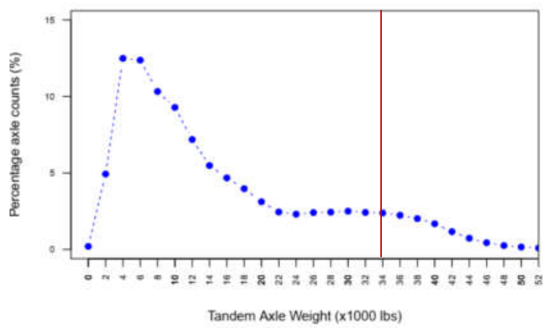


(l) WB Lanes, Site ID 245-0218

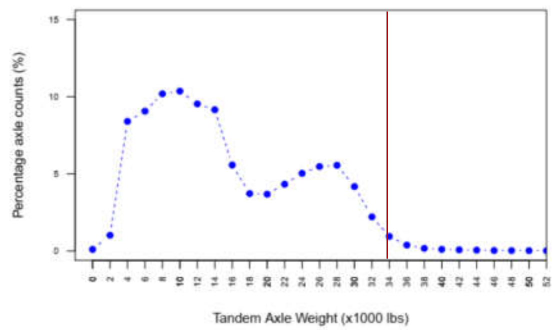
Figure 31 Continued – Class 9 Single Axle Load by Traffic Direction.

5.5.2 Class 9 Tandem Axle Load Spectrum in Each Traffic Direction

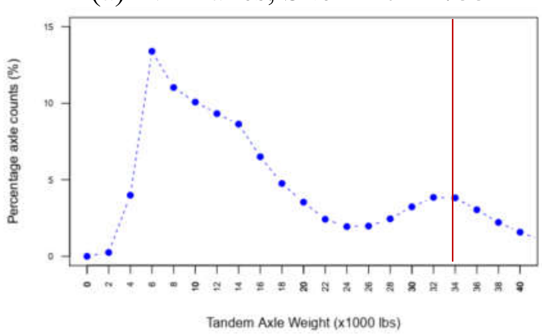
This section graphically reviews the tandem axle load spectra. These visual representations are expected to show a bi-modal distribution. The tandem axle load of a vehicle allowed to drive without a permit is 34,000 lbs. As evident in Figure 32, the tandem axle load distribution is overall bi-modal; however, the distribution is right-skewed overall at Site ID 051-0368. In addition, the NB lanes of Site ID 021-7334, the EB lanes of Site ID 051-0368, and the SB lanes of Site ID 127-0312 show higher percentages of tandem axle loads. Overall, Site ID 245-0218 in particular has a higher frequency of tandem axle loads exceeding 34,000 lbs. This tandem axle weight in the x-axis is intentionally placed on a different scale to observe the full spectra of loads, and the 34,000 lb limit is indicated with a red vertical line unless all tandem axle loads are well within 34,000 lbs.



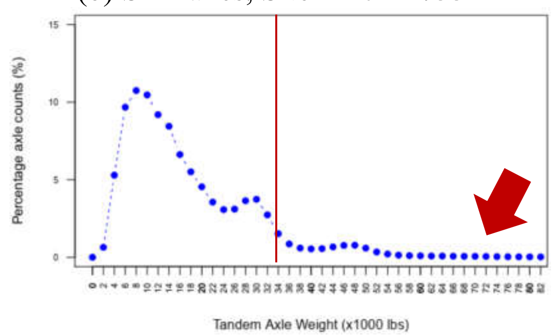
(a) NB Lanes, Site ID 021-7334



(b) SB Lanes, Site ID 021-7334

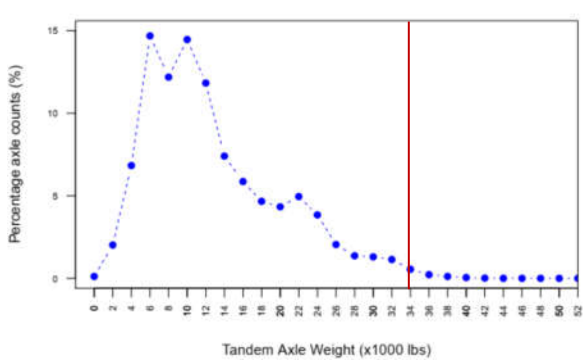


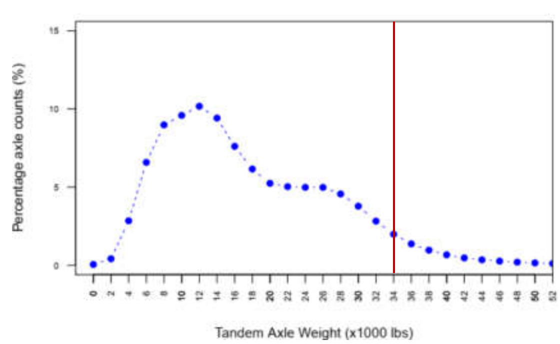
(c) EB Lanes, Site ID 051-0368



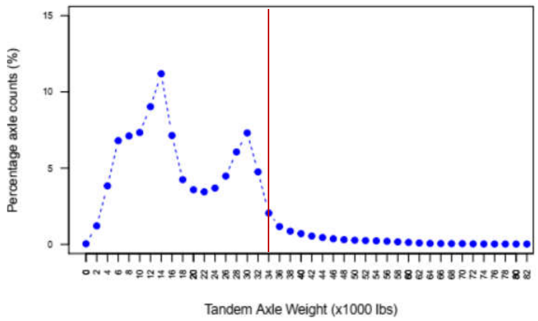
(d) WB Lanes, Site ID 051-0368

Figure 32 – Class 9 Tandem Axle Load by Traffic Direction.

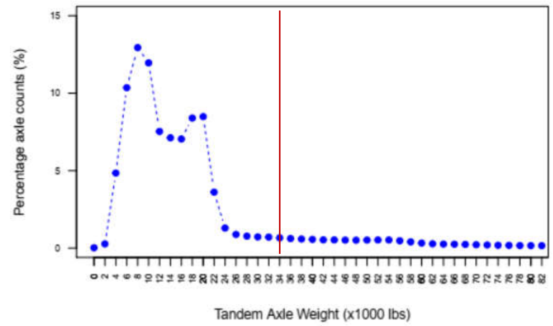




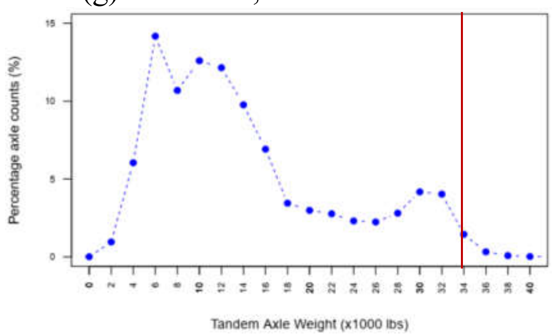
(e) NB Lanes, Site ID 127-0312



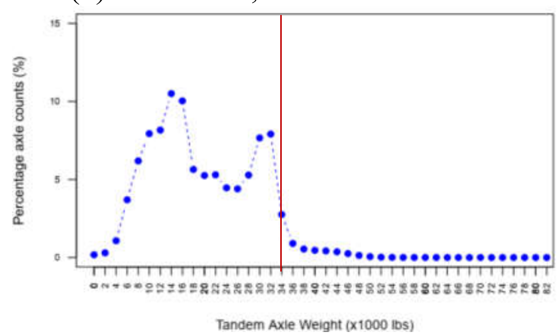
(f) SB Lanes, Site ID 127-0312



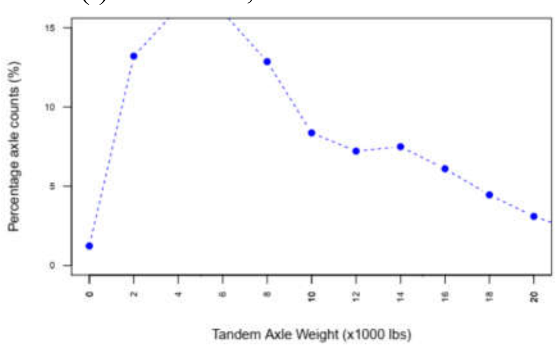
(g) EB Lanes, Site ID 143-0126



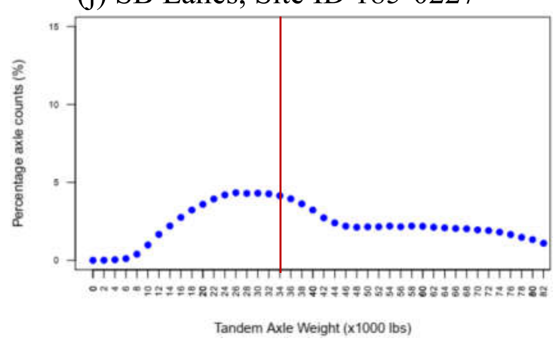
(h) WB Lanes, Site ID 143-0126



(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



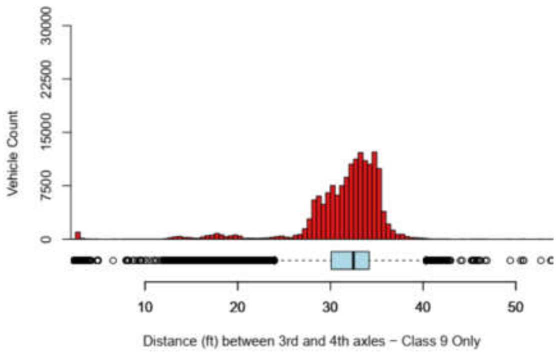
(k) EB Lanes, Site ID 245-0218

(l) WB Lanes, Site ID 245-0218

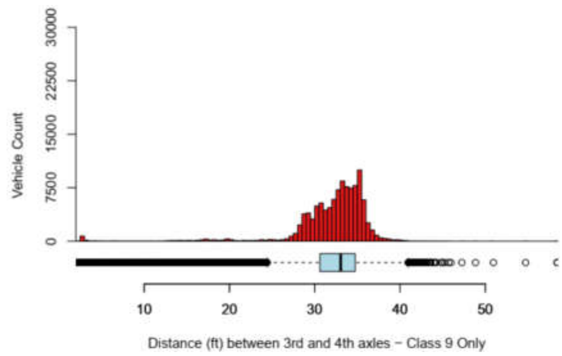
Figure 32 Continued – Class 9 Tandem Axle Load Spectrum by Traffic Direction.

5.5.3 Class 9 Axle Spacing Spread

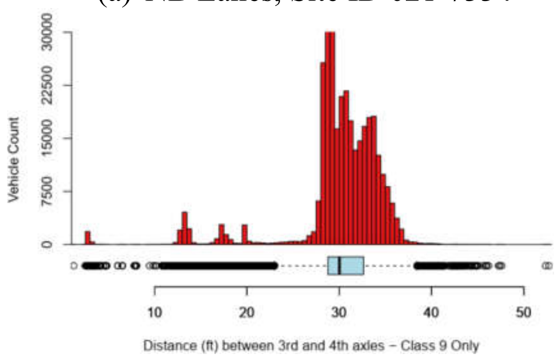
Overall, the spread in the axle-spacing data for Class 9 vehicles is higher than expected. For instance, the distance between the third and fourth axles for Class 9 vehicles is expected to range between 2 ft (61 cm) and 75 ft (2286 cm). In the box-histogram plot in Figure 33, however, spacings appear outside of this range. The scale for the y-axis is intentionally limited to 30,000 whereas as the x-axis scale changes as the distance varies among sites.



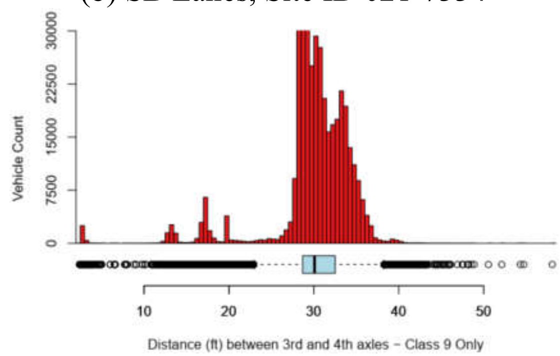
(a) NB Lanes, Site ID 021-7334



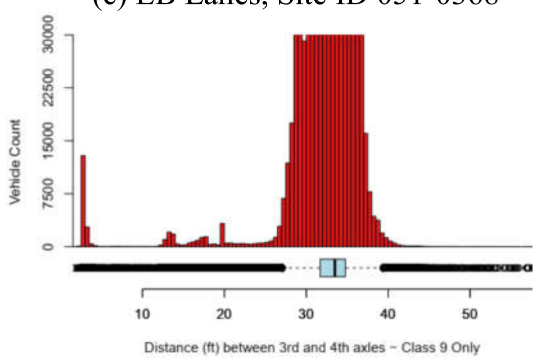
(b) SB Lanes, Site ID 021-7334



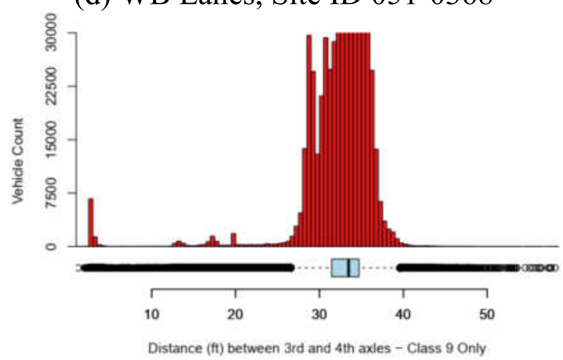
(c) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

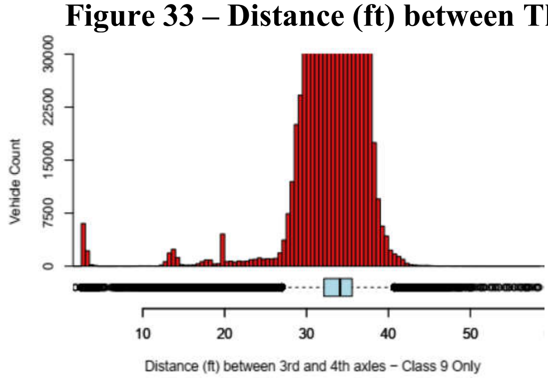


(e) NB Lanes, Site ID 127-0312

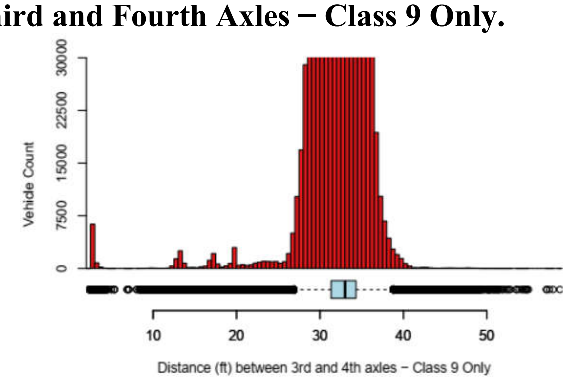


(f) SB Lanes, Site ID 127-0312

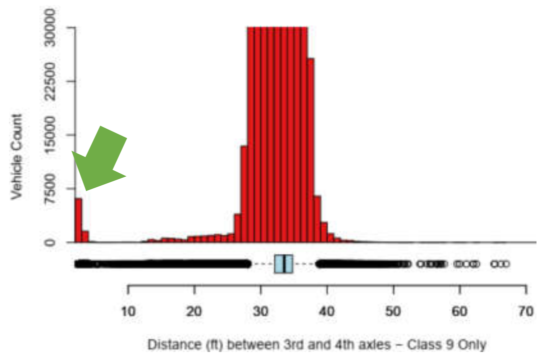
Figure 33 – Distance (ft) between Third and Fourth Axles − Class 9 Only.



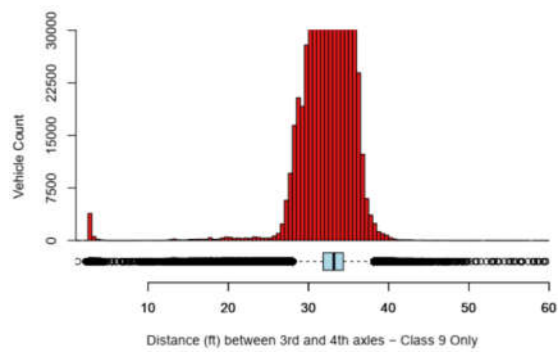
(g) EB Lanes, Site ID 143-0126



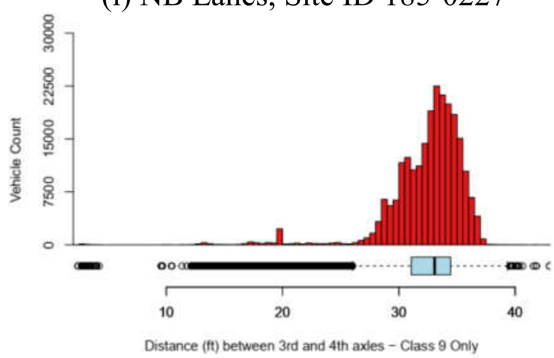
(h) WB Lanes, Site ID 143-0126



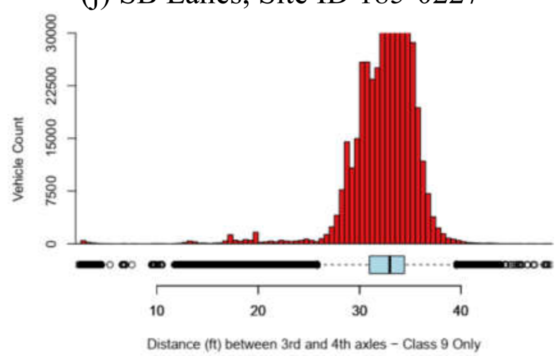
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218

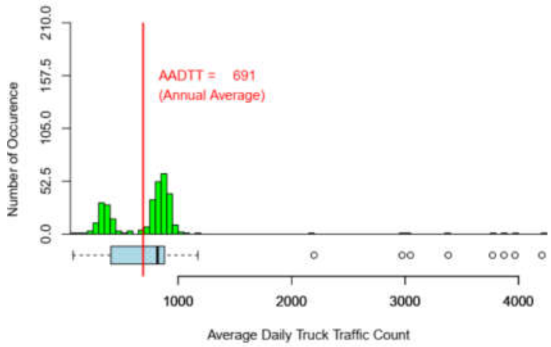


(l) WB Lanes, Site ID 245-0218

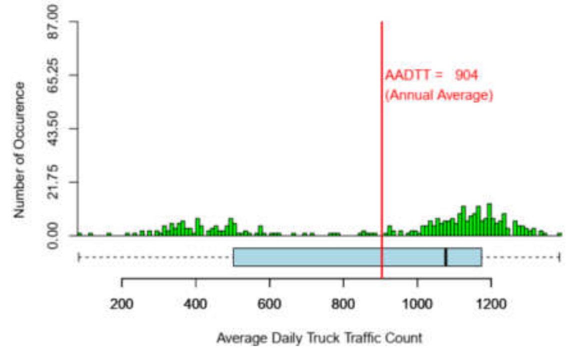
Figure 33 Continued – Distance (ft) between Third and Fourth Axles – Class 9 Only.

5.5.4 Daily Truck Traffic Spread

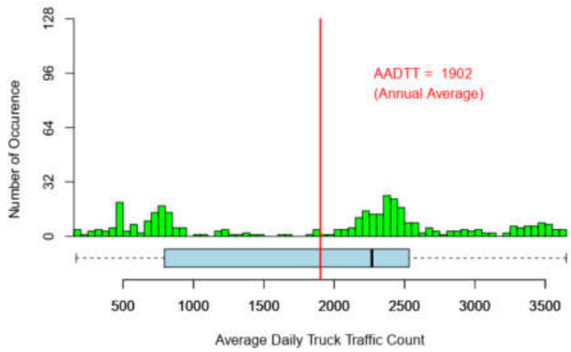
Figure 34 shows the spread in daily truck traffic distribution when the usable data is analyzed. The mean of daily truck traffic observations and the AADTT counts (i.e., the total number divided by the number of days) are significantly different. At Site ID 021-7334, the daily truck traffic spread is higher in the SB lanes than the NB lanes, which means that some NB data may have been unusable and thus removed. At Site ID 127-0312, the high frequency of low truck traffic counts in WB lanes is unusual compared to the traffic in the EB lanes and at other sites. This AADTT information captures unusual truck traffic volume and/or maintenance activities that may exist at the site.



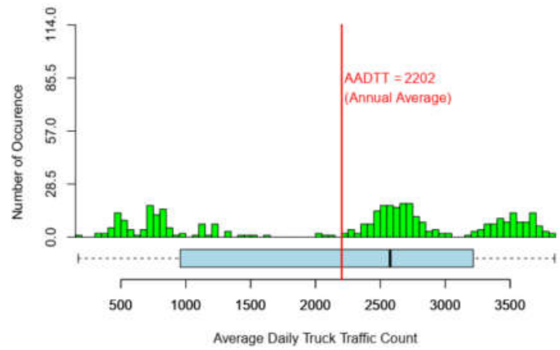
(a) NB Lanes, Site ID 021-7334



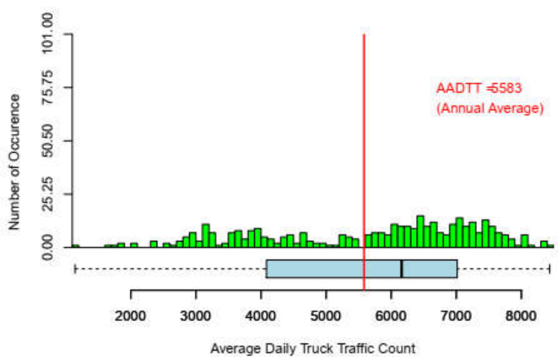
(b) SB Lanes, Site ID 021-7334



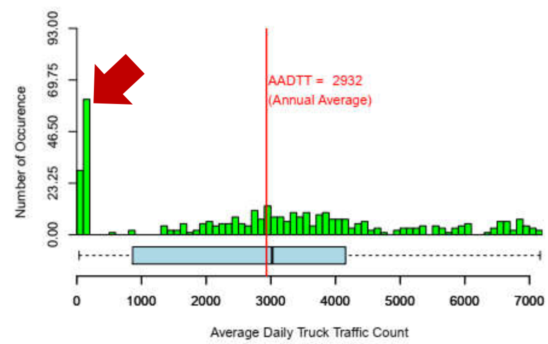
(c) EB Lanes, Site ID 051-0368



(d) WB Lanes, Site ID 051-0368

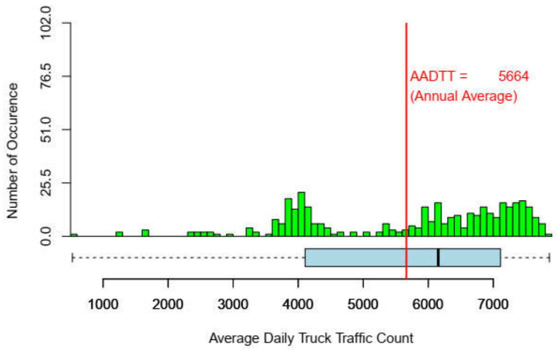


(e) NB Lanes, Site ID 127-0312

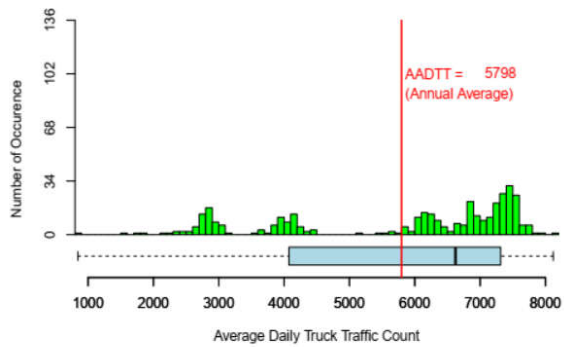


(f) SB Lanes, Site ID 127-0312

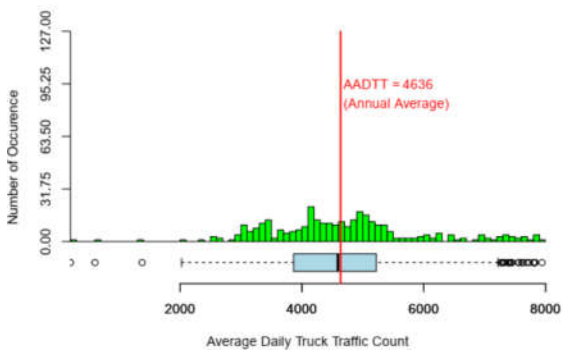
Figure 34 – Frequency of Average Daily Truck Traffic Count.



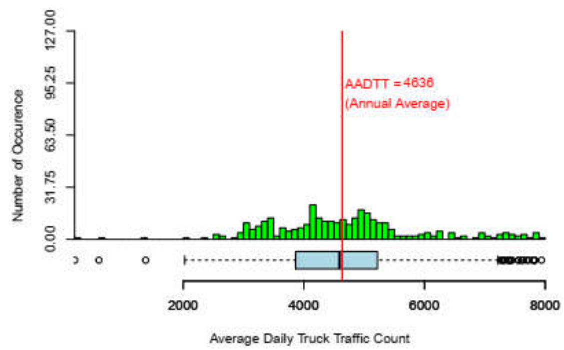
(g) EB Lanes, Site ID 143-0126



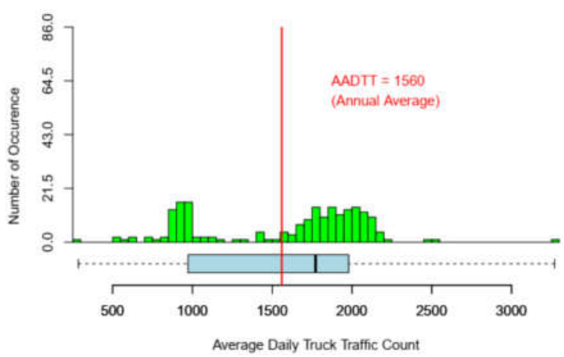
(h) WB Lanes, Site ID 143-0126



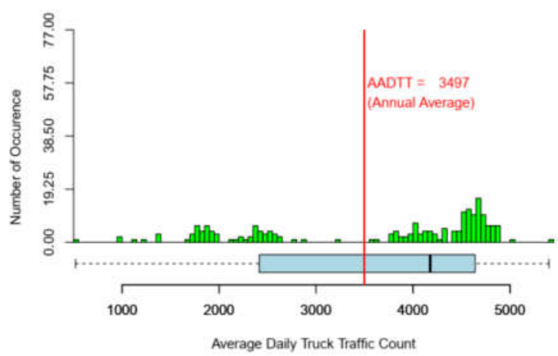
(i) NB Lanes, Site ID 185-0227



(j) SB Lanes, Site ID 185-0227



(k) EB Lanes, Site ID 245-0218



(l) WB Lanes, Site ID 245-0218

Figure 34 Continued – Frequency of Average Daily Truck Traffic Count.

5.6 Comparison of Numerical and Graphical Summaries

Table 9 (Summary of Proportions of Vehicle Classes) shows several large percentages of Class 9 vehicles in select lanes within Sites ID 143-0126, 127-0312, and 185-0227 which exceed reported TADA total counts (see Table 11) for Class 9 vehicles for all traffic lanes. Specifically, Site ID 185-0227 has 33.4% unusable weight records affecting mostly lanes

7 and 8, SB Center and SB Fast, respectively (see Figure 17); at the same time, the remaining counts of Class 9 vehicles remain high by percentage. Accordingly, data from these specific sites and respective lanes should be marked for review against data for the next two years as the study team establishes a CDS. Similarly, Sites ID 021-7334 and 245-0218 contain a significantly higher percentage of Class 15 vehicles compared to percentages for the four other sites.

Table 12 (ADT and AADT Counts by Lane) shows several lanes departing notably from the other lanes in terms of vehicle counts compared to averaged values. Specifically, the truck traffic count values for Site ID 143-0126 LN1 EB exceed the ADT count of all classes combined. The other extreme is evident at Site ID 245-0218 LN2 EB (class-only instrumentation, see Figure 11), registering no daily traffic counts in the entire data set.

5.7 Lessons Learned from Spectating FDOT's Load Cell Calibration Process

Based on observing FDOT's WIM device calibration process, the study team found that a third-party observation ensures reliable calibration factors and is beneficial for QA. Additionally, FDOT's calibration process involving three trucks with known weights/spacings and multiple vehicles passing at different speeds establishes a reasonable procedure for load cell calibration. GDOT has the same vendor as FDOT, yet at present the vendor does not require a third-party presence during the calibration process in Georgia. Another difference is that the vendor employs a single truck for Georgia. The rest of the calibration process is consistent for FDOT and GDOT.

6 LIMITATIONS

This study is limited to an off-site data check and thus is neither able to confirm precision in the axle weight and spacing parameters nor the accuracy to describe 1) the difference between a vehicle's weight measurement and its actual weight and 2) the discrepancy between the axle spacing identified by the system and its actual spacing. These two parameters must be validated by means of field calibration.

The study identifies parameters for which there are invalid and/or missing data and parameters yielding data that appears unreasonable. The later are evident in large spreads in the data, significant changes in means, data inconsistencies (e.g., monthly weight shifts), and anomalies (e.g, in the single and tandem axle load spectra).

6.1 Precision of Vehicle Weight for Varying Speed and Temperature

Due to the lack of temperature data, this study is not able to provide a complete analysis of temperature sensitivity. Based on a review of monthly weight variations at the sites with a quartz sensor, no significant monthly variation is observed.

6.2 Accuracy of Vehicle Weight

Although the quartz sensors should be able to capture dynamic weight at a speed over 80 mph, it is not feasible to calibrate the load sensors above this speed. Additionally, this calibration is beyond the scope of the ASTM 1318-09 (2017) standard. Therefore, confirming the validity of weight data for vehicles exceeding 80 mph is not possible. Further, while the six sites studied herein were considered because they had quartz sensors installed when this study began in 2018, some of their lanes still use BL sensors, which the vendor maintains for obtaining class-only information. An analysis excluding weight from the sensors' data may be considered in the Phase-II study although the amount of usable data is expected to decrease significantly.

6.3 Precision and Accuracy of Axle Spacing

Precise axle-spacing measurements must be in a calibration log, and the accuracy of these measurements should be validated as part of the WIM device calibration process using trucks of known axle spacings. The study team plans to employ an image-processing tool in the subsequent study to capture axle spacings in images and support this effort.

6.4 Accuracy of Vehicle Classification

The accuracy of vehicle classification should depend on the combination of factors presented in Sections 6.1 through 6.3 (Hallenbeck et al., 2014). Current WIM system classification, however, appears to mainly depend on the number of axles and axle spacings. Because the vendor uses the Hi-TRAC EMU3 data logger, vehicle classification should be subject to the number of axles and spacings shown in Table 14(a). Yet, as Moses (2019) indicated, the decision-making process in the classifier available through the data logger is complex. Therefore, a clear classification process for Georgia needs to be mapped, provided any difference from the default setting in the data logger exists, before the accuracy provided by the classifier can be evaluated. The discrepancy between the default and Georgia's classification shown in Tables 14(a) and 14(b) must be reviewed in conjunction with the FHWA's vehicle classification rules shown in Table 13 and the LTPP program's classification rules (Selezneva et al., 2016) shown in Table 15. The study team finds the underlying rational for the current classification selected by the vendor unclear or at least not clearly documented. For Class 9 vehicles, for instance, the third axle spacing should range between 2.5 ft and 65 ft (i.e., 76.2 cm and 1981.2 cm) per Table 15, yet it ranges between 2 ft and 75 ft (i.e., 61 cm and 2286 cm) per Table 14(b). This shows how the current vehicle classification is contentious because it is unclear which axle spacings yield more accurate classification and thus should be used.

Table 15 – FHWA LTPP (Selezneva et al., 2016) Vehicle Classification Showing Selected Classes.

Class	Vehicle Type	No. of Axles	Spacing Between Axles 1 and 2 (ft)	Spacing Between Axles 2 and 3 (ft)	Spacing Between Axles 3 and 4 (ft)	Spacing Between Axles 4 and 5 (ft)	Spacing Between Axles 5 and 6 (ft)	Spacing Between Axles 6 and 7 (ft)	Spacing Between Axles 7 and 8 (ft)	Spacing Between Axles 8 and 9 (ft)	Gross Weight Min-Max (Kips)	Axle 1 Weight Min (Kips)[1]
9	Semi, 3S2	5	6.00-30.00	2.50-6.29	6.30-65.00	2.50-11.99	----	----	----	----	20.00 >	5.0
9	Truck+Full Trailer (3-2)		6.00-30.00	2.50-6.29	6.30-50.00	12.00-27.00	----	----	----	----	20.00>	3.5
9	Semi, 2S3		6.00-30.00	16.00-45.00	2.50-6.30	2.50-6.30	----	----	----	----	20.00 >	3.5
11	Semi+Full Trailer, 2S12		6.00-30.00	11.00-26.00	6.00-20.00	11.00-26.00	----	----	----	----	20.00 >	3.5
10	Semi, 3S3	6	6.00-26.00	2.50-6.30	6.10-50.00	2.50-11.99	2.50-10.99	----	----	----	20.00 >	5.0
12	Semi+Full Trailer, 3S12		6.00-26.00	2.50-6.30	11.00-26.00	6.00-24.00	11.00-26.00	----	----	----	20.00 >	5.0
13	7-Axle Multi-trailers	7	6.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	----	----	20.00 >	5.0
13	8-Axle Multi-trailers	8	6.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	----	20.00 >	5.0
13	9-Axle Multi-trailer	9	6.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	3.00-45.00	20.00 >	5.0

6.5 No Comparison Data Set Available

Since this study involves an initial analysis of 2018 WIM data, a CDS for a year period is not available. Further, the study team does not know when the quartz sensors were (or will be) calibrated, which means the team could not identify a reliable month-long data set for comparison. Both month-long and year-long CDSs are needed for a comparative analysis to understand the weight and class distributions at each site. This procedure is consistent with practices employed by other DOTs.

6.6 Lanes Instrumented for Reviewing Class-Only Information

The weight data from the lanes instrumented with BL sensors are not considered accurate by the vendor. This assertion appears to be true based on the findings presented in Section 5.5.1. Accordingly, due to the limited number of lanes instrumented to provide weight data, the available data do not capture the full spectra of axle weights for the six WIM sites studied herein.

7 CONCLUSIONS

Through this Phase-I study, the research team had the first chance to request and process raw 2018 WIM data provided by Drakewell Limited. The prime contractor, Southern Traffic Services, Inc., subcontracts the data hosting service to Drakewell and is responsible for installing and maintaining WIM equipment and ultimately collecting and providing the data to GDOT. The study team employed a visualization technique using R and Python scripts to review the results from analyzing the 2018 WIM data of six sites with newly replaced/installed quartz sensors and found that three of the six sites exceed the 25% limit of missing/invalid weight data records. This marked inconsistency in the data significantly affects the quality of usable data. From the vendor, the study team learned that the missing weight data is attributed to the use of BL sensors in select lanes and lanes instrumented to obtain class-only information. Although BL sensors are able to measure weights, the vendor only uses the data from lanes with these sensors to collect axle-spacing information (i.e., for classification only).

The other key factor affecting the quality of weight data is passing speed exceeding 80 mph. Of the six WIM sites, three sites have approximately 75% usable raw data, primarily based on valid axle-spacing and weight parameters. Of the remaining 75% of the raw data, only about 80–95% is valid when excluding vehicles exceeding a speed of 80 mph. This leaves between 60% and 70% of the raw data usable and valid for a vehicle weight analysis. At Site ID 051-0368, for example, 99.8% usable data is observed with fewer than 3.8% of the entries exceeding 80 mph. Yet, in reviewing Class 9 single axle load spectrum at the site, significant weight shifts are observed in the months of January, February, and May (see Section 5.5.1). Such shifts suggest the importance of reviewing and analyzing both numerical and graphical summaries. The Class 9 single axle load frequency and spectrum is relatively more consistent for Site ID 021-7334 (see Section 5.5.1) than for the other sites, and Table 16 shows that Site ID 051-0368 generates an acceptable level (>95%) of valid vehicle data, but the site's quartz sensors require calibration.

Table 16 – Findings and Recommendations from QC Checks.

% Usable and Valid Data \ Site ID	**021-7334**	**051-0368**	**127-0312**	**143-0126**	**185-0227**	**245-0218**
a. % of Raw Data Considered Usable (Raw data that do not have missing weight)	99.3%	99.8%	74.4%	99.8%	66.6%	74.4%
b. Meet the Recommended Threshold for Providing Weight Information (≥ 97% of the raw data)	Yes	Yes	No[(a)]	Yes	No[(a)]	No[(a)]
c. % of the Usable Data Considered Feasible (Usable data with speed ≤ 80 mph)	92.6%	96.2%	96.2%	81.7%	80.6%	97.4%
d. % of the Raw Data Considered Usable and Valid for a Weight Analysis (e.g., MEPDG traffic input and bridge load rating) = a × c	92.0%	96.0%	71.6%	81.5%	53.7%	72.5%
e. Meet the Recommended Threshold for Providing Valid Weight Information (≥ 95% of the raw data)	**No[(b)]**	**Yes**	**No[(b)]**	**No[(b)]**	**No[(b)]**	**No[(b)]**
f. % Quartz Sensor Instrumented (Number of lanes instrumented with a quartz sensor/Total number of lanes)	100%NB 100%SB	100%EB 100%WB	50%NB 0%SB	50%EB 50%WB	33% NB 33% SB	33%NB 0%SB
g. Need a (Quartz) Load Cell Calibration based on Reviewing Monthly Class 9 Single Axle Weight and GVW Distribution	No[(c)]	Yes - all lanes	Yes - NB lanes only	Yes - all lanes. GVW is relatively high.	Yes - all lanes. GVW is relatively high.	Yes - WB lanes only

Notes:
(a) Some lanes do not provide valid weight information due to BL sensors employed or sensors not instrumented to provide weight.
(b) The site % of the Raw Data Considered Usable and Valid for a Weight Analysis is less than 95%, which means more than 5% of vehicle data from the WIM site may not be useful, mainly because some lanes are not instrumented or have a BL sensor, and vehicle passing speeds exceed 80 mph.
(c) Need a load cell calibration for lanes indicated. During the calibration, the accuracy of axle spacings must be documented within the limits of a classifier available in the equipment. The device sensitivity and tolerance in axle weight and spacing measurements must be documented (FHWA, 2018b).

In addition to the need for weight calibration, the default axle-spacing criteria (see Table 14(a)) in the data logger system (EMU3) are not consistent with the "Class" assigned in the data. In the data, vehicles with four axles are classified as Class 6, but they should have three axles based on their FHWA classification (see Table 13). In addition, based on the review of axle spacing (cm) in Section 5.4.2, the axle-spacing data and criteria used by the vendor (see Table 14(b)) appear to be slightly different, particularly for vehicle Classes 9 and 11 with five axles. Section 6.6 discusses this inconsistency in detail.

The following major conclusions are drawn from this study:

- The zero weight entries mainly result from lanes instrumented with BL sensors as well as lanes instrumented for obtaining class-only information.
- Less than 1% of the data are unclassified (i.e., Class 15) vehicles.
- No significant month-to-month variations that appear to be associated with temperature are observed.
- The definition of vehicle classification criteria does not appear consistent with the number of axles and axle spacings observed in the data.
- More than 3% of the WIM data comes from vehicles driving over 80 mph. The corresponding weight data should not be considered valid if the vehicle speed exceeds 80 mph. This is consistent with the ASTM E1318-09 (2017) standard.
- Monthly weight shifts in quartz sensors are observed. The validity of such shifts should be verified by establishing a CDS for each site.
- A significant number of vehicles (see Table 10) are considered overweight and oversized, and this number was greater than anticipated. Such a high number is mainly attributed to BL sensors skewing vehicle weights to the right on the heavier side within the axle load spectra. Significantly lower weights appear attributed to noises.

- The ASTM E1318-09 (2017) standard states that a Type I WIM system should produce **all data** for each vehicle processed, including: Wheel Load, Axle Load, Axle-Group Load, Gross-Vehicle Weight, Speed, Center-to-Center Spacing Between Axles, Vehicle Class (via axle arrangement), Site Identification Code, Lane and Direction of Travel, Date and Time of Passage, Sequential Vehicle Record Number, Wheelbase (front-most to rear-most axle), Equivalent Single-Axle Loads, and Violation Code. However, the following weight parameters are missing due to the use of BL sensors or class-only instrumentation as indicated in Item f of Table 16: Wheel Load, Axle Load, Axle-Group Load, Gross-Vehicle Weight, and Equivalent Single-Axle Loads.

8 FUTURE STUDY AND RECOMMENDATIONS

8.1 Recommended WIM Data Quality Requirements

As much as the data owner and users care about WIM data and its quality (specifically weight and spacing data), the contractors care even more about delivering quality data. Therefore, the following WIM data quality requirements are recommended for OTD:

- An annual off-site office data QC check is recommended. OTD is supporting this effort by funding a subsequent study at the University of Georgia.
- When an annual QC check is conducted, each WIM site must deliver more than 97% of usable data, unless otherwise documented (e.g., severe weather and unanticipated conditions) and/or approved by OTD. To achieve this, the vendor will have to replace all BL sensors with Kistler's quartz sensors or an equivalent. Upon installation, WIM sensors must be calibrated for weight and axle spacings.
- The vendor has indicated that some lanes are designated for class-only information, yet the site sketches provided by the vendor show a load cell in each lane. To capture a full spectrum of vehicle weights on a route, it is strongly recommended that WIM sensors be installed in all of these lanes, particularly if a site is designated as a WIM site. For sites that aim to obtain class-only information from select lanes, this objective needs to be documented.
- Vehicle classification is generally determined based on the number and spacing of axles by means of a vehicle classifier available through a data logger. Classification via data collection may be useful when GDOT desires to capture and monitor specific vehicles that are important to the state. However, when a traffic lane is also instrumented with a WIM scale, it is possible to use the weight of the first axle or the GVW in conjunction

with axle-spacing data to better classify a passing vehicle (see Table 15) and thus validate vehicle classes. The same vehicle can be classified very differently by two different pieces of equipment depending on whether the device supports vehicle classification only based on the axle number and spacing or the system uses WIM scales in conjunction with axle information to classify vehicles (see discussion in Section 6.4). Therefore, the availability of axle weight in all lanes will result in a more accurate and comprehensive vehicle classification system.

- The vehicle classification criteria vary. The data logger default classifier (see Table 14(a)) differs from the vehicle spacing criteria used by the vendor (see Table 14(b)). As well, the FHWA classification (see Table 13) slightly differs from the classification scheme employed by the vendor (see Table 14(b)). Lastly, the FHWA LTPP (Selezneva et al., 2016) criteria (Table 15) differ from the three aforementioned classification schemes (see Table 13, Table 14(a), and Table 14(b)). These inconsistencies should be further investigated.
- The number of days in the usable data within a year other than 365 (see Table 7) must be explained in a maintenance log. This maintenance log should be made available to the party conducting off-site QC checks.
- The vendor should conduct and document WIM system calibration periodically. Specific recommendations are reviewed in the following section.
- After the calibration of each WIM site, a month-long comparison data set (CDS) for the following month should be established.

- Using the CDS, monthly weight shifts in Class 9 single axle load spectra should be monitored. If a significant (>5%) shift in weight is observed, a re-calibration should be warranted within three months, allowing time for planning and scheduling.
- A year-long CDS should be established and reviewed to allow exceptions to the 5% weight shift threshold. Some sites may actually be subject to a monthly weight shift. Over time, such trends should become apparent by continuously analyzing multi-year WIM data.

8.2 Recommendations for WIM Data Managers

The subsequent (Phase-II) study aims to review the WIM data QC summary for years 2019–2021 and synthesize findings. Meanwhile, it is recommended that GDOT communicates Section 8.3 with its WIM data collection vendor. The following recommendations are made based on findings from this initial study:

8.2.1 Third-party Observation of WIM System Calibration

Periodical calibrations of the WIM system at more than 30 sites may not be sustainable. Some states require a calibration as often as every six months. A more realistic process may involve a performance-based approach. That is, if a WIM system performs well after calibration, calibration factors (e.g., impact factor) in the system will not need to be changed. This way, it is in the best interest of the WIM vendor to maintain the system adequately. Additionally, when a calibration is performed, it has to be reliably conducted by the vendor and thus confirmed by a third party to increase the reliability as well as the accountability of the calibration process. A similar process is already used by FDOT and the WIM vendor. GDOT stands to benefit from following this procedure, as well.

- Third-party observation/validation of a WIM system calibration at three different vehicle speeds for three to five randomly selected sites each year is recommended. This is a more realistic approach than conducting a calibration at all sites annually. OTD may select the sites based on a review of an annual QC report. This QA measure is recommended in addition to performance-based calibrations. The use of three Class 9 trucks with a wide range of axle weights and spacings is strongly recommended for this annual procedure. Currently, the vendor uses a single truck with a GVW of 76,500 lbs.

8.2.2 Speed Limit Enforcement to Enhance Weight Data

WIM sensors are generally calibrated for vehicle speed up to 80 mph. In addition, the legal speed limit is another constraint at each site. Therefore, the validity of axle weights for vehicles driving over 80 mph is contentious.

- GDOT should consider installing a speed detection device to monitor vehicle speed or investigate other means of enforcing the legal speed limit near WIM locations. Although quartz sensors can detect weights from high speed vehicles, weight measurements from sensors that have not been calibrated for such speeds should not be considered valid.

8.2.3 Replacement of BL Sensors and Class-Only Data Collection

It is recommended that GDOT encourages the vendor to replace BL sensors with quartz sensors as soon as possible. Based on the results of this study, the weight data from the BL sensors do not appear reasonable. The vendor is aware of this outcome and thus has already begun replacing them. Currently, lanes instrumented with a BL sensor are considered class-only-instrumentation lanes by the vendor. There are two different types of vehicle classifiers: one that uses the number of axles and axle spacings to classify vehicles and the other that more accurately classifies vehicles using weight information obtained from a WIM scale in conjunction with the axle number and spacing information. The vendor mainly uses the former although the classification scheme (see Table 14(b)) indicates its classifier is able to recognize both. Two potential consequences arise from the existing site setup which features a significant number of lanes with class-only instrumentation (see Item e in Table 16):

(1) GDOT is not able to obtain the full axle load spectra on the routes where WIM devices have been installed.

(2) WIM sensor instrumentation should give more accurate vehicle classification and/or provide an opportunity to validate vehicle classes by recording the weight of the first axle and GVW.

If not deemed practical to install WIM sensors in all lanes at all WIM sites, specific goals and reasons why GDOT collects class-only information for specific sites should be documented.

8.2.4 Communication with the Department of Public Safety

If possible, the number of permits issued for overweight vehicles should be obtained from the Department of Public Safety (DPS). This information will enable the study team and OTD to understand the percentage of overweight vehicles that are legally allowed to drive on the routes along which WIM device have been installed. Analyzing the number of permitted overweight vehicles from DPS in light of the WIM data can help determine those that are legally overweight, illegally overweight, or falsely reported as overweight due to possible errors in the system. This task has been proposed as part of the subsequent study. In turn, damage to Georgia’s bridges and roads from illegal overweight trucks may also be estimated and/or used to justify the cost of increased weight/speed enforcement, WIM installation, or transportation asset maintenance.

8.3 Recommendations for WIM Data Collection Vendor

The study team recommends that the WIM vendor review the following items and address each item below:

- Vehicle Entries with Zero (or Invalid) Weight – Entries with no (or invalid) weight are not acceptable under any circumstances. If such entries come from BL sensors, consider replacing these sensors with quartz sensors as soon as possible.
- No Temperature Data Available – The temperature data, if available, can be used to evaluate the temperature sensitivity, if any, of weight measurements. While quartz sensors are generally insensitive to temperature variations, seasonal variations in temperature, if any, will be captured by a temperature probe installed at the site.
- Entries with Missing Vehicle Class – While the reason for a Class 15 (i.e., unclassified vehicles) designation may be acceptable (<2%), the reason for a missing class field must be explained.
- Entries with Missing Headway (or Gap) – This information is needed to quantify traffic density, specifically side-by-side and following probabilities. If the distance between two vehicles is calculated to be less than the length of the first truck, the vehicles are considered to be side-by-side. For example, this side-by-side probability is recorded and can be compared to the 6.7% threshold (Nowak, 1999). If the distance between two vehicles is less than 100 feet, then a following probability is recorded and compared to the 2.0% threshold (Nowak, 1999). Theses thresholds were used as design/anslysis basis for bridges.

- Entries with Missing Speed – Speed information is critical to evaluate the validity of the weight measurement. Since WIM sensors are not calibrated beyond the speed limit of 80 mph, speed values may be used to explain the dynamic vehicle load well above the legal weight limit.
- Transparency in Load Sensor Types and Data Logger/WIM Classifier Decision-Making Process – Axle spacing and the decision-making tree in the current classifier must be clearly communicated by the vendor to a party conducting a data QC check so that the party can look for consistency. Currently, the study team has been provided with the axle-spacing criteria used by the vendor (see Table 14(b)). Load sensor types and models—such as Roadtrax's piezo-polymer BL sensors and Kistler's piezoelectric quartz sensors—offer important information regarding weight accuracy, acceptable vehicle speed, and temperature sensitivity. The vendor indicated using the Hi-TRAC EMU3 as the main data logger in Georgia. According to the manufacturer's data sheet, this device provides interfaces to piezoelectric sensors and a road-installed temperature probe and offers a vehicle classifier (Table 14(a)), which uses different axle-spacing criteria from the FHWA (see Table 13) and FHWA LTPP classification schemes (see Table 15). The decision-making process in the vehicle classifier, if different from the default setting, must be described, and underlying rationales for the current vehicle classification criteria selected by the vendor must be documented.
- Transparency in Maintenance Logs – Well-documented maintenance logs will explain reasons for downtime, if any, as well as invalid data and/or shifts in the weight and spacing data, if present. When publicly available or within GDOT, these logs can

inform potential users of the WIM data of any limitations and/or challenges the vendor faces in maintaining the WIM devices.

- Transparency in Calibration Reports – Once a WIM site is calibrated for axle spacings and weights, the data generated immediately after the calibration can be used as a CDS for monitoring significant shifts in axle weights and spacings and, in turn, for identifying the need for re-calibration. Date of calibration, equipment sensitivity, and calibration tolerance on both axle spacings and weights must be clearly stated in a calibration report. FHWA (2018b) provides sample calibration, inspection, and maintenance forms.

8.4 Recommendations for Transportation Asset Managers

WIM locations are generally identified based on a traffic study and the need for asset (e.g., pavement and bridge) management. At the same time, the installation of a WIM device is limited by traffic logistics as well as pavement conditions. If additional WIM locations are deemed necessary, particularly at a site with asphalt pavement and bridges near a logging industry, site locations must be discussed with the WIM vendor and prepared by GDOT for the vendor. This allows the vendor to sustain a WIM device for more than two to three years at the proposed location. The vendor is compensated according to the data generated per site and thus is responsible for suitably maintaining each WIM device. Adding a WIM site is a relatively easy task; however, pavement and/or site traffic conditions (e.g., too frequent vehicle stopping) often prevent installation as the return on investment under these conditions is negative and no reasonable contractor would take on such work.

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APPENDIX A – LIST OF ELECTRONIC SUBMITTALS

A.1 Six PDF files produced for six WIM sites, respectively.

A.2 ZIP files including R and Python script files used to produce the PDF files.

APPENDIX B – Draft Weigh-In-Motion (WIM) Data Quality Control Guide