Implementation and Evaluation of a Low-Cost Weigh-In-Motion System

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Building a WIM system around polymer piezoelectric film sensors, called BL sensors, costs only a fraction of the traditional WIM system built around crystalline-quartz piezoelectric sensors called Lineas sensors. However, BL sensors are highly sensitive to temperature, which limits the accuracy of weight measurements. The objective of this research was to investigate the performance of BL sensors head-to-head with Lineas sensors by installing a BL WIM system and collecting data from the same highway.

After the test site installation, pavement temperatures were recoded as part of each vehicle record from both Lineas and BL sensor-based WIM stations. The analysis of data collected over 10 months showed that temperature dependency of BL sensors can be removed in terms of average but not variance. More specifically, the average of axle weights after temperature-based calibration was about the same for both BL and Lineas sensors, but the variance was much higher for BL sensors.

In conclusion, if BL sensors are used, pavement temperatures must be recorded as part of vehicle records. Then, the weights calibrated based temperature would be as accurate as Lineas sensors in terms of the average but not variance.</td></tr>
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Weigh-in-Motion (WIM) systems provide detailed traffic information that includes traffic volume, speed of each vehicle, axle spacing, individual axle and gross vehicle weights, vehicle classification, Equivalent Single Axle Load (ESAL), estimated freight load data, and more. Recently, WIM systems began to integrate digital pictures of vehicles as part of the data, providing visual information on the vehicle, which would lead to even more usages and applications. Such detailed traffic information would provide benefits for making better decisions on transportation systems, but one caveat is that the cost of installation and maintenance of a WIM system is very high. Therefore, the Minnesota Department of Transportation (MnDOT) has been looking into ways to reduce the overall WIM cost, and this research project is one of those efforts.

This project consists of two parts. The first part is the development of a low-cost WIM system in which the cost is reduced as much as possible with minimal loss of data quality. The second part is evaluation of the low-cost WIM system by installing one on a highway and then comparing the collected data with another type of WIM system.

In building a low-cost system, the cost savings were done in three areas. First, low-cost piezoelectric polymer film sensors (will be simply called BL sensors, which is a short name for the product name, Roadtrax BL Piezoelectric Axle Sensor) were used instead of the expensive crystalline-quartz piezoelectric sensors (will be simply called Lineas sensors, which is also a short name for the product name, Lineas Quartz Sensor). Second, a customized PC-based controller was built based on off-the-shelf parts and used. This was much cheaper than proprietary controllers available on the current market. Third, loop detectors were not used and were replaced with an algorithm. Thus, the cost of installation and maintenance of loop detectors was saved. With these multi-facet efforts, the total material cost of a four-lane highway WIM system excluding installation was $8,885. The same four-lane system using the conventional Lineas sensors and a commercial controller was estimated at $133,072. Consequently, the research team was able to cut the WIM system cost by 93%.

To evaluate the low-cost WIM system, the site chosen by MnDOT was the Automatic Traffic Recorder (ATR) #213 site (a retired ATR site) which is located at mile point (MP) 18.1 on Minnesota Highway 61 (MN 61). This site has an instrumentation cabinet, power, a phone line for modem communication, and other wiring infrastructure for convenience, reducing the overall project cost. BL sensors were installed on all four lanes, and an in-house custom WIM controller (a PC-based controller) was installed in the instrumentation cabinet. A major advantage of selecting this site was that the WIM #30 site is available for comparison at about 1.8 miles south from this site. The WIM #30 site uses Lineas WIM sensors and is equipped with a same type of a PC-based, in-house built controller.

Data was collected for over 10 months and analyzed. Since one of the issues was how the known thermal sensitivity of BL sensors affects accuracy of measurements, both sites collected pavement temperature data and recorded it as part of each vehicle record. To collect WIM data under a wide range of temperature conditions, data were collected from the coldest months of winter to the warmest months of summer. The analysis was focused on the original goal of

finding ways of increasing the accuracy of the low-cost WIM system through calibration of weights based on temperature.

Accuracy of any WIM system depends on three factors: the accuracy of axle sensors themselves, quality of installation, and calibration accuracy. It was assumed that quality of installation and weight calibration based on a known vehicle was the same, although there are some differences in installation methods that may affect accuracy. All weight analyses were done using class-9 steer axles, since they are known to have a tight predictable distribution of weights.

Data showed the following results. Root Mean Square Error (RMSE) of daily volumes computed over 10 months (from 12/23/2014 to 10/31/2015) was 94 vehicles per day, which is about 1.47% of the WIM #30 average volume. Given that there are three exits between the two WIM sites of the highway, these daily volume differences are considered minimal, implying that both BL and Lineas sensors made no differences in volume counts.

According to class-9 steer axle data, weights measured by BL sensors changed from an average of 5 kips to an average of 20.7 kips when pavement temperature was increased from –22.5°F to 97.5°F. This is a 314% weight increase over the temperature increase of 120°F, which clearly indicates that the errors are too high and weights must be calibrated based on temperature. On the other hand, Lineas sensors increased only a small amount over the same temperature change, i.e., it only increased from 9.0 to 11.2 kips on average, which is a 24% increase. This result clearly indicates that BL sensor data will not be useful unless weights are calibrated based on temperature, while Lineas sensors maintain reasonably stable weights over the same temperature range. After temperature based calibration, the average of class-9 steer axle weights measured by both BL and Lineas sensors were approximately the same, but BL sensors produced a 46% higher standard deviation.

In summary, a low-cost WIM system was successfully built and installed by cutting cost by 93%. The data analysis showed that the average of the weight measurements by the low-cost WIM system could be as accurate as the conventional WIM system built using Lineas sensors, as long as the weights are calibrated based on pavement temperature. However, standard deviation of the low-cost WIM system was much higher than that of the Lineas sensor based system.

CHAPTER 1: INTRODUCTION

1.1 Background

Weigh-In-Motion (WIM) systems measure vehicle's axle weights while the vehile is in motion on the road. Although WIM systems are primarily designed to measure axle weights, having a pair of axle load sensors placed at a known distance per lane enables measurements of two more valuable traffic parameters, axle-to-axle spacing and speed. Axle-to-axle spacing along with axle weights serve as inputs for computation of classification and Equivalent Single Axle Load (ESAL) while speed information serves for multiple types of traffic applications. In general, WIM systems provide more detailed traffic information than other types of traffic sensors, and that information includes axle weights and spacing, gross vehicle weight (GVW), number of axles, vehicle classification, ESAL, speed, volume, etc. Recently, WIM systems began to integrate digital pictures of vehicles, providing visual information which would even further extend current applications of WIM data [1].

Although WIM systems provide high quality, detailed traffic information, one major drawback has been its high cost that includes initial installation and recurring maintenance costs. It is so expensive that WIM deployment price range is in general out of reach for most small County Public Works Departments and local transportation offices. Even for state transportation departments, its high cost has been a barrier for expanding WIM systems to many locations to obtain higher density of WIM measurements. What this suggests is that if the overall cost of WIM systems can be substantially lowered, more WIM systems would be deployed by transportation agencies; and consequently, higher quality of traffic data would be collected and used, which would lead to a better decision making and design of transportation systems.

As a solution for load monitoring on local roads, a portable WIM (PWIM) system was recently developed by the University of Minnesota Dulutth through a Minnesota Department of Transportation (MnDOT) sponsored project [2]. This system works much like a portable pneumatic vehicle counter, except it produces WIM data, i.e., the sensors are installed on a pavement for a short period of time at a location of interest and then removed. Initial tests of the PWIM system were successful [2,3], and MnDOT Office of Transportation System Management (OTSM) saw a potential of this system and suggested to take the PWIM technology and adapt to a permanent roadside WIM system. This suggestion led to a formulation of the current project, and the consequential system was named "low-cost WIM system." The objective of this research was thus to install and evaluate the performance of a low-cost WIM system adapted from the PWIM system.

A significant portion of any WIM system is the sensor cost. Today, two types of piezoelctric sensors are widely used. The first type is the conventional quartz crystals cut at specific angles, called crystalline-quartz piezoelectric sensors. This sensor will be called Lineas sensors in this report, which is a short name for the complete product name, Lineas Quartz Sensor, manufactured by Kistler Instrumente AG [4]. The next type uses the basic material called the polarized fluoropolymer polyvinylidene fluoride (PVDF) [5], and the sensor is produced by shielding a copolymer film of PVDF using brass material shaped in a long string of linguini. This sensor is manufactured by Measurement Specialties Inc. and called the Roadtrax BL Piezoelectric Axle Sensor [6]. A shorted name, BL sensors, is used throughout this report.

Lineas-sensor based system requires four 1.5 meter (5 feet) sensor segments per lane, and the per-lane cost was $24,928 in 2015. On the other hand, BL-sensor based system requires two Class-1 11-feet sensor strips, and its per-lane cost was $1,600 in 2015. The cost of sensors generally rises yearly, and the provided costs may vary depending on the location and price-break quantity. In this simple comparison, Lineas sensors are about 16 times more expensive than BL sensors per lane. This is the reason that the PWIM system used BL sensors, and the same sensors were used in the low-cost WIM system as well.

Although BL sensors are cheaper, a critical deficiency known is the temperature sensitivity in that charge signals are generated not only by loads applied to the sensor but also by higher temperatures. This temperature dependency must be removed if the load measurement must maintain its accuracy up to the limit of the original sensor design. There are two basic solutions for resolving temperature dependency: the first one is to correct the signals at the charge amplifier. The second one is to correct measurements after data collection, based on recorded temperature data. In the PWIM system, the charge amplifier was designed to remove slowly generating charge signals caused by thermal effects [2]. This approach worked reasonably well for the PWIM system, since it only collects data for a short-period of time in which the range of temperature changes is somewhat limited. This approach does not work if the range of temperature changes is very large. In a permanent WIM system, the range of temperature swing is very large since the sensor goes through from hot summer days to cold winter days. Therefore, the latter approach is more desirable and used. A thermocouple was added to the system, and the pavement temperature data was recorded for each vehicle. This added data gave an opportunity to study the effect of temperatures on axle weights, and it led to development of a temperature-based axle-weight calibration method.

Another effort of lowering the overall WIM system cost was building an in-house WIM controller utilizing an off-the-shelf PC, an analog-to-digital data acquisition board, and custom-designed low-cost printed circuit boards (PCB) for charge amplifiers. The cost analysis is discussed in Section 1.2.

To evaluate the low-cost WIM system against Lineas-sensor based WIM system, the site chosen by MnDOT was the ATR #213 site (a retired ATR site) which is located at Mile Point (MP) 18.1 on MN 61 highway. A major advantage of selecting this site was that the WIM #30 site is available for comparison in about 1.8 miles south from this site. The WIM #30 site uses Lineas sensors and equipped with a same type of a PC-based, in-house built controller.

Since one of the issues will be analyzed through this project is the effect of pavement temperature on the load sensors, both sites collected temperature data as part of each vehicle record. To collect WIM data from a wide range of temperature, data were collected from the coldest months of winter to warmest months of summer. The analysis will be focused on the original goal of finding ways to increase the accuracy of the low-cost WIM system without increasing the overall cost.

1.2 Cost Analysis of WIM Systems

The purpose of building a low-cost WIM system is not just building a cheap WIM system, but it should also produce a reasonably good quality of WIM data. In order to design such a system, system components with respect to cost and quality are analyzed.

First, the choice of sensors is considered. Table 1.1 summarizes prices of two different types of sensors based on the data supplied by MnDOT in 2015, and it shows that Lineas sensors are about 15.6 times more expensive than BL sensors in per-lane cost. If a WIM system is installed on a 4-lane road, the price difference is as big as $93,312. Therefore, BL sensors were the natural choice for the low-cost WIM system. Temperature dependency of BL sensors is a major problem to be solved, but if this problem can be resolved, BL sensors provide a much better cost/performance ratio. The approach employed in this project was integration of a thermocouple to the system to measure and record pavement temperatures as part of vehicle records. This temperature information is later used to compute temperature-based calibration of axle weights.

Table 1.1: Per-Lane Cost Comparison of Sensors

Part Number	Description	Company	Unit Cost	Quantity required per Lane	Per Lane Cost	4-Lane Cost
9195F421	Quartz Lineas 1.75 m sensor with 100m lead cable	Kistler	$6,232	4	$24,928	$99,712
1005333-7	Roadtrax BL 11 ft sensor with 400 ft lead cable	Measurement Specialties	$800	2	$1,600	$6,400

In addition to utilizing low-cost axle sensors, an in-house custom-designed controller was constructed using off-the-shelf products to further reduce the overall system cost. For Lineas sensors, MnDOT uses IRD iSinc controllers which would cost about $26,000 per site in 2015. Recently, PC prices have dropped to under $1,000, and the total cost of building a custom off-the-shelf WIM controller was only $1,729 as summarized in Table 1.2. It should be noted that building a WIM controller using an off-the-shelf PC is not complicated, and it was demonstrated in the previous projects that it can be easily built using simple tools [2, 7]. PCs also give an advantage that it has built-in remote access and communication functions for data downloading and system control, as well as web and Internet capabilities and protections. For this project, a controller similar to the one used in the PWIM system was constructed. It used the same type of Analog-to-Digital Converter (ADC) and charge amplifiers. The actual components and purchase prices are summarized in Table 1.2. What this table shows is the retail prices you pay for a small quantity. The total price could be significantly reduced if a large quantity is purchased.

Table 1.2: Components and Cost of the Low-Cost WIM Controller

Part Number	Description	Unit Price	Quantity	Extension
SL-DK-P8H61-ID	Micro Tower PC,8G RAM, Intel Core i-5, Win 7	$804.88	1	$804.88
PCI-DAS6013	16bit ADC Board, 200k Samples/Sec	$419.00	1	$419.00
USB-2001-TC	USB Thermocouple	$99.00	1	$99.00
CIO-MINI50	50-pin Universal Screw Terminal	$89.00	1	$89.00
C100HD50-3	50-Conductor Ribbon Cable, 3 ft	$68.00	1	$68.00
Custom	Two-Chanel Charge Amplifier	$35.79	4	$143.16
L182-ND	Aluminum Enclosure, 3.5x12x9”	$105.75	1	$105.75
	Total			$1,728.79

Since loop detectors can detect metal body of vehicles, they are integrated to WIM systems to detect the length of vehicle body and the corresponding axle signals that belong to that vehicle. More specifically, loop signals are used to identify the end and beginning of each vehicle from a continuous stream of axle signals. In the low-cost WIM system, axle signals are analyzed based on known axle spacing patterns of vehicles, and then an algorithm determines the start and ending axles of a vehicle without using loop signals. Since loops are not used, it saves loop installation and detector card costs, as well as its maintenance costs. A block diagram of the final low-cost WIM system is depicted in Figure 1.1. Each lane uses two BL sensor strips, and the PC can accommodate WIM data collection up to four simultaneous lanes. Since the ADC card has 16 channels but it currently only uses 8 channels, four more lanes could be added by simply connecting charge amplifiers to the additional channels. Adding one more ADC card would be able to handle up to 16 simultaneous lanes.

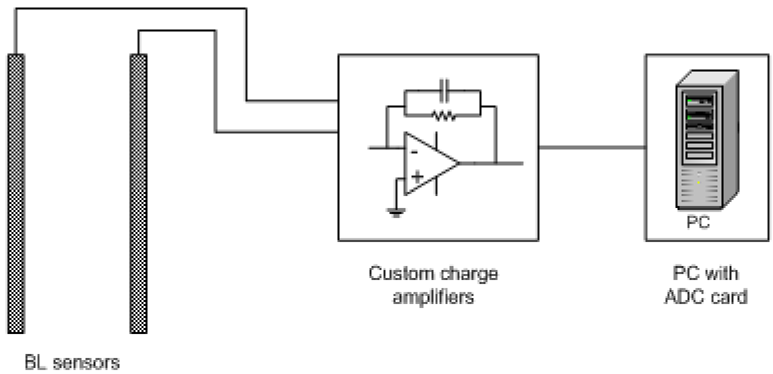


Figure 1.1: Proposed low-cost WIM system

Next, installation and maintenance costs of a WIM system are considered. Installation cost is in general determined by travel distance to the site, pavement type and time of year, but not much by the type of sensors. In Minnesota, installation cost in 2015 was in the range of $10,000 - $15,000 per lane, depending on the distance to the site. One item related to difference of sensor types in installation is the cost of grouts and the number of buckets required per lane. Lineas sensors need 6 buckets per lane and each bucket costs $328. This amounts to $7,872 for a four-lane highway. BL sensors, on the other hand, require only 3 buckets per lane and each bucket costs $63. Thus, the grouts needed for Lineas sensors cost about 10 times more than that of BL sensors.

Finally, Table 1.3 summarizes the result of price comparison for the two WIM systems that can be equally installed on a four-lane highway. One system is built using Lineas sensors with an IRD controller, and the other system is built using BL sensors with an in-house PC-based controller. Installation costs are considered similar to both systems and thus excluded from the comparison table. Notice that the proposed low-cost WIM system costs only 7% of the cost of the Lineas-sensor based WIM system. Another way of looking at would be, one would be able to buy 15 low-cost WIM systems for the price of a single Lineas WIM system.

Table 1.3: Cost Comparison of WIM Systems for a Four-Lane Highway

	Lineas-Sensor Based WIM System	BL-Sensor Based Low-Cost WIM System
Sensor Total	$99,712	$6,400
Controller	$26,000	$1,729
Grouts	$7,872	$756
Total Cost	$133,584	$8,885

CHAPTER 2: TEST SITE PREPARATION

This chapter describes how the WIM sites were prepared for this study. WIM #30 was setup as the baseline for studying the BL sensors at WIM #213 (ATR #213). Between two sites, there exist only two crossing roads, Alseth Road and Central Avenue, where traffic can exit and enter. However, the amount of traffic is minimal at both crossing roads, providing a similar traffic amount for both sites.

2.1 WIM #30 Site

The WIM #30 site is located at mile point (MP) 16.3 on Minnesota State Highway 61 (MN 61). MN 61 is a four-lane highway that runs from a junction with Interstate Highway 35 in Duluth and continues to U.S. – Canadian border. The speed limit of this highway is mostly posted at 65 mph. This site is equipped with Lineas WIM sensors, Kistler charge amplifiers, and an experimental WIM controller developed by the University of Minnesota Duluth called Bulldog. The Bulldog WIM controller was developed using an off-the-shelf industrial PC and a PCI data acquisition board (PCI DAS6013) [7].

The Bulldog controller software at WIM #30 was written in 2007 as an experimental system [7]. Since then many small revisions were made to correct errors but it became clear that the software ran its life and had to be rewritten using a fundamentally different approach. During Jan 2014, a new WIM controller software was written from ground up to create a more reliable and yet user friendly version. The basic coding technique was changed to an event driven approach from multi-threading to make the code more tractable. This new controller software was eventually adapted and loaded to the current PWIM and low-cost WIM systems. The software was closely monitored and improved for several months by setting it to halt if any errors or problems were encountered. The software became stable as of December 23, 2014, and the executable was set to trap errors and report them without halting execution. This approach still can capture the system errors but through an error log. The error log was empty after running more than six months, which indicates that most of coding errors that cause exceptions were fixed.

The basic WIM sensor configuration which was used at WIM #30 consists of two loop detectors and two load sensor strips per lane as shown in Figure 2.1. The loop detectors are used for vehicle end detection, i.e., it determines the first and last axle of a vehicle. One of the main features of the new WIM controller is that it automatically detects malfunctioning sensors and optimizes WIM data computation based on availability of functioning sensors. More specifically, if one of the loops does not work, the software automatically detects the malfunctioning loop and then uses the remaining loop for vehicle end detection. If both loops fail simultaneously, it then automatically switches to an axle-signals-only mode in which vehicle end detection is achieved solely using an axle-spacing-based algorithm. The reason for using a pair of load sensor strips is to measure the vehicle speed. If one of the load sensor strips fails, speed cannot be computed and thus the weight cannot be calculated. In this case, the speed is estimated through the speed of an adjacent lane, i.e., the user specifies which adjacent lane to use along with an adjustment factor (percent of adjacent lane speed) for each lane. For example, if one of the driving lane sensor strips is not working but the pair in the passing lane are working, the speed of driving lane is estimated using the passing lane by reducing the speed at a certain percent set by the user. If the load sensor strips in both its own and adjacent lane are broken, the system then gives up weight computation. Errors are reported in the vehicle record if any of the sensors in the basic configuration (Figure 2.1) fails, but all WIM data are still computed.

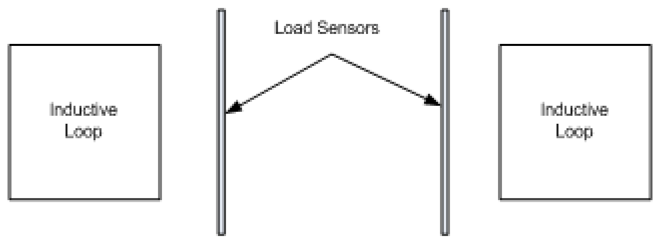


Figure 2.1 WIM sensor configuration per lane

Figure 2.2 shows inside of the WIM #30 site cabinet. In addition to a WIM controller which is basically an industrial PC with a data acquisition board, there is another enclosure that houses charge amplifiers and loop detector cards. It is also equipped with an analog modem for remote control and data downloads but later it was replaced with a wireless modem (provided by Verizon). The system also includes a thermocouple for collecting pavement temperature data. The controller produces a daily data file that contains individual vehicle records, and the file is automatically downloaded to lab.

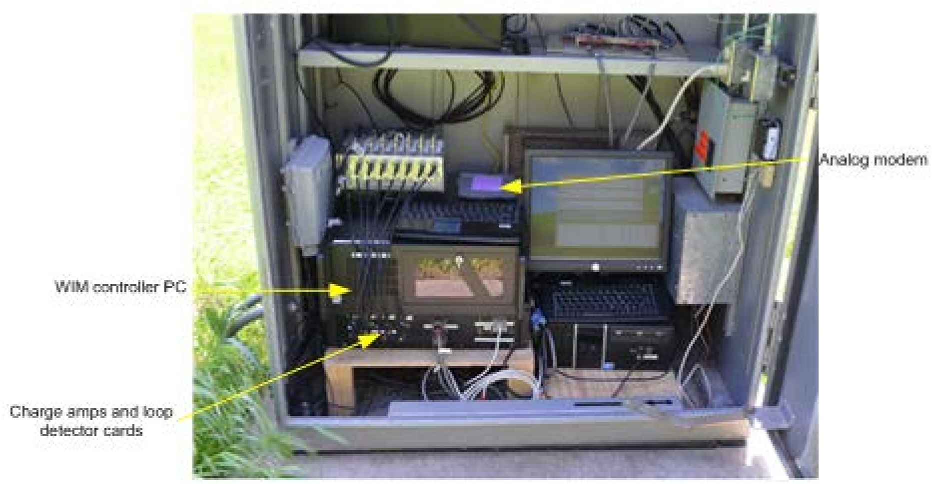


Figure 2.2: WIM #30 Cabinet

2.2 WIM #213 Site

The site selected by MnDOT for the low-cost WIM system study was a retired automatic traffic recorder (ATR) site, ATR #213, located at MP 18.1 on MN 61. This site is located 1.8 miles north of the same highway from the WIM #30 site. Both sites have a similar traffic volume and pattern. ATR #213 is equipped with an instrumentation cabinet, AC power, analog phone line for modem communication, underground conduits for wire-crossing of the highway, and other infrastructures. This availability of infrastructure made possible to significantly reduce the overall project cost. Since this site is turned into a WIM site, this site is referred to as WIM #213 in this project report.

For WIM axle sensors, eight RoadTrax BL Piezo Sensors (11 feet in sensor length and 200 feet in lead coaxial cable length) were installed. Sensor installation was completed by a contractor on October 10, 2013, and the configuration diagram is shown in Figure 2.3. All loops were configured as a 6×6 feet square, and axle sensors in each lane were spaced 12 feet. Loop to axle sensor or axle sensor to loop distances were all spaced at 3 feet. Axle sensor spacing between adjacent lanes for Lanes 1 and 2 was 12 feet while it was only 1 feet between Lanes 3 and 4. This close spacing of adjacent-lane sensors often generated false axle signals when vibration from the adjacent lane is spilled over or tire steps both lanes. In the future, spacing of at least 12 feet between adjacent lane axle sensors is recommended, i.e., the northbound setup in Figure 2.3 is recommended.

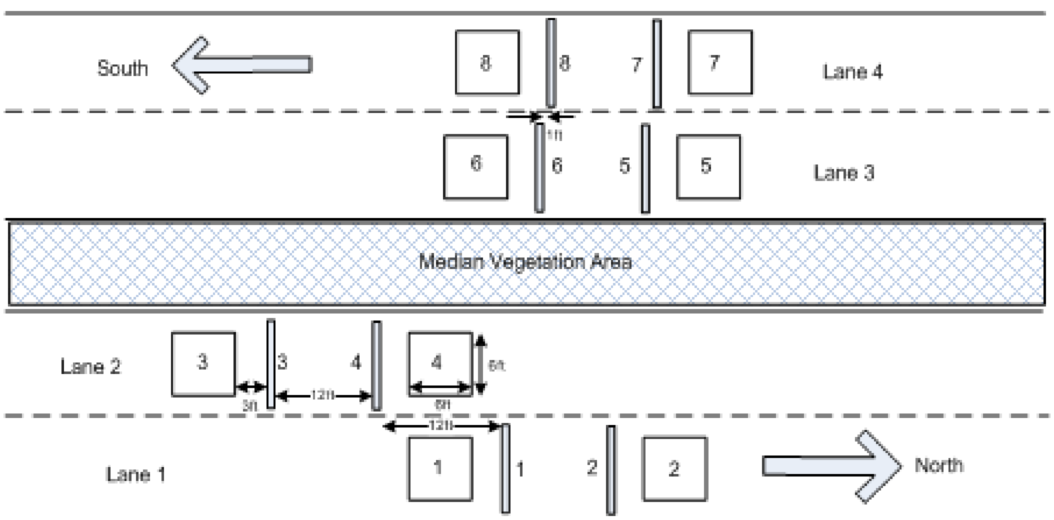


Figure 2.3: WIM #213 sensor configuration

Another important characteristic regarding BL sensors is that sensor material is not uniform with respect to the distance from the end of sensor. Figure 2.4 is a data sheet on uniformity of a BL sensor strip that comes with when a sensor strip is purchased. This graph shows that the sensor reading of vehicle weights can be different up to about 10 percent, depending on which part of the sensor strip was driven even if everything else is the same. This uniformity characteristic of BL sensors is one of the limiting factors of the sensor's accuracy.

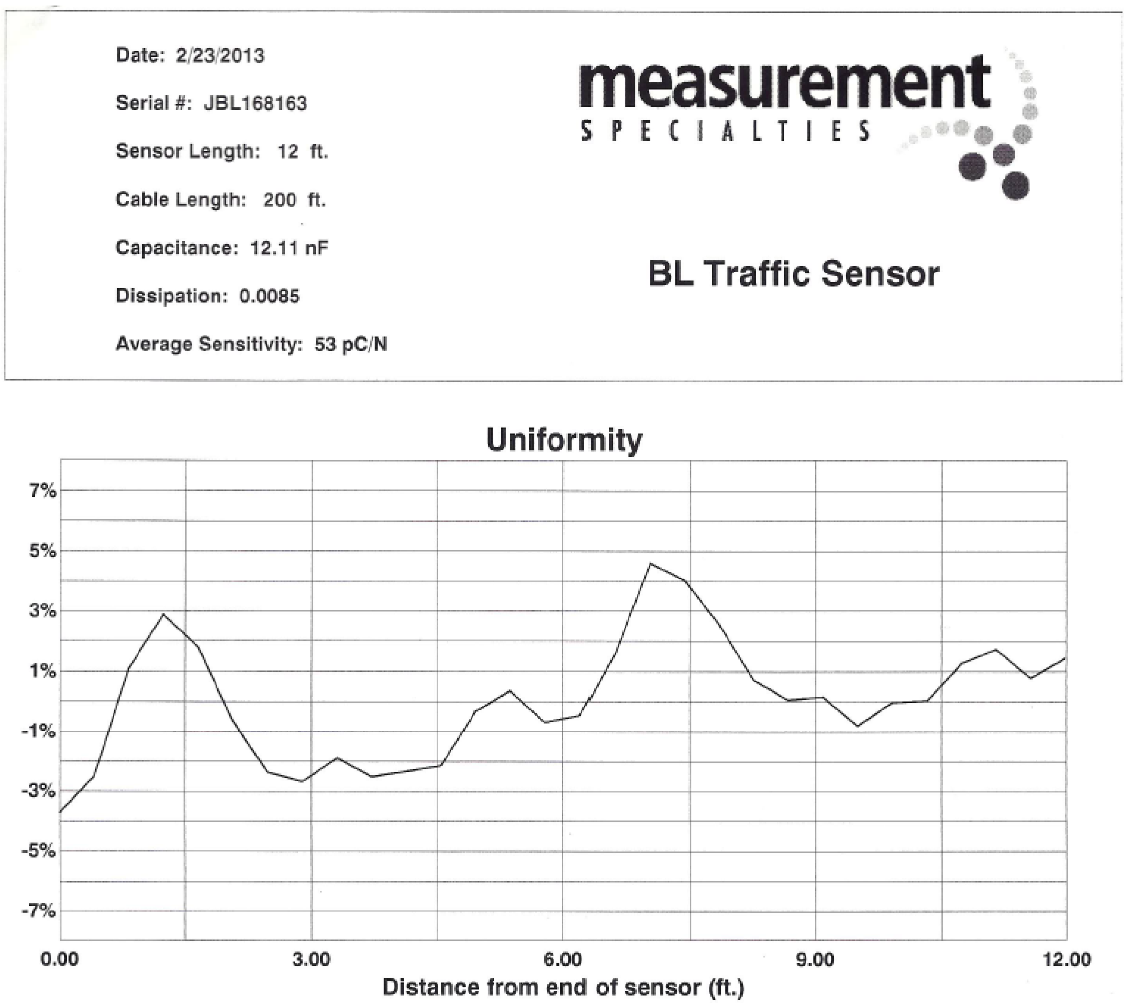


Figure 2.4: Uniformity of BL sensor (Source: Measurement Specialties Inc.)

Figure 2.5 shows the instrument cabinet of the WIM #213 site after installation. A small footprint PC equipped with a data acquisition board is connected to an enclosure that contains charge amplifiers. The axle load sensor outputs are directly connected to inputs of charge amplifiers. For the PC display, a USB monitor was used. This USB monitor is normally not plugged in, and it is only used when operator wishes to see the screen. The equipment in the cabinet includes an analog modem (V.92) for remote access and a temperature controlled heater to cope with Minnesota winter. In addition, a K-type thermocouple was installed and records pavement temperature data. Although inductive loops were wired as shown in Figure 2.3, the system does not use them in this study. This is because if loops are not used, tens of thousands of dollars of installation and instrumentation costs can be saved. Since the main objective of this project was to develop and evaluate a low-cost WIM system, the decision was made towards cutting cost. The controller software was the same version used in WIM #30, which was an in-house developed version by the current author. The WIM PC was configured as an ftp server to provide remote downloading of WIM data. The system was also set as a Remote Desktop host to allow Remote Desktop connections from a remote computer and remote control of the instrument PC.

Figure 2.5: WIM #213 instrument cabinet

2.3 Axle Load Sensor Calibration

Both sites were calibrated using the MnRoad class-9 truck (shown in Figure 2.6) on June 18, 2014. This truck has been used for WIM site calibrations at MnDOT for many years, and its axle weights are evenly distributed for stability. Gross vehicle weight (GVW) of this vehicle was 79.8 kips, and its axle weights were from steer to the last axle, 12, 16.7, 18.1, 17.1, and 15.9 kips. On the calibration day, the low, high, and mean temperatures were 55, 66, and 60^{o}F, respectively. During the calibration which took place between 10:30 to 12:30 AM, the temperature was in the range of 62 to 63^{o}F, and wind speed was between 16 and 26 mph. This data was confirmed through www.wunderground.com.

Calibration data was recorded only for WIM #213 and it is summarized in Table 2.1. The vehicle was driven up to seven times per lane and GVW was recorded by setting all calibration factors to 1. Calibration factor for each lane was computed by (known weight)/(measured weight). Because the system uses signal amplification of 1.66, the theoretical calibration factor was 0.6. Note from Table 2.1 that the final calibration factors for each lane was 0.48, 0.38, 0.51, and 0.69 for Lanes #1-4, respectively. The average of the calibration factors was 0.52 which is close to the theoretical value 0.6.

WIM #30 was calibrated by MnDOT personnel, and the calibration factor was computed and entered for each passage of the calibration truck until the measured GVW is close to the known

GVW, i.e., instead of averaging an adaptive approach was used. The actual measurement data was not recorded (by MnDOT personnel) and thus not available.

Figure 2.6: MnRoad calibration truck

Table 2.1 GVW of Calibration Runs for Each Lane, WIM #213

Runs	Lane 1	Lane 2	Lane 3	Lane 4
1	165.0 kips	204.4 kips	150.4 kips	111.3 kips
2	177.9 kips	205.4 kips	157.2 kips	117.4 kips
3	158.9 kips	210.6 kips	161.5 kips	117.0 kips
4	161.0 kips	210.8 kips	153.7 kips	112.0 kips
5	155.2 kips	215.2 kips	158.9 kips	133.6 kips
6	181.5 kips	215.7 kips		105.8 kips
7				114.0 kips
Average	166.5 kips	210.4 kips	156.3 kips	115.9 kips
Calibration factor	0.479	0.379	0.51	0.689

2.4 Signal Strength Comparison of Axle-Load Sensors in WIM #213

Lineas and BL sensors are somewhat differently installed on pavement. For Lineas sensors, the top surface of the sensor block is first aligned flush to the pavement surface and then grout is filled to bottom and side spaces [8]. Thus, the top of sensor block is always aligned flush to the pavement and directly touches tires when a vehicle passes through. This installation approach makes sensor depths nearly identical for all lanes and between sensors, which would result in consistent signal strengths between sensors. However, it also makes sensors vulnerable to damage due to direct touches of sensor surfaces by heavy truck tires.

For BL sensor installation, the sensors are first dropped down to the prepared slot in the pavement and then grouts are filled to flush to the pavement surface. Consequently, sensors do not directly touch tires. The manufacturer recommends to install BL sensors at 3/8” deep from the pavement surface [6]. Clips are used for the BL sensors to keep them at a uniform depth. BL sensors last longer because they do not directly touch tires of moving vehicles.

This section analyzes uniformity of signal strengths between sensor pairs and between lanes for the WIM #213 site. The signal strength comparison would provide information on the depth of the sensor strips buried in the pavement. Axle signals are recorded from each sensor strip driven by the same test vehicle. A picture of this test vehicle is shown in Figure 2.7, which is a 2005 Toyota Sienna van. This vehicle was driven at close to 65 mph for all lanes.

Since the WIM #213 site has four lanes, a total of eight sensor strips were installed. In Figure 2.8, plots of axle signals from Lanes 1 through 4 are shown. The first two spikes with the same color in each lane shows the front and rear axle signals of the vehicle from the upstream sensor, and the next pair are the downstream front and rear axle signals. Among signals, notice that Lane-3 upstream signals show the least strengths, implying that the sensor strips are buried deeper than other sensor strips. Also, the signal strengths between upstream and downstream sensors are not same, except for the signals at Lane 4, but the differences are small, which indicates similar sensor depth and/or uniformity of sensor material.

Another application of signal strength analysis is that this information is used for setting up the signal threshold of each sensor strip for detection of axles. After observing axle signals of the test vehicle, it is clear that the threshold level of the Lane-3 upstream sensor should be set lower than other sensors.

Figure 2.7: Test vehicle used for axle signal strength test

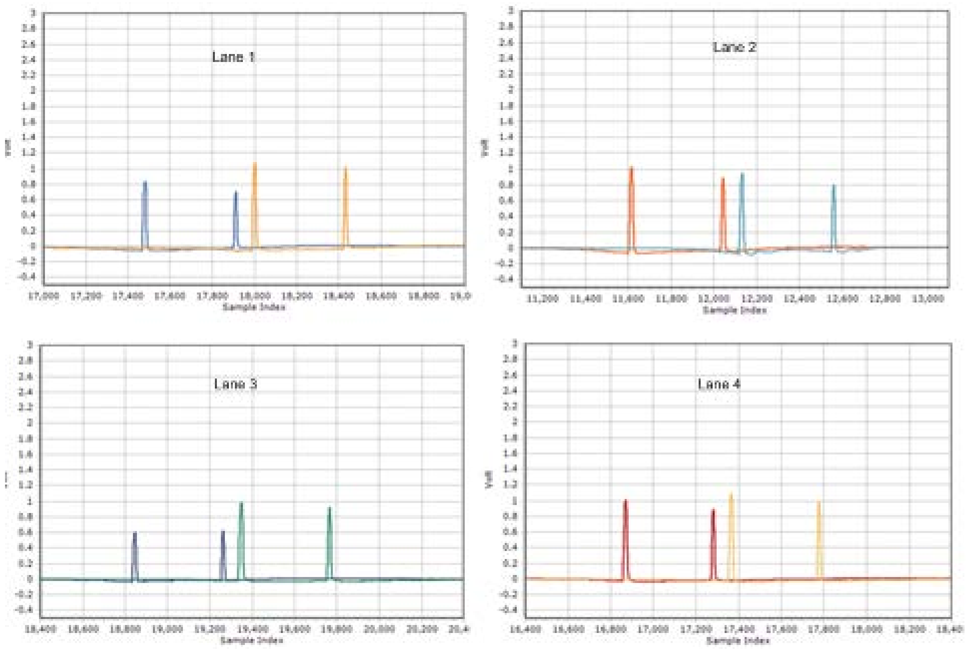


Figure 2.8: Signal strength comparison of axle sensors

2.5 Problems Encountered

This section summarizes various problems encountered during the project period and solutions sought. This problem documentation may be useful in the future if similar problems are encountered.

2.5.1 Sensor problem caused by butt splice of coaxial cables at WIM #213

The length of coaxial lead cable required to run from Lane 4 sensors (Sensors #7 and #8 from Figure 2.3) to the instrument cabinet well exceeds 200 feet that came with the sensors. Thus, extending cable length through splicing was required. Unfortunately, the sensor installation contractor extended the coaxial cables using simple butt splices. There are two major issues with butt splicing of coaxial cables. The first issue is shield leak in the splice, which introduces noise to the line. The second issue is the short circuit created when it is submerged under water. Since all cables cross the highway through underground conduits, splices are placed in a manhole which is likely filled with water. Indeed, resistance measurement of Sensors #7 and #8 showed zero ohm, and water submerge was confirmed.

This problem was solved by replacing the butt splices with BNC couplings and then by water proofing. Each end was connected to BNC male connectors, and both ends were connected through a BNC coupler. The BNC couplers were then sealed using water resistant tape to prevent water seepage.

2.5.2 Conflict between PCI 32-bit driver in BIOS and Windows-7 64-bit

The A/D converter cards used in the custom designed PC-based WIM controller were PCI-DAS6013 manufactured by Measurement Computing. This card was originally designed to work with one of the PCI 32-bit bus slots under Windows XP. The problem encountered was that the whole PC was locking up after continuously running 5 to 10 days. When the system events were logged, it indicated that a conflict exists in PCI 32-bit bus. After close inspection, it was determined that the conflict was caused by software interface between the 64-bit Windows 7 and the 32-bit PCI driver in the basic input output system (BIOS). This problem was unsolvable at the user level since the BIOS of the motherboard must be fixed. Unfortunately, the motherboard manufacturer was not able to provide the BIOS fix either since they did not write the software either. This motherboard was manufactured by a not well-known company, and it appears that the BIOS was not properly imported. Eventually, the motherboard was replaced with a well-known brand, and this lockup problem immediately disappeared. A lesson learned from this experience was that when a motherboard is purchased for instrumentation, one should always purchase a well-known brand even if it is slightly expensive. This fix (replacement) occurred on September 23, 2014.

2.5.3 Windows-7 dialup server problem

For creating a dialup sever at a remote Windows-7 PCs (both WIM #30 and #213), “New Incoming Connections” button in the “Network Connections” window is used to create a dialup server. If the dialup server created works correctly, it shows an “Incoming …” icon in the “Network Connections” window. In the initial try, this “Incoming …” icon was not visible in the site computers in the “Network Connections” window, instead the following error message appeared. “*Incoming connections depend on the Routing and Remote Access service, which was unable to start. For more information, check the system event log*.” Checking the system event logs did not help solve this problem, but a simple solution was accidently found. Windows-7 apparently combines Routing and Remote Access Services together and they calls it RRAS. Since routing requires at least two active ports available in the system, i.e., one for incoming and the other for redirecting, the dial-up server was activated only if a second network connection is live. A simple solution was to connect an Ethernet port of PC to a dummy Ethernet switch. This created another active connection and RRAS was successfully launched.

Later, the remote access connection at WIM #30 was changed to a wireless modem from a dialup modem, provided by Verizon wireless. This replacement solved the phone line problems encountered in 2014, which were mainly line breakages caused by road construction. Wireless modem worked faster and also more reliably than traditional dialup modems.

2.5.4 Loop detector card problem

There was a loop detector card problem in WIM #30. In WIM #30, two inductive loops per lane were installed in all four lanes, equipping a total of eight loops for the site. To process the 8 loops, the system uses two Canoga loop detector cards (Canoga 924). During the winter of 2013/2014, these two loop detector cards began malfunctioning and produced stuck-at-one errors. Because the controller software was designed to automatically detect loop detector errors and automatically switch to the axle-sensor-based algorithm, it indeed automatically switched the axle-sensors only mode and continuously recorded WIM data. MnDOT eventually purchased two new Canoga 924 cards, and they were replaced on November 8, 2014.

CHAPTER 3: DATA COLLECTION AND ANALYSIS

3.1 Data Collection

WIM sensors at the test sites were calibrated on June 18, 2014, and the WIM data was collected since then. However, most of the data collected in 2014 was not good due to controller software errors and few interruptive problems that were encountered as described in Section 2.5. For WIM #213, power loss occurred most of September 2014, which was due to an upgrade of power equipment in the region by the local power utility company. With no electricity available in the instrument cabinet, all electronics were off and no data were collected. Another event of hardware problem occurred at WIM #30 was the loop detector cards which were broken and not working properly since January 2014. This problem persisted until the broken cards were finally replaced on November 8, 2014. There were also data loss on WIM #30 between December 6 and 7, 12 – 22, 2014, due to a halt mode set for capturing exception errors.

In summary, WIM data were collected from both sites since installation of WIM controllers in the respective site. However, due to the events described above, acceptable quality of WIM data were available only after 12/23/2014. Therefore, 10 months of data collected from 12/23/2014 to 10/31/2015 were used for all data analyses in the subsequent sections.

3.2 Volume Comparison

Daily volume counts are compared between WIM #30 and #213 in terms of directional and total volumes. Figure 3.1 shows configuration of lanes and exits around both sites. Notice that there are three exits where vehicles bypass the WIM sensors: two exits are in northbound lanes near WIM #213 and one exit is in the southbound lane near WIM #30. Because of these three exits, volume counts on both sites cannot be identical, but it should be similar since exit volumes are relatively a small amount.

A graph of daily volumes, which was plotted over 10 months from 12/23/2014 to 10/31/2015, is shown in Figure 3.2. The top two lines show total volumes of the two sites. Both lines are mostly overlapped, indicating similar traffic counts. The bottom four lines show directional volumes of the two test sites. Again, directional volume curves are mostly overlapped, indicating similar volume counts. It is also interesting to notice seasonal differences that January (winter) daily volumes are around 6,000 and then the volume increases to nearly 1,200 in July (summer).

Root Mean Square Error (RMSE) of daily volumes computed over 10 months (from 12/23/2014 to 10/31/2015) was 94 vehicles per day which is about 1.47% of the WIM #30 average volume. Given that there are three exits between the two WIM sites of the highway, these daily volume differences are considered minimal, implying that both BL and Lineas sensors made no differences in volume counts. Table 3.1 shows a sample of daily directional volume data for 15 days, from 11/9/2014 to 11/23/2014, which shows typical volume differences between two sites.

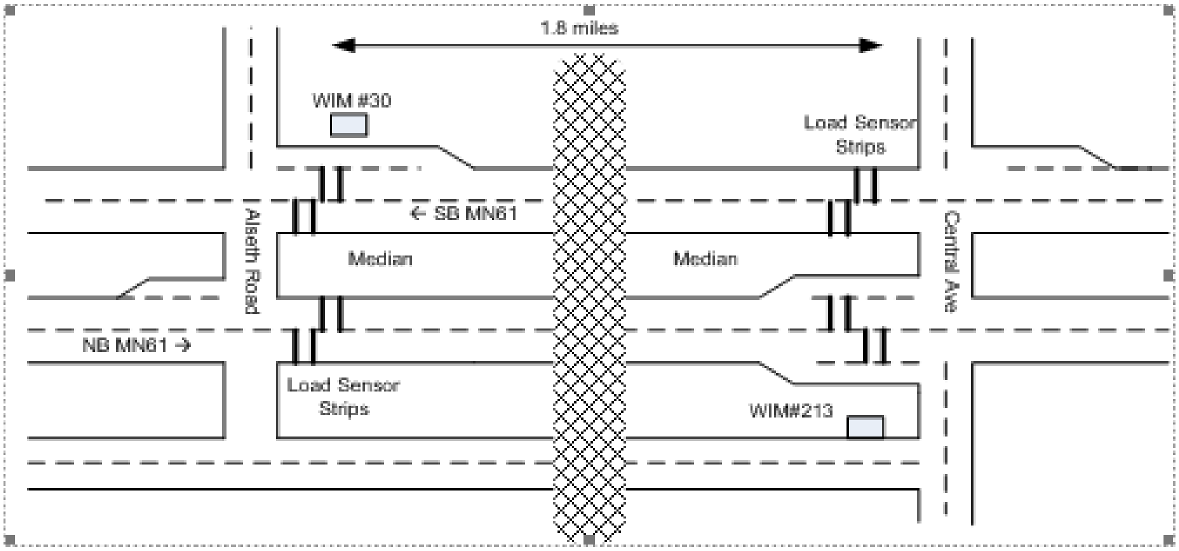


Figure 3.1: WIM #30 and #213 sites and exit lanes

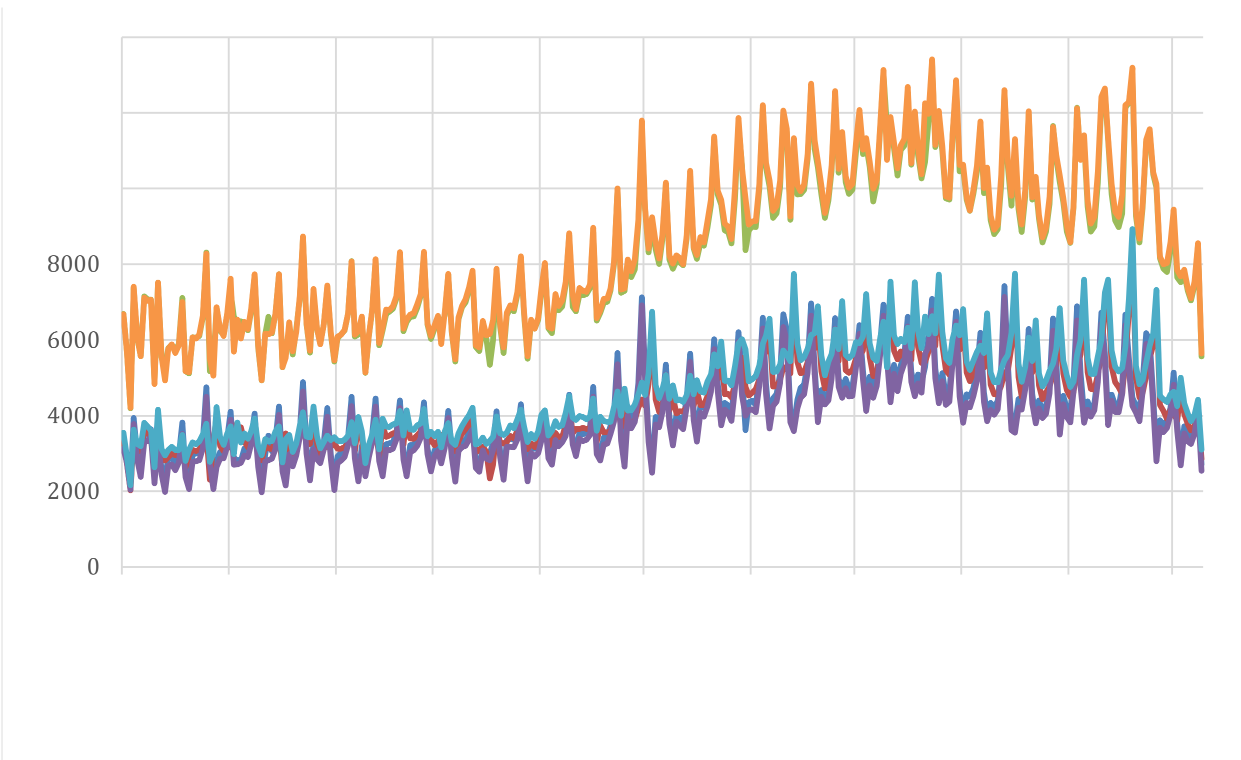


Figure 3.2: Daily directional and total volumes of WIM #30 and #213 sites

Table 3.1: Sample Daily Volumes

Date	NB-#030	SB-#030	Total-#030	NB-#213	SB-#213	Total-#213
11/9/2014	2654	3973	6627	2517	4164	6681
11/10/2014	2527	2957	5484	2295	3126	5421
11/11/2014	2615	2902	5517	2422	3047	5469
11/12/2014	3277	3396	6673	3156	3583	6739
11/13/2014	3366	3469	6835	3211	3654	6865
11/14/2014	4217	3934	8151	4042	4084	8126
11/15/2014	2593	2773	5366	2455	2895	5350
11/16/2014	2457	3009	5466	2321	3152	5473
11/17/2014	3189	3270	6459	2974	3459	6433
11/18/2014	3217	3229	6446	3027	3406	6433
11/19/2014	3196	3267	6463	3057	3453	6510
11/20/2014	3512	3541	7053	3286	3729	7015
11/21/2014	3863	3799	7662	3677	3966	7643
11/22/2014	2741	2780	5521	2603	2944	5547
11/23/2014	2428	2825	5253	2300	2994	5294

3.3 Daily Averages of Class-9 Steer Axle Weights

This section investigates temperature sensitivity of axle sensors through class-9 WIM data collected. The weights of class-9 steer axles are known to be most consistent among different models and distributed in the range of 8 to 12 kips. This consistent weight distribution can be used as a reference for weight-related analyses and also for sensor calibrations. Both sites are equipped with temperature sensors (thermocouple), and controllers recorded pavement temperatures as part of a vehicle record. This temperature data along with class-9 steer axle weights are used for thermal effect analyses.

Figure 3.3 shows daily average pavement temperatures (olive-green, right axis) and daily averages of steer axle weights measured by BL sensors (dark-red) and Lineas sensors (royalblue). Notice that daily average temperature swings widely but the trend remains firm, rising from about -6ºF in January to 80ºF in July. The steer axle weights measured by BL sensors in WIM #213 is clearly following the temperature trends while averages measured by Lineas sensors do not. This data indicates that BL sensors have a high temperature sensitivity, i.e., it rose from 6 kips to 15 kips or 250% when temperature increased from -6ºF to 80ºF. This temperature sensitivity was the reason that PVDF piezoelectric films (base material of BL sensor) are often used for temperature sensing, i.e., BL sensors use the same materials used for temperature sensing.

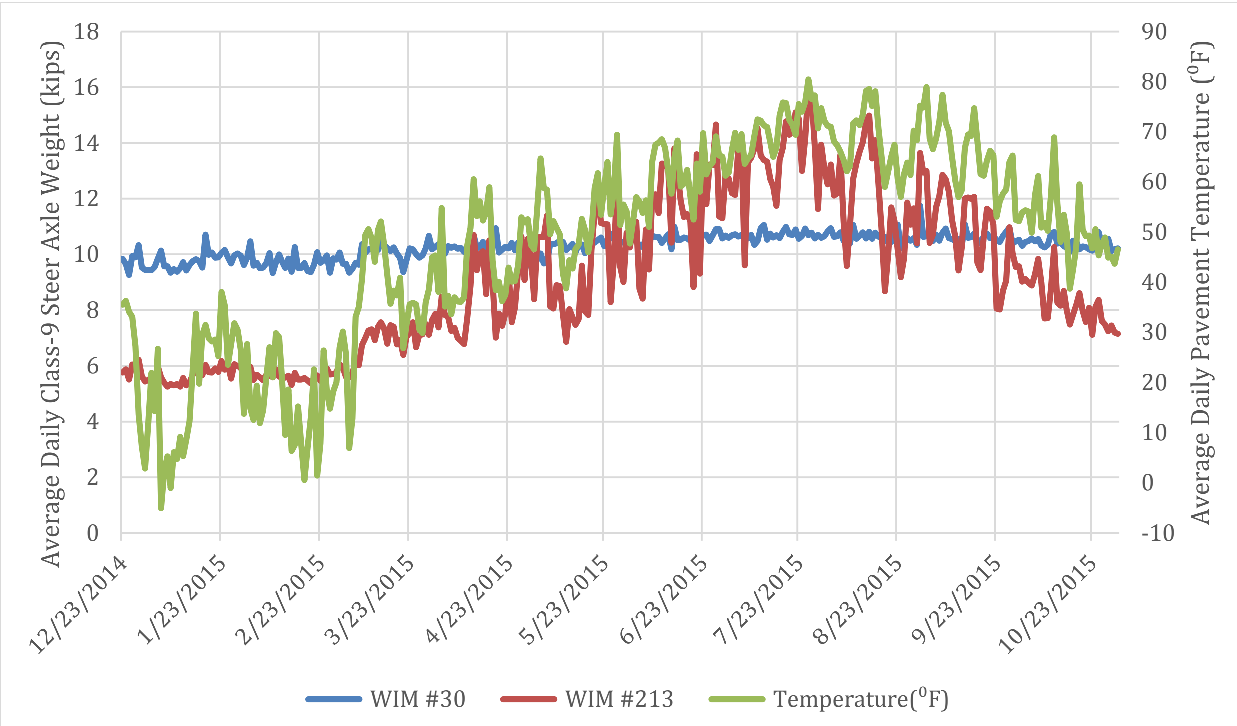


Figure 3.3: Daily averages of class-9 steer axle weights and pavement temperatures

3.4 Thermal Effect of Axle Sensors and Modeling

In Figure 3.3, daily averages of class-9 steer axle weights over 10 months were plotted along with daily average temperatures, and the BL sensor data clearly followed the seasonal temperature trends. However, daily averages do not reveal detailed information on how much weight values were changed as a result of temperature differences, since temperatures in a day can swing over a large range.

In order to more accurately evaluate thermal effects, 10 months of class-9 steer axle weight data were first binned for 5ºF increments in the range from -25ºF to 100ºF, i.e., the bins are -25 to 20, -20 to -15, …, 95 to 100ºF. Each temperature bin contains all of the class-9 steer axle weights collected over 10 months in the assigned temperature range. The average of each bin was plotted for both BL and Lineas sensors, and it is shown in Figure 3.4. The horizontal axis shows the mid value of each bin. Standard Deviation (SD) of each bin is also shown in Figure 3.5. Data shows that weights measured by BL sensors change from 5 kips at -22.5ºF to 20.7 kips at 97.5ºF. This is about 314% increase, which clearly indicates a large error of weights caused by temperature. On the other hand, Lineas sensors increased only a small amount over the same temperature range, i.e. 9.0 to 11.2 kips or 24%. For BL sensors, SD increased along with temperature as well (see Figure 3.5).

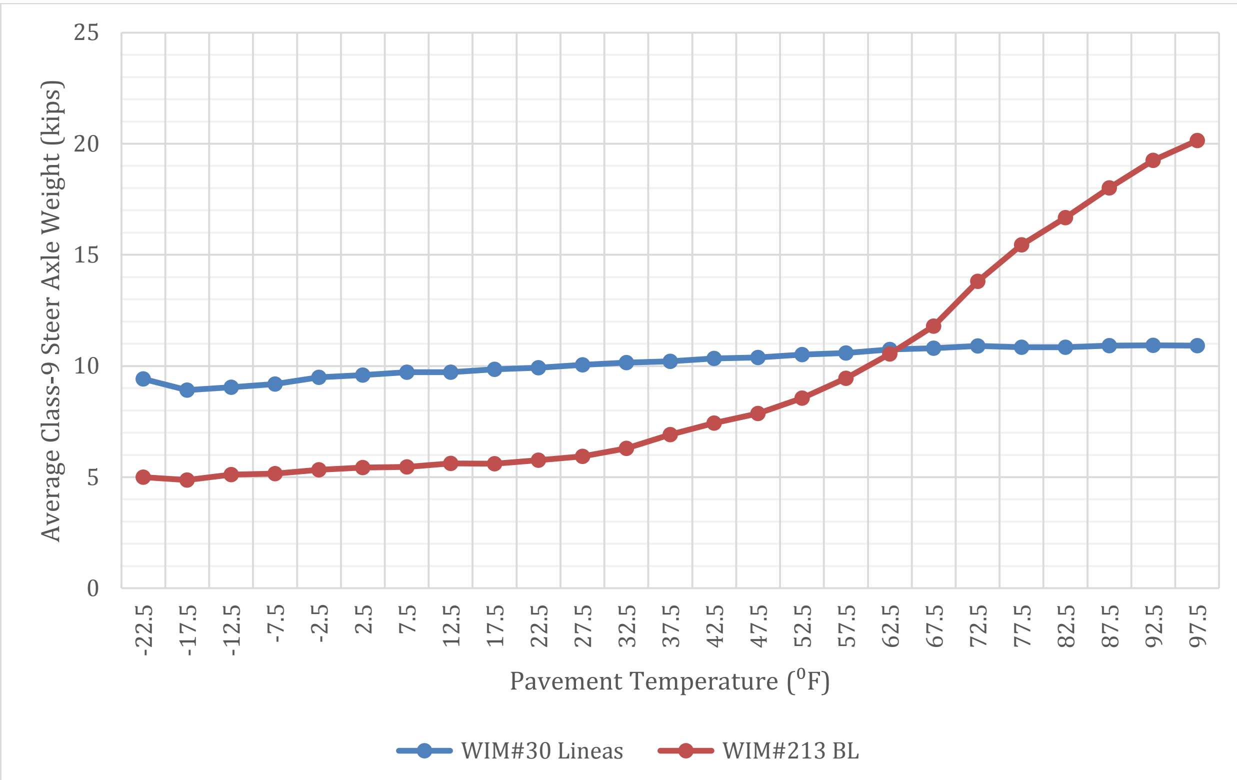
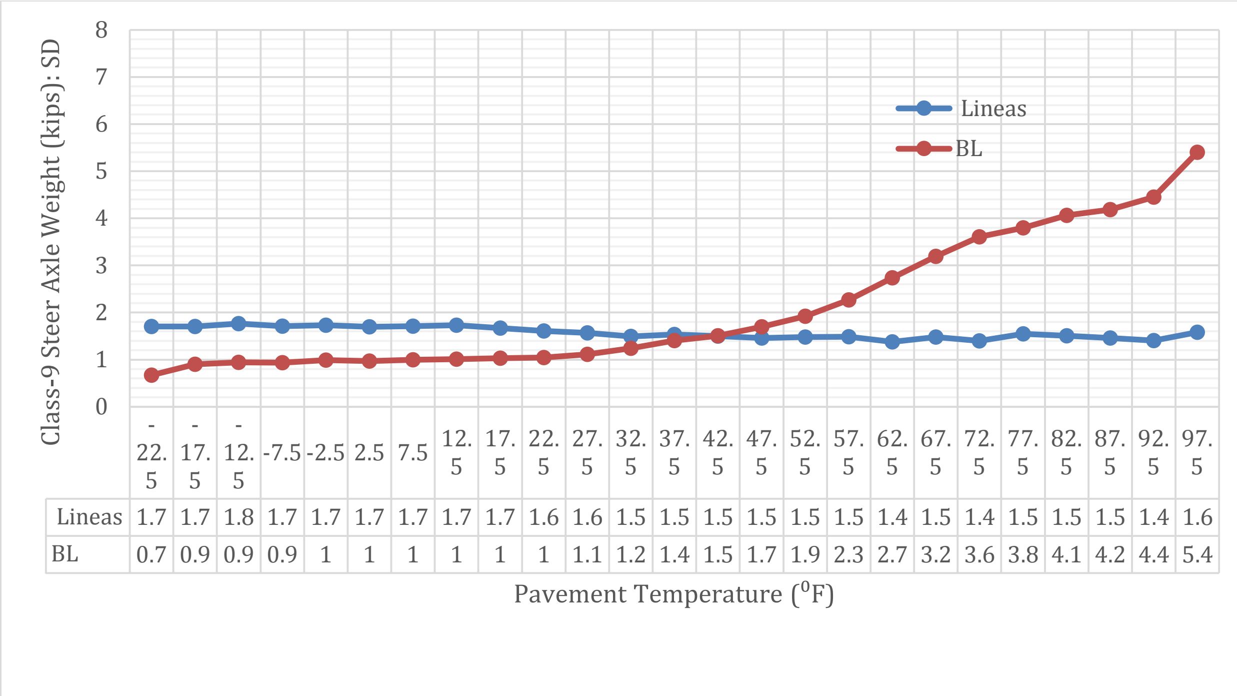


Figure 3.4: Averages of the class-9 steer axle weighs in 5ºF temperature bins



	-22.5	-17.5	-12.5	-7.5	-2.5	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5	92.5	97.5
Lineas	1.7	1.7	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.5	1.4	1.5	1.5	1.5	1.4	1.6
BL	0.7	0.9	0.9	0.9	1	1	1	1	1	1	1.1	1.2	1.4	1.5	1.7	1.9	2.3	2.7	3.2	3.6	3.8	4.1	4.2	4.4	5.4

Figure 3.5: Standard Deviations (SD) of class-9 steer axle weights in 5^{o}F temperature bins

Modeling of temperature effects on axle weights is required to properly compensate temperature effects or to remove temperature dependency. Suppose that class-9 steer axle weight, *y*, is a function of temperature, *x*, i.e.,

$$y = f(x) \qquad (1)$$

If we take 10 kips as the mean weight of class-9 steer axles, the calibration factor by temperature is given by

$$\text{Temp\_Factor} = 10/y \qquad (2)$$

The temperature-calibrated axle weight is then given by

$$\text{Calibrated\_Axle\_Weight} = \text{Measured\_Axle\_Weight} * \text{Temp\_Factor} \qquad (3)$$

Therefore, finding Equation (1) using the observed data is critical and should be the first step. First approach considered is modeling of the function using linear regression, and the result is shown in Figure 3.6. It can be observed that the slope of BL sensor measurements changes around 32^{o}F (blue dots in the graph). When the two sections are separately linearly modeled, its crossing point occurs at 38^{o}F, and the combined model is expressed as

$$y = \begin{cases} 0.0211 * x + 5.3498, & \text{if } x \leq 38 \\ 0.2426 * x - 3.0652, & \text{if } x > 38 \end{cases} \qquad (4)$$

where *x* is temperature in Fahrenheit. This linear fit function is shown in Figure 3.6 using a maroon-color line.

A more precise fit can be achieved using a polynomial function. Figure 3.6 shows a 3-rd degree polynomial function:

$$y = 0.000007x^3 + 0.0009x^2 + 0.008x + 5.0584 \qquad (5)$$

However, it must be cautioned that this polynomial fit could be an over fit and may not be a good predictor for outside the range of the available data.

In contrast, the slope of Lineas sensor measurements do not significantly vary, i.e., it only increased about 2 kips when temperature changed from -22.5ºF to 97.5ºF. Consequently, it is linearly modeled. The computed linear model with respect to temperature *x* in Fahrenheit is shown in Figure 3.8 and the equation is given by

$$y = 0.0176 * x + 9.4244 \qquad (6)$$

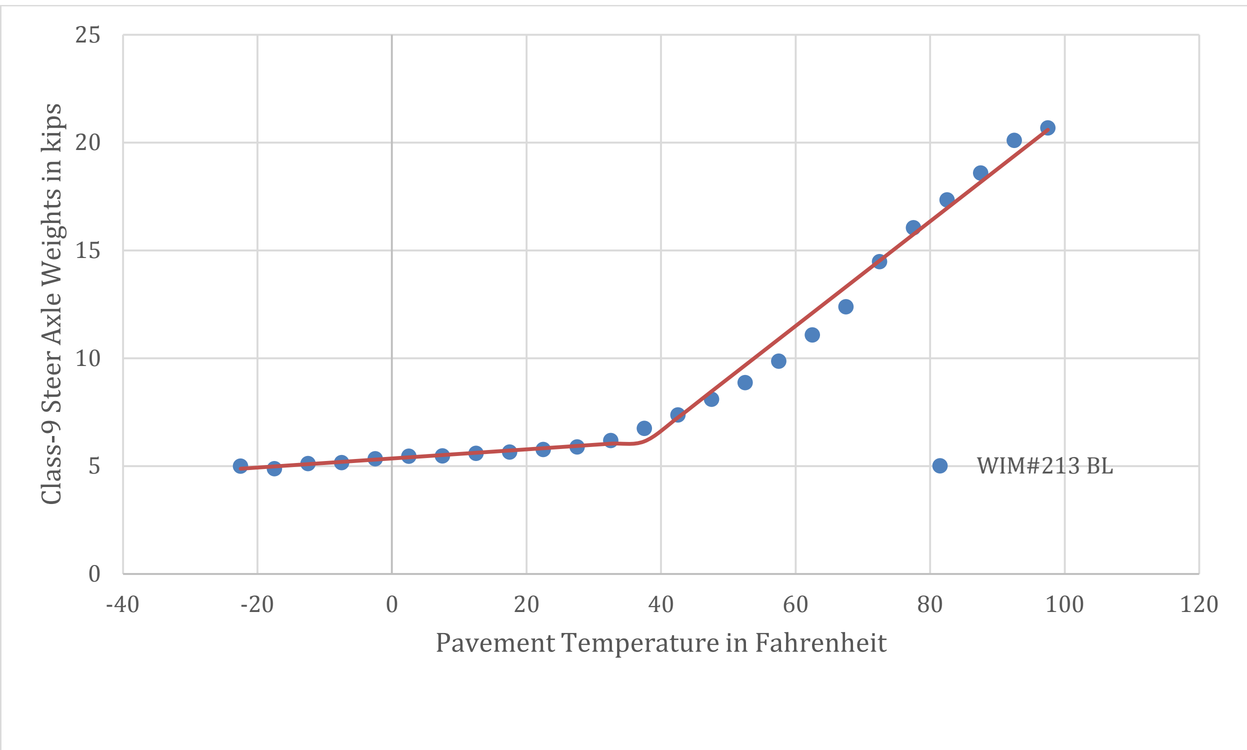


Figure 3.6: Linear modeling of BL sensor temperature sensitivity

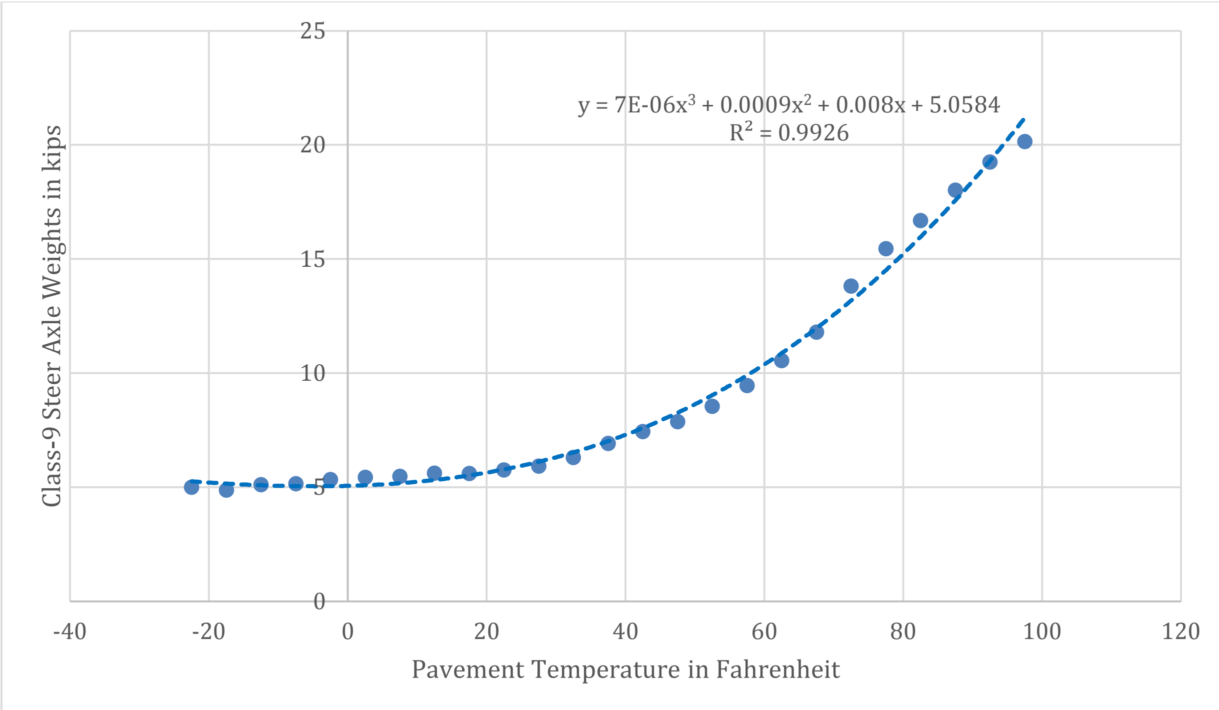


Figure 3.7: Polynomial function modeling of BL sensor temperature sensitivity

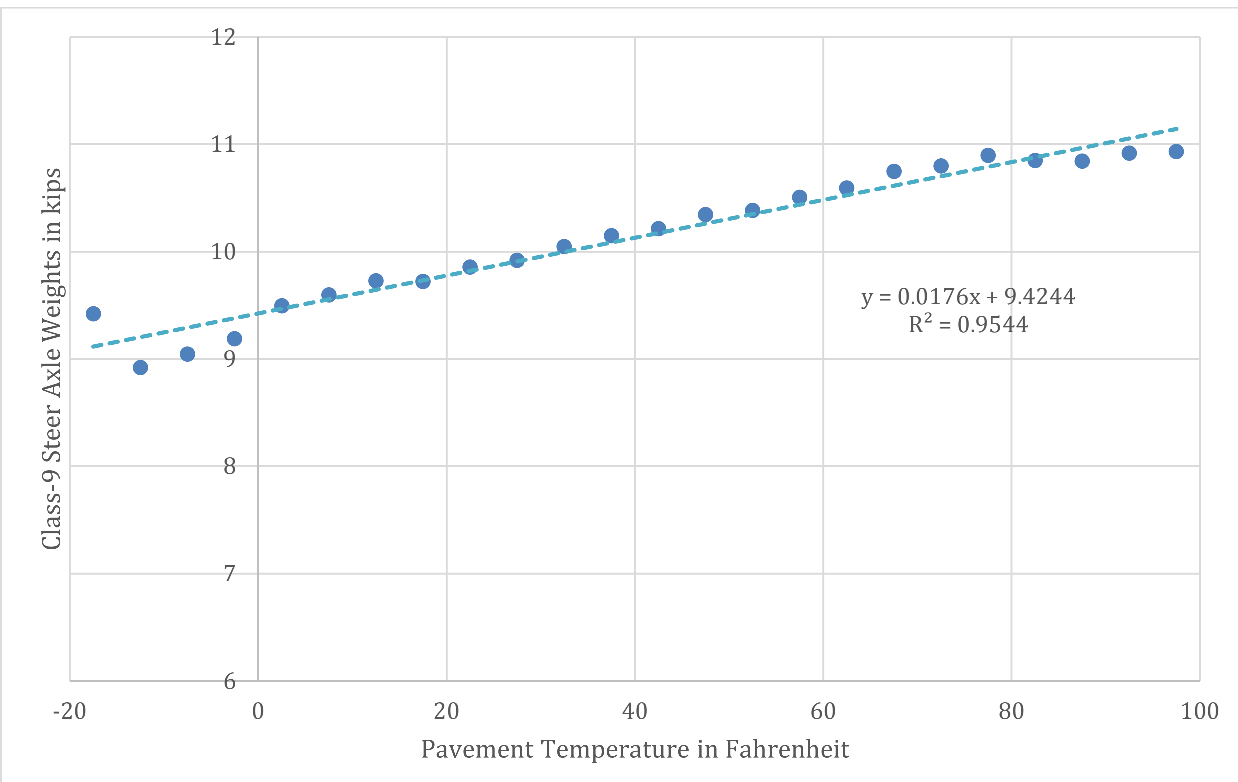


Figure 3.8: Linear modeling of Lineas sensor temperature sensitivity

3.5 Steer-Axle Weight Distribution of Before-and-After Temperature-Based Calibration

Based on the mathematical models established in Section 3.4, the axle weights can now be calibrated according to recorded temperatures. This section shows the effect of before-and-after calibration on weight distribution.

Again, the same data set, class-9 steer axle weights over 10 months, are used for this analysis. Although the computation was done for all ranges, the temperature bins are selected from one low temperature and one high temperature for graphing, i.e., (-10: -5)^{o}F and (75: 80)^{o}F for showing the results.

Figure 3.9 shows the histogram (distribution) of steer axle weights of BL sensors on two selected temperature ranges before calibration. The bin size of this histogram was 1 kip and the horizontal axis shows the mid value of each bin. Notice that the averages of the steer axle weights were shifted from 5.5 to 7.5 kips, when the temperature ranges increased from (-10: -5)^{o}F to (75: 80)^{o}F. This data clearly shows that weights increase with respect to temperature for BL sensors. Notice also that there is a much higher population in the temperature range, (75: 80)^{o}F, which simply means that more class-9 vehicles traveled through Highway 61 in summer.

The objective of temperature calibration is to move the class-9 steer axle weight distribution to approximately the same expected value (10 kips was chosen). The axle weights were calibrated using Eq. (3) based on the calibration model in Eq. (5). The weight distribution of after calibration is shown in Figure 3.10. Notice that the distribution centers are now moved to near 10 kips for both temperature ranges. Notice also that the support area of the distribution in the range, (-10: -5)^{o}F widened after calibration, and it would have matched with (75: 80)^{o}F range if more population of data are available. This indicates that temperature sensitivity can be calibrated to correct its measurement deviation.

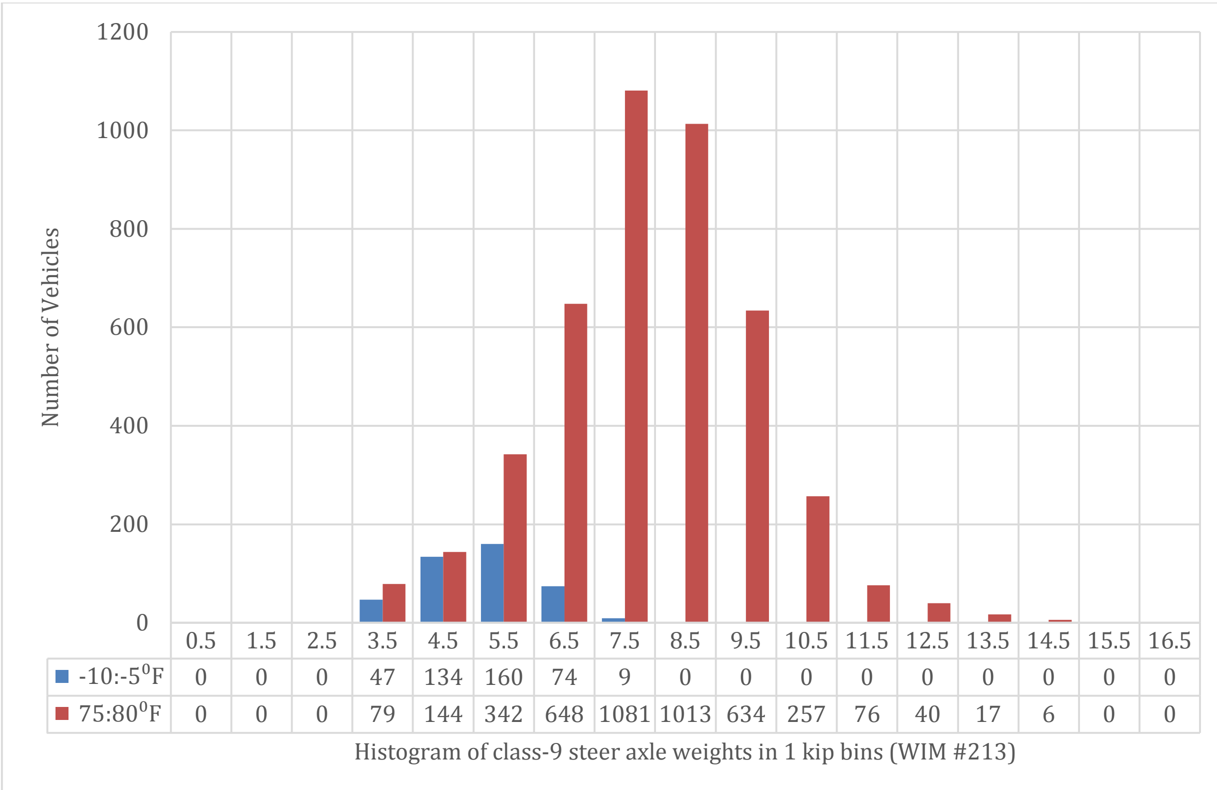


Figure 3.9: Histogram of class-9 steer axle weights of WIM #213 site in two different temperature ranges: before calibration

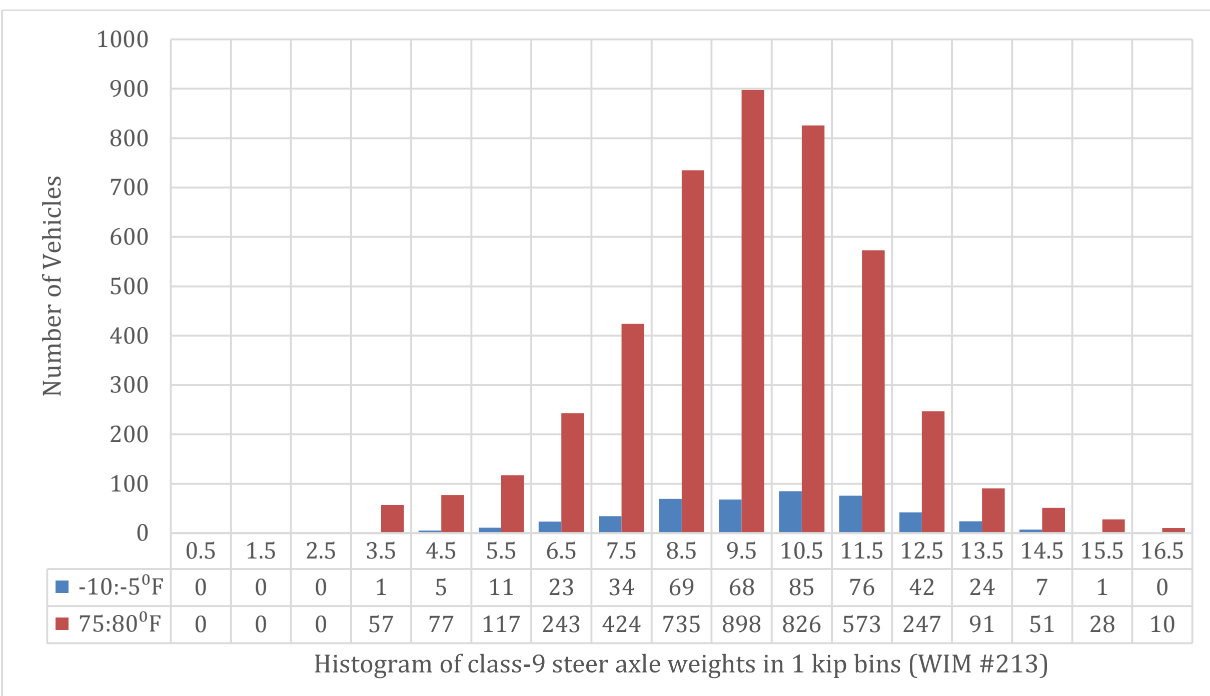
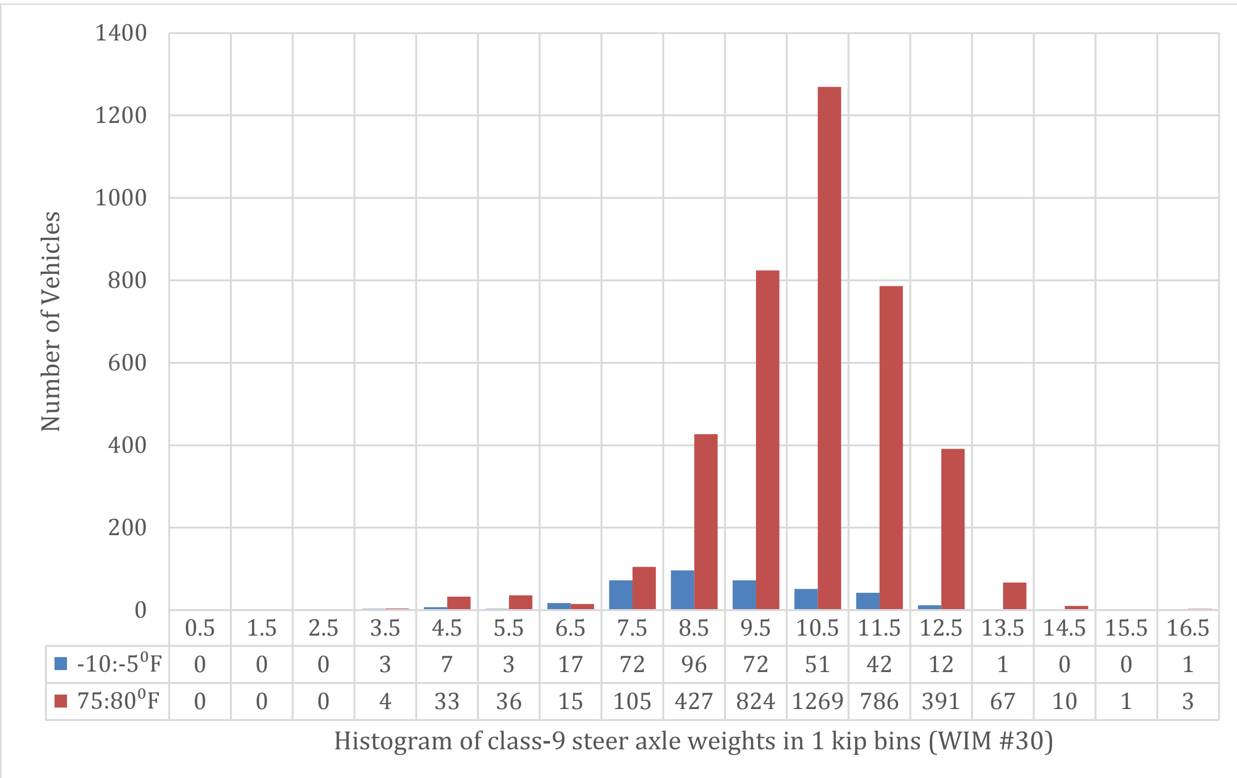


Figure 3.10: Histogram of class-9 steer axle weights of WIM #213 site in two different temperature ranges, after temperature-based calibration

A similar computation was done for the Lineas sensors (WIM #30) and plotted, i.e., histograms of class-9 steer-axle weights for temperature ranges (-10: -5)°F and (75: 80)°F. This plot is shown in Figure 3.11. Notice that the weight averages of two temperature ranges were increased from 8.5 to 10.5 kips, indicating about 20% increase of temperature influence.

For calibration, the linear mode in Eq. (6) was used for Lineas sensors (WIM #30). After calibration, the histogram was plotted again and is shown in Figure 3.12. Notice that the distribution centers are now near 10 kips for both selected temperature ranges.

Another characteristic that can be observed is that the dispersion of BL measurements is wider than that of Lineas sensors. This means that Lineas sensors would provide more consistent measurements.



	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
-10:-5°F	0	0	0	3	7	3	17	72	96	72	51	42	12	1	0	0	1
75:80°F	0	0	0	4	33	36	15	105	427	824	1269	786	391	67	10	1	3

Figure 3.11: Histogram of class-9 steer axle weights of WIM #30 site in two different temperature ranges: before calibration

	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
-10:-5^{o}F	0	0	0	1	6	4	10	33	79	89	56	52	35	10	1	0	0
75:80^{o}F	0	0	0	4	33	35	23	141	540	1012	1205	669	273	26	5	3	2

Figure 3.12: Histogram of class-9 steer axle weights of WIM #30 site in two different temperature ranges, after temperature-based calibration

In Figure 3.4, the weight averages of class-9 steer axles over 5^{o}F incremental bins in the temperature ranges from -25^{o}F to 100^{o}F were plotted. This plot was redrawn after temperature-based calibration and shown in Figure 3.13. Notice that steer axle weights are now near 10 kips on all temperature ranges for both BL and Lineas sensors. This demonstrates that temperature-based calibration can correct the deviation caused by temperature. Figure 3.14 shows SD after calibration and it shows that SD is also reduced and consistent over the measured temperature range.

The original daily-average plot shown in Figure 3.3 was redrawn after temperature-based calibration, and it is shown in Figure 3.15. After calibration, notice that both Lineas and BL sensor data no longer follows daily temperature trends, which indicates removal or minimization of temperature dependency.

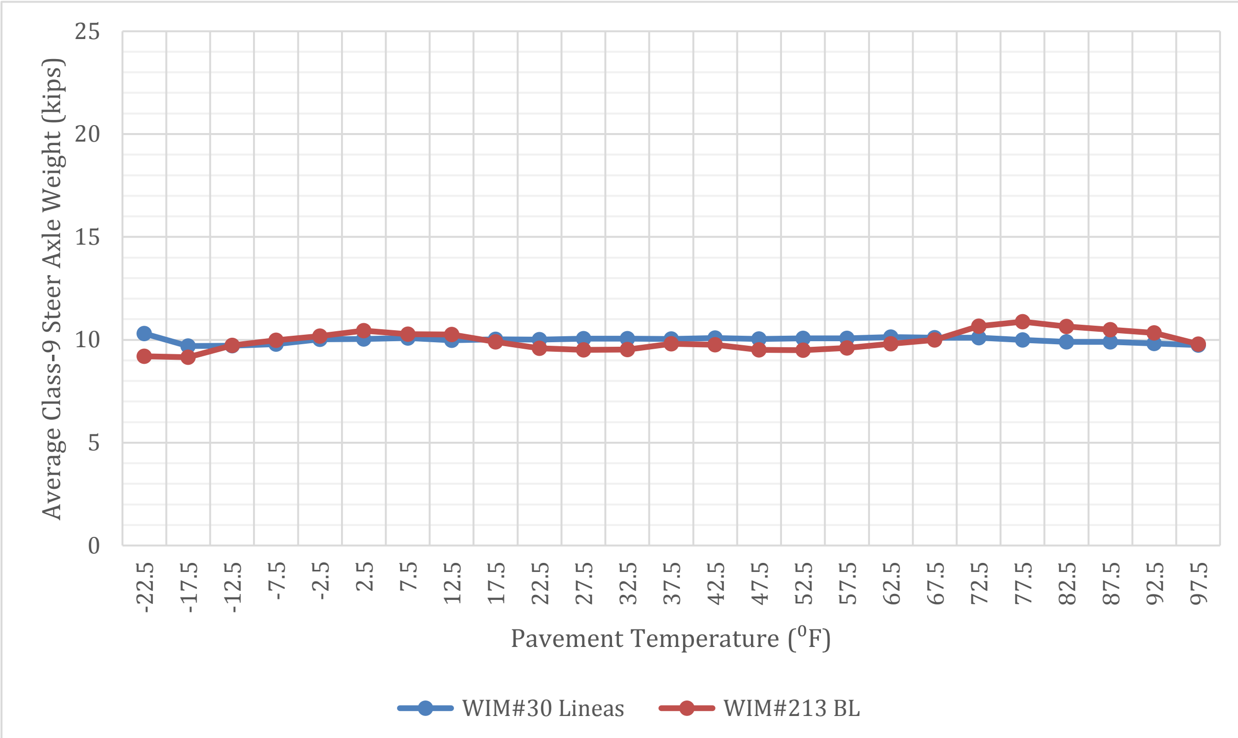


Figure 3.13: Average of class-9 steer axle weight in 5^{0}F temperature bins after temperature-based calibration

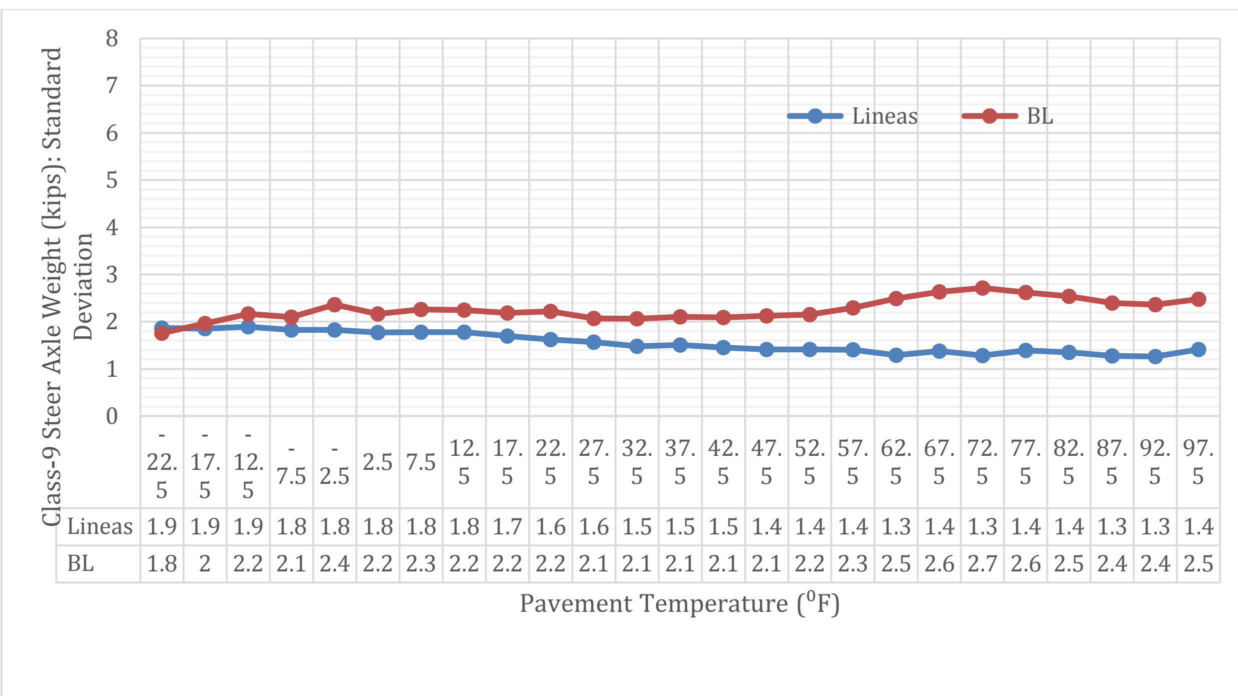


Figure 3.14: Standard deviation of class-9 steer axle weights in 5^{0}F temperature bins after temperature-based calibration

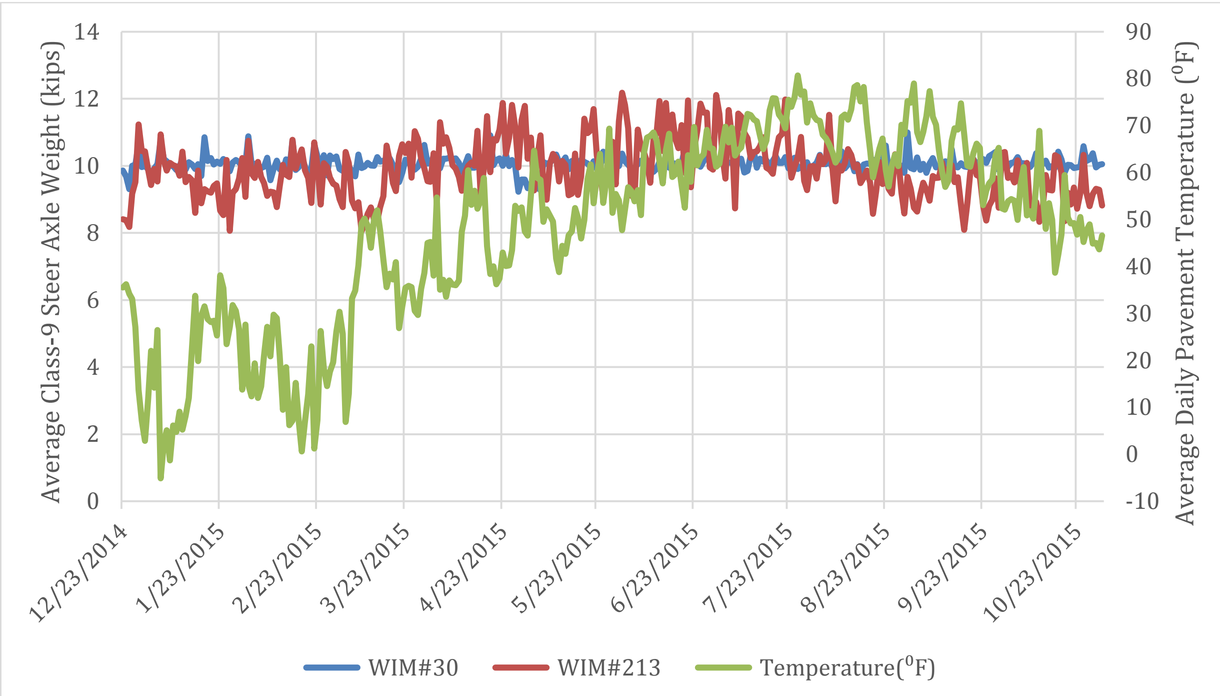


Figure 3.15: Daily average of class-9 steer axle weights and pavement temperature, after temperature-based calibration

3.6 GVW Distribution of Before-and-After Temperature-Based Calibration

In the previous sections, weight distribution of class-9 steer-axle weights on two different temperature ranges were analyzed. This section shifts the focus to Gross Vehicle Weight (GVW). It is expected that GVW distributions have a similar effect in relation to temperature.

Similarly to class-9 steer axle analyses in Figure 3.9-15, GVW data in two temperature ranges, (-10: -5)^{o}F and (75: 80)^{o}F are analyzed. There were 424 class-9 vehicles in the range (-10: -5)^{o}F and 4,336 vehicles in (75: 80)^{o}F for WIM #213. Histogram of each temperature range was computed for 1 kip bin size and its plot is shown in Figure 3.16. Blue bars show the histogram of the temperature range (-10: -5)^{o}F and red bars show the histogram of the temperature range (75: 80)^{o}F. Notice that GVW distribution appears as a distribution of two bell curves, consisting of two peaks and one valley. This is a typical shape of class-9 GVW distribution, in that the first bell curve shows distribution of unloaded vehicles and the second bell curve shows distribution of loaded vehicles. The valley of the curve occurs around 27.5 kips in the temperature range (-10: -5)^{o}F and 40 kips in the temperature range (75: 80)^{o}F. It clearly shows that the valley moves to a higher kips value as temperature rises. Moreover, the distribution is not only shifted to higher weights but also spread wider in the higher temperature range.

GVW distribution after temperature-based calibration using Eq. (5) is shown in Figure 3.17. It can be clearly seen that bell curve peaks and valleys are more in synchronous, indicating removal of temperature dependency.

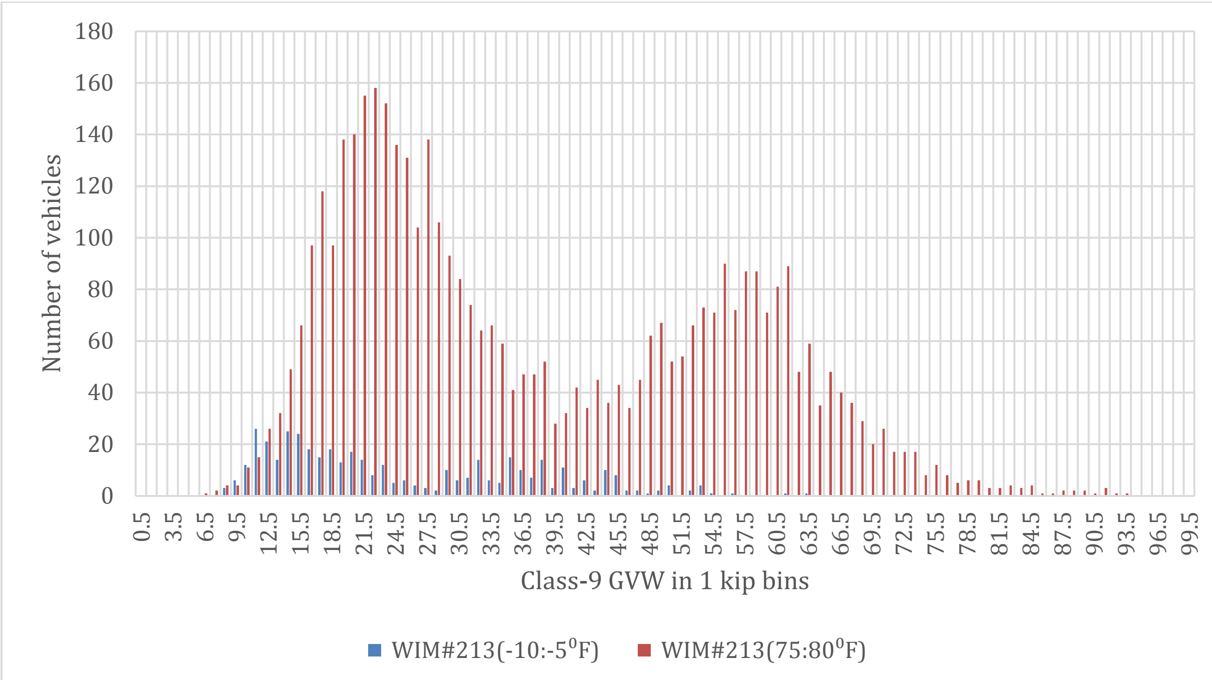


Figure 3.16: Histogram of GVW at WIM #213 in two different temperature ranges, before calibration

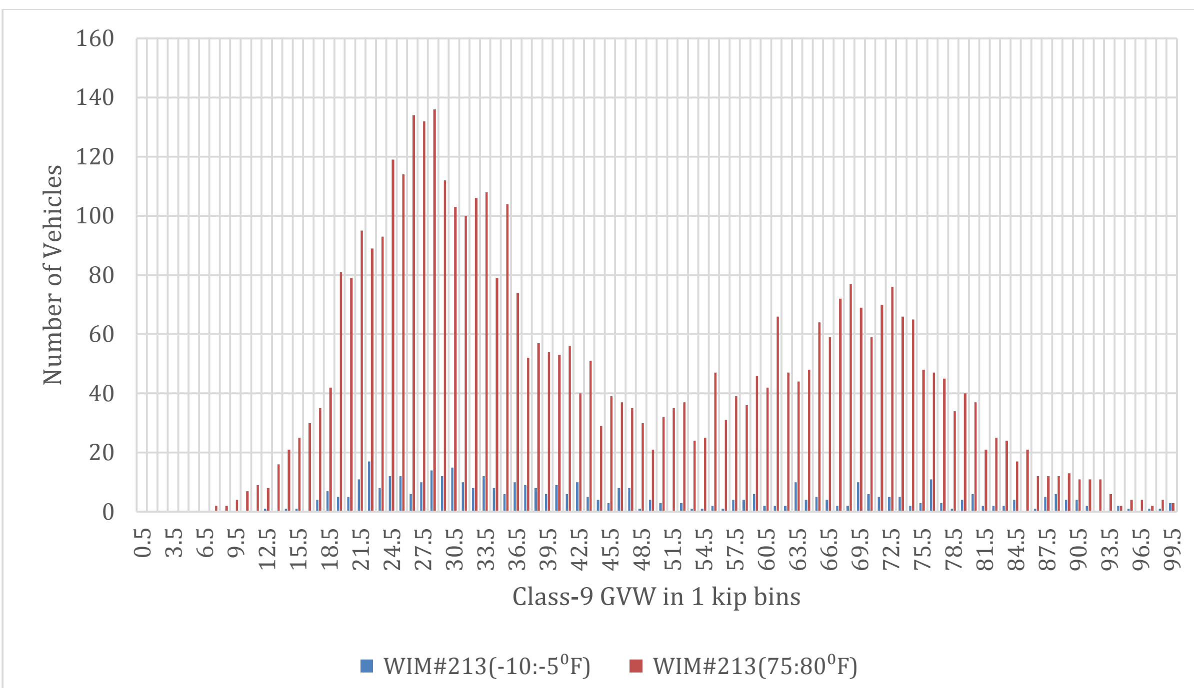


Figure 3.17: Histogram of GVW at WIM #213 after temperature-based weight calibration

For WIM #30 Lineas sensors, histograms of two temperature ranges were computed and plotted similarly to the WIM #213 data, and it is shown in Figure 3.18. The major difference from WIM #213 data is that weights are distributed in a similar range for both temperature ranges, i.e., (-10: -5)^{o}F and (75: 80)^{o}F. The valley formed by two bell curves was around 45 kips in the temperature range (-10: -5)^{o}F and 58 kips in the temperature range (75: 80)^{o}F.

Distribution recomputed after temperature-based calibration using the Eq. (6) is shown in 3.19. Notice that the difference is not as significant as WIM #213 data, but the peaks and valleys are shifted to reduce temperature dependency. This shows that it is a small amount of improvement but temperature dependency of Lineas sensor was also reduced after a temperature-based calibration.

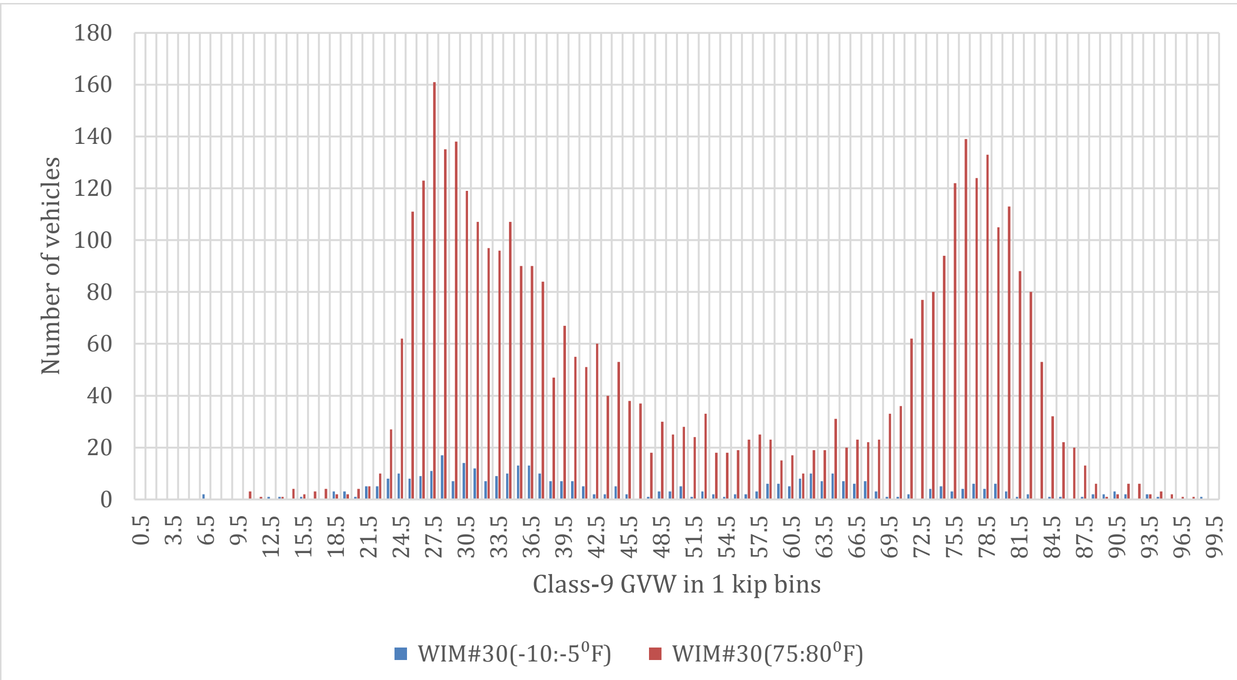


Figure 3.18: Histogram of GVW at WIM #30 site in two different temperature ranges: before temperature calibration

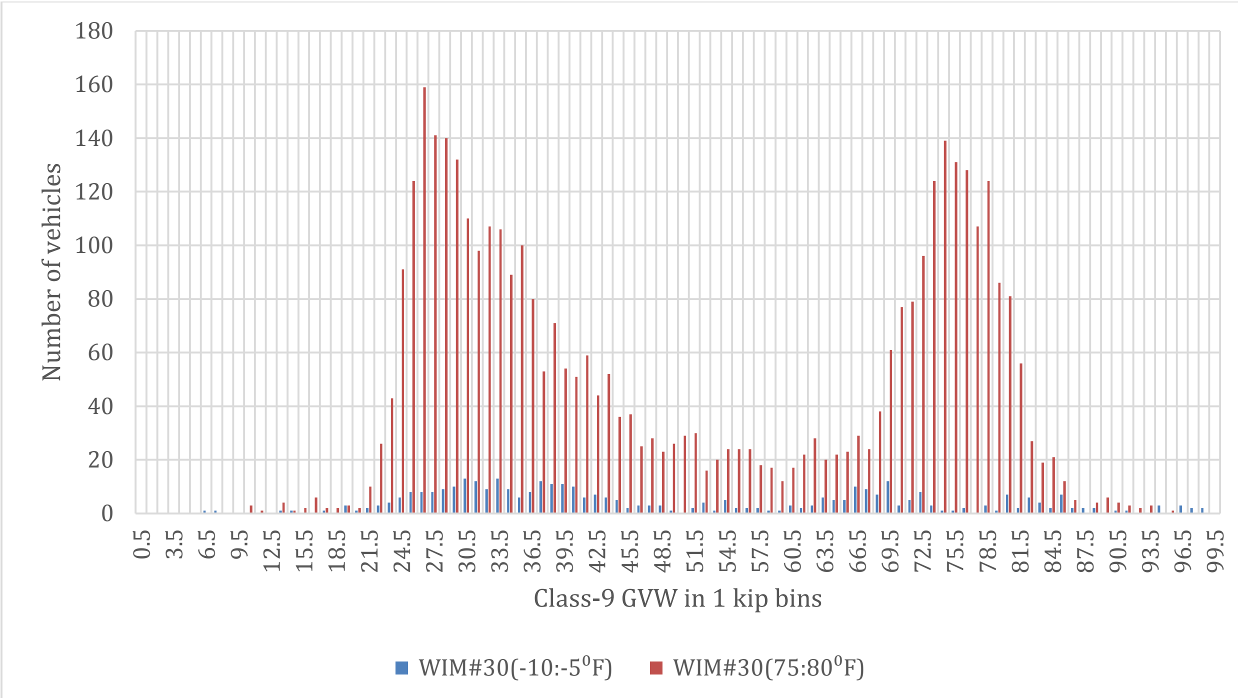


Figure 3.19: Histogram of GVW at the WIM #30 site after temperature-based weight calibration

Next, in order to observe the differences between GVW measurements by Lineas (WIM #30) and BL (WIM #213) sensors in relation to before-and-after temperature-based calibration, distribution of both sensor data are plotted in the same graph in Figure 3.20, and after temperature-based calibration in Figure 3.21. Before calibration, distribution of WIM #213 data is more skewed to lower GVW and severe displacement of curves was observed, i.e., the curves are not aligned and chaotic. After calibration, the weight distribution curves are more closely aligned together (see Figure 3.21). Especially, GVW distributions of the temperature range, (-10: -5)^{o}F, at both sites are now closely aligned in a similar spread range. However, it can be also observed that Lineas data has a narrower distribution than BL data in the temperature range (75: 80)^{o}F. This indicates that Lineas sensors are more consistent than BL sensors even after temperature-based calibration. Notice from Figure 3.21 that the loaded class-9 vehicles of WIM # 213 has a much wider width and lower height distribution than that of WIM #30. This difference is not observable from the temperature range, (-10: -5)^{o}F. This shows that SD is smaller on lower temperature ranges and larger on higher temperature ranges for BL sensors.

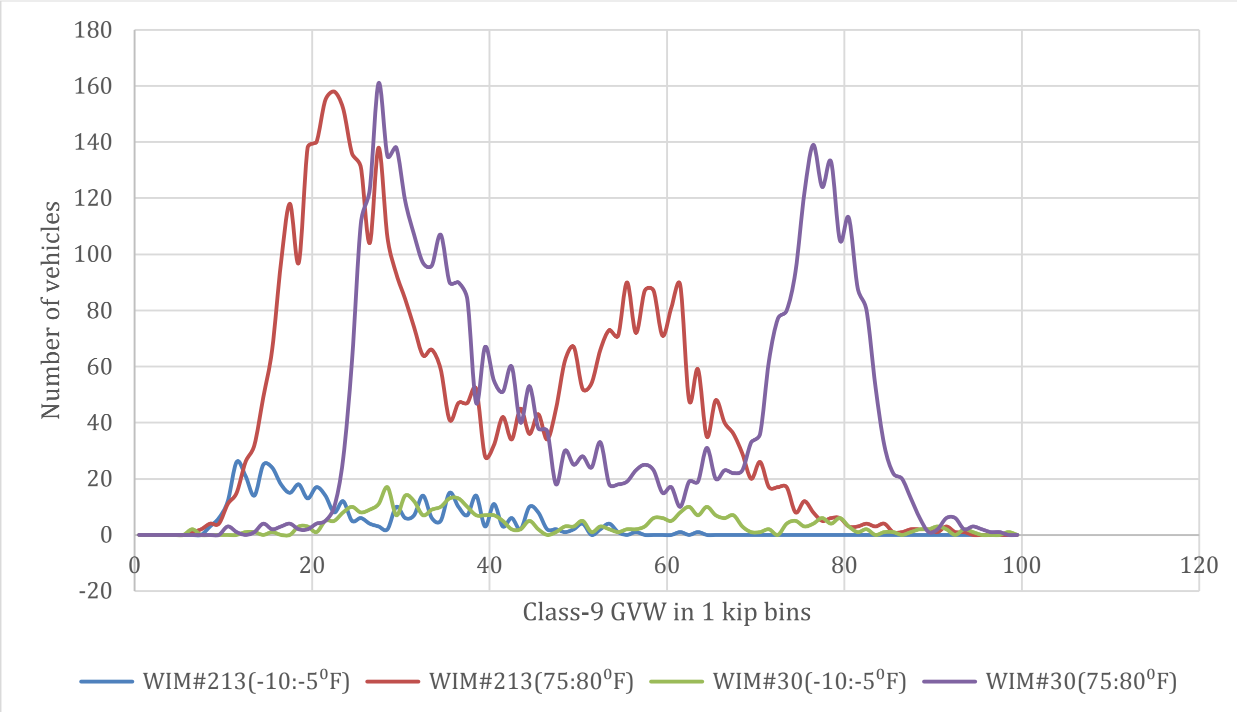


Figure 3.20: Distribution of class-9 GVW of two sites before temperature-based calibration

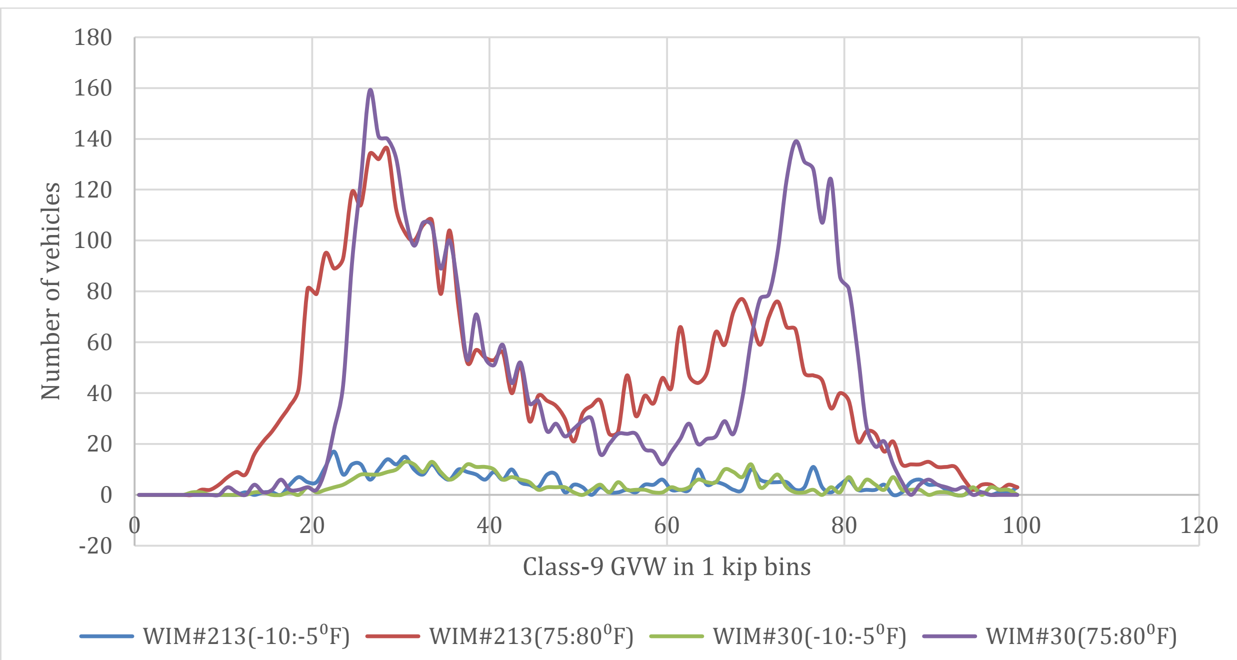


Figure 3.21: Distribution of class-9 GVW of two sites after temperature-based calibration

3.7 Vehicle Classification Comparison

This section compares vehicle classification between the two test sites, WIM #213 and #30. Tables 3.2 and 3.3 summarizes daily classification from 7/10/2015 to 7/20/2015 after calibration. It shows daily total of each class and total for the 11-day period. The daily vehicle classification data shown in these two tables are typical and can serve as samples for observation.

It can be noted that the number of vehicles in most classes are similar, except for classes 14 and 15. WIM #30 has only 24% and 12% of WIM #213, respectively. Class 14 is a type of vehicles that the classification algorithm failed to identify or classify, and class 15 are defined as vehicle fragments in the current MnDOT algorithm. Both classes are likely caused by WIM signal errors such as bouncing or thermal noise. Since WIM #213 has more vehicles in classes 14 and 15, it indicates that BL sensors are more prone to bouncing and thermal noise. A close observation of data showed that single axle vehicles were detected from some of class-2 vehicles in WIM #213 and they were classified as vehicle fragmentations. A better vehicle end detection algorithm should help reduce number of vehicles in class-15.

Table 3.2: WIM #213 Daily Vehicle Classes

Date	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14	c15	Total
7/10/2015	7614	3670	49	222	45	5	51	204	42	4	2	0	314	545	12774
7/11/2015	7018	3165	37	115	18	0	17	59	10	3	0	3	280	532	11270
7/12/2015	6441	3215	41	111	2	1	22	79	14	3	0	0	263	524	10722
7/13/2015	5718	2909	49	221	20	3	57	240	34	1	2	7	266	547	10081
7/14/2015	5412	2551	50	212	46	4	49	235	36	1	0	3	231	514	9348
7/15/2015	5556	2833	59	224	36	3	47	219	57	0	0	3	256	524	9823
7/16/2015	5992	3118	39	184	29	10	51	262	60	2	2	14	276	559	10601
7/17/2015	7185	3896	59	189	36	5	62	189	61	5	0	5	315	556	12572
7/18/2015	6633	2949	35	111	8	1	18	59	17	2	0	0	219	453	10516
7/19/2015	7094	3295	47	109	1	1	22	75	15	3	0	1	269	543	11495
7/20/2015	5826	2979	64	215	31	1	45	245	49	2	0	4	278	580	10329
Total	70489	34580	529	1913	272	34	441	1866	395	26	6	40	2969	8577	119531

Table 3.3: WIM #30 Daily Vehicle Classes

Date	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14	c15	Total
7/10/2015	7906	3887	49	230	48	21	87	197	41	8	3	0	68	136	12685
7/11/2015	7274	3265	41	122	15	11	35	48	9	3	0	1	71	145	11047
7/12/2015	6860	3235	38	115	4	21	57	72	10	3	1	0	62	75	10558
7/13/2015	6078	3016	38	243	29	11	48	222	34	1	3	8	65	42	9841
7/14/2015	5864	2673	30	197	46	12	47	208	41	1	0	3	52	47	9222
7/15/2015	6001	2954	42	204	39	18	47	194	58	1	2	4	60	55	9680
7/16/2015	6402	3230	28	221	31	26	73	245	62	2	1	15	69	74	10479
7/17/2015	7612	3985	43	215	40	23	77	174	56	8	1	6	94	110	12447
7/18/2015	6913	3054	28	116	8	11	44	51	18	3	0	1	56	109	10419
7/19/2015	7421	3482	36	104	2	4	31	74	13	5	0	1	53	141	11375
7/20/2015	6238	3143	32	217	35	12	47	233	50	1	1	5	60	89	10164
Total	74569	35924	405	1984	297	170	593	1718	392	36	12	44	710	1023	117917

CHAPTER 4: CONLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Two most commonly used WIM axle sensor types in the current market are piezoelectric polymer film sensors shielded in brass material called BL sensors and crystalline-quartz piezoelectric sensors called Lineas sensors. Building a WIM system around BL sensors using a PC-based controller costs only a fraction of the Lineas-sensor based system, but BL sensors have a high temperature sensitivity that limits measurement accuracy. Because of this temperature sensitivity problem, MnDOT has not been using BL-sensor based systems, even though they are much cheaper. The objective of this research project was to investigate the performance of BL sensors head-to-head with Lineas sensors on the same highway.

For the temperature sensitivity problem, two approaches were examined. The first approach was the new charge amplifier design used in the portable WIM system in which a time-constant based filtering was used to remove slowly changing thermal signals. This approach did not work under wide temperature swings. The second approach was recording pavement temperatures for each vehicle and adjusting axle weights based on a temperature-based calibration. The data analysis showed that temperature sensitivity can be removed in the average sense but not in the variance sense. More specifically, the average of the axle weights after temperature-based calibration was about the same for both BL and Lineas sensors, but the variance was bigger for BL sensors. This bigger variance is expected from BL sensors since its uniformity of sensor material is less consistent than that of Lineas sensors.

In conclusion, if BL sensors are used along with pavement temperature measurements and calibration, the measurements would be as accurate as Lineas sensors in terms of the average but not in terms of variance.

4.2 Recommendations

There are some recommendations that could improve accuracy of the low-cost WIM system, which are summarized below.

In the present project, k-type thermocouples were installed on the concrete pedestal of the instrumentation cabinet, instead of directly installing the probe on the pavement. This approach provided a reasonable estimate of pavement temperature with minimal efforts, but it was not as good as direct installation on the pavement. In future studies and practices, installation of temperature probes in the pavement is recommended, perhaps in the same depth as the BL sensors.

The pavement temperature range observed from this project was -25°F to 110°F which was available in Minnesota from winter to summer. However, we do not know how the weights are affected outside this temperature range, and the mathematical model developed may not work outside this range. To develop a mathematical model that covers a wider range of temperatures, it is recommended to build a temperature chamber and obtain an accurate mathematical model for the entire operating range, typically -40°F to 160°F, under well controlled environment.

It is a far-fetched idea, but combining a Road Weather Information System (RWIS) with a WIM system as an integrated station may be beneficial for applications of both data sources, i.e., WIM analysis can use weather information from RWIS, and RWIS applications can use traffic information from WIM system. Since both stations use one or more video cameras and a remote communication channel, the basic infrastructure could be shared, reducing cost. In addition, more applications for both data sources could be developed.

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