OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

DEVELOPMENT OF A PORTABLE WEIGH-IN-MOTION SYSTEM

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16. ABSTRACT

Weigh-In-Motion (WIM) data is used for a variety of roadway design and safety purposes. In compliance with Federal Highway Administration (FHWA) mandates, many states have installed permanent WIM sites to measure vehicle weight. Expanding current site coverage to include more roadways and highways requires significant roadside construction and expensive infrastructure support. Moreover, as the number of commercial trucks increases, the ability to enforce weight regulations is decreasing. The distance between inspections and roadside weigh stations for commercial trucks is often significant. Commercial trucks have been known to avoid weigh stations altogether by using bypass routes. An alternative approach to building additional permanent WIM sites is the development of a portable WIM system that provides necessary time and location flexibility for deployment. In addition to DOTs, law enforcement officials could benefit from mobile WIM stations. This project details the development and road-deployment of a heavy truck-centric portable WIM system. This novel approach is a cost-effective alternative to permanent WIM systems. At merely 10% of permanent site costs, the acquisition and quality of needed data is not compromised. This report documents the comprehensive design and development of the portable WIM site trailer; power system; sensors layout and installation method; WIM controller electronic system configuration and calibration; wireless connectivity; real-time monitoring; and data retrieval. Various WIM electronic controller devices, WIM sensor technologies, and portable sensor layouts were investigated. A number of sensor installation methods were studied. Portable-specific WIM controller calibration factors, settings, and configurations were reached. Site-specific deployment of the portable WIM system, its revised setup, installation steps, and data collection is described herein.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

ACKNOWLEDGMENTS

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THE DEVELOPMENT OF A PORTABLE WEIGH-IN-MOTION SYSTEM

Final Report
September 2013

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Executive Summary

The Federal Highway Administration (FHWA) issues the Mechanistic Empirical Pavement Design Guide (MEPDG) to aid engineers in improving states' paved road designs. MEPDG must report accurate truck weight input data to calculate optimal pavement thickness. Various US Departments of Transportation (DOTs) employ permanent weight-in-motion (WIM) sites placed primarily on interstate highways to accomplish this task. Additionally, states often install permanent static weight stations at ports of entry into their interstate highways. The cost of a single permanent WIM installation exceeds $200k. Cost for a static weight station exceeds $800k. Hence, implementing weight-monitoring systems on intrastate highways is cost prohibitive. This project reports a solution by developing an inexpensive portable WIM system made from off-the-shelf components that leverages commercially available WIM controllers. Such a system provides weight data required for use in the MEPDG. Additionally, the data can be used to aid law enforcement of weight policy violations, i.e., detect drivers traveling on intrastate highways in overweight trucks. This report describes research and testing for a portable WIM system developed from commercially available piezoelectric WIM sensors and electronics equipped with broadband modems for the purpose of collecting real-time weight data.

The developed portable WIM system is comprised of two metal galvanized steel fixtures, two piezoelectric sensors, one International Road Dynamic (IRD) iSINC Lite WIM electronics system, a computer controller, a broadband modem, and a video camera. Each steel fixture houses a WIM road sensor that enables the collection of traffic weight data. The fixtures are installed on the road using either PK nails or concrete screws—a process that requires road closure of merely 2 hours or less per lane. Sensors are placed on the road at a preset distance from one another so that upon contact with vehicle tires, the sensor generates an electrical voltage. The WIM electronics system measures the voltage, and then calibrates it to a weight measurement that is stored in the system for retrieval at a later time and/or transmitted in real-time using a cellular network provider available in the region of deployment. In addition to collecting weight data, the system is equipped with a camera to capture images of overweight trucks. Powered by solar-charged batteries, the system can collect weight data for extended deployment periods. Total cost of the developed system is approximately $20k, including trailer, cabinet, three 100watt solar panels, two 100Amp/hr batteries, iSINC Lite controller, and four piezoelectric sensors for instrumenting two lanes. This configuration was designed so only sensors need be replaced with replacement frequency dependent upon sensor handling and number of deployments. Notably, road surface sensors require replacement more frequently than traditional in-road installations at permanent sites.

The developed portable WIM was field tested on pavement and concrete sites within close proximation to permanent WIM sites. Weight data obtained at the proposed portable sites were compared with permanent sites for weight accuracy. Analyses confirmed that to obtain accurate weight measurements by the developed portable WIM system, the following conditions must be met: 1) Calibration is required upon site deployment; 2) Calibration coefficient is required for each speed bin (10 mph bin spacing is suggested); 3) Piezoelectric sensors should be installed firmly onto the road, as excessive sensor vibrations significantly decreases vehicle detection and classification accuracy; 4) Concrete screws should be used in favor of PK nails for optimal and durable roadway installation; and 5) Deployment in concrete roadways is superior to asphalt pavement roadways.

Study analyses focused on heavy trucks class 6 to 13, including the highly popular class 9 vehicles—their gross vehicle weight (GVW), vehicle classification, and vehicle speed. Results confirm that the developed portable WIM achieved accuracy for 26% GVW, 3% classification, and 4% speed measurements on concrete deployments. Inaccurate weight measurements and classification detection persisted when the portable WIM system was deployed on asphalt pavement.

Chapter I

Introduction and background

Introduction

Keeping the public's roadways, highways, and bridges in good condition is not only vital to our nation's safety, it is necessary to avoid expenditures in the billions of dollars each year for road repair and replacement. In 2009, a study of highway cost allocation conducted in the state of Oregon showed that heavy vehicles account for 79% (or $60 million) of annual expenditures required for new roadway repaving. Likewise, heavy vehicles are responsible for 66.8% (or $27 million) for pavement and shoulder reconstruction; 65.1% or (or $145 million) for pavement and shoulder rehabilitations; and 61.5% (or $140 million) for pavement maintenance [1]. Road deterioration is the result of many factors, including: road characteristics (pavement materials and thickness); weather conditions (temperature cycles and precipitation); and dynamic interaction between vehicle and road (speed, suspension characteristics, and surface roughness), in addition to loads distinguished by axle spacing, tire pressure, and weight per axle [2]. Of these, vehicle axle weight proves to be the factor most significantly accelerating road wear. "Reducing the average weight of truck axles would substantially reduce the rate of pavement wear. Reducing the load on an axle by half, for example from 30,000 to 15,000lbs, would reduce wear by a factor of roughly 16"[2]. A study of the American Association of State Highway Transportation Officials, (AASHTO) [3] found that removing a single, significantly overweight truck, e.g., 20,000lbs above the weight limit, would have the same positive impact on roadway conditions as eliminating 44,500 passenger vehicles [4]. Given this information, one can see that it is imperative to engineer a solution to reduce the rate of road deterioration resulting from heavy vehicle wear.

Both appropriately weighted and overweight trucks are chiefly responsible for rapid road deterioration. Collecting accurate weight data to aid in the improvement of pavement design, and then enforcing weight limit on highways could mitigate unnecessary wear. Accordingly, the life expectancy of roads and bridges would increase, while maintenance costs would decrease.

To slow the rate of road deterioration, weight-monitoring systems should be deployed across interstate and intrastate roadways and highways. Stated currently employ permanent weigh-in-motion (WIM) and/or static weight stations. High installation costs limit system implementation to interstate highways and state port of entries. Single permanent WIM installation costs exceed $200k per site, and static weight station installation costs exceed $800k per site. The project reported herein presents research critical to implementing an inexpensive portable WIM system to monitor and enforce heavy vehicle weight limits. The system uses piezoelectric technology to detect and weigh traveling vehicles by measuring applied force. The system integrates a commercially-available WIM sensor, controller, and camera equipped with a roadside embedded extensible computing equipment (REECE) unit.

Background and existing knowledge

For over 40 years, WIM has been considered an effective means of collecting data for highway planners, pavement designers, and weight enforcement. The American Society for Testing and Materials (ASTM) defines WIM as "the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle" [5]. Modern technologies enable WIM devices to collect dynamic information that can be compared to a static scale—defined in 1998 by the National Institute of Standards and Technology—for accurate measurement. With its dynamic capability, a WIM device can perform weight measurement for vehicles traveling at high speeds and minimize unnecessary stops and delays inherent with a more invasive type of regulation enforcement.

WIM devices are commonly divided into three categories: permanent, semi permanent, and portable systems. Each is comprised of two elements—a sensor and a controller—for data collection and analysis. Categories are differentiated based on equipment portability. Permanent devices collect and analyze data on a single location, while semi-permanent systems have sensors built into the pavement, and the system controller is moved from one site to another. Portable device equipment, as inferred by the name, can be moved as a system from site to site.

Accurately measuring vehicle weight using a WIM proves challenging dependent upon various conditions, requirements, and factors, e.g. quality of the deployment site [6]; WIM sensor installation and road placement [7]; system calibration; vehicle dynamics at the time the WIM sensor is impacted; and accurate vehicle classification.

WIM site selection criteria include grade, curvature, cross-slope, width, speed, surface smoothness, pavement rutting, visibility, and effects from dirt or leftover sand administered during winter conditions. A level grade is required to prevent the effects of weight shifting between front and back axles of a loaded truck. WIM site performance is best when traffic is traveling at a constant speed. A straight and visible section of the road should be selected to prevent drivers from changing speed or lane, and sites should be located away from highway entry and exit ramps.

Vehicle speed, acceleration, and deceleration dynamics impact the weight measurement accuracy of vehicles as they travel over the WIM sensor[8]. Likewise, vehicle air pressure and travel direction (e.g., lane changing) are also factors that impact measurement accuracy. Unlike site selection, such dynamics are beyond the control of WIM site selection.

Improving the accuracy and increasing the life span of WIM devices has been investigated extensively in the literature. Generally, researchers have discussed two approaches. The first is improving calibration techniques, which can be established by either taking advantage of statistical analysis of road pavements and vehicle data[9]-[10] or by applying signal processing techniques [11]-[12] on the originated signal by the sensor, thus increasing the system's immunity to noise. The second approach is applying new sensor technologies, such as acoustic wave WIM [13], multisensory WIM [14], fiber optics WIM [15][16], or bridge WIM [17][18], to the system. Although new technologies have been presented, WIM systems remain inadequate and suffer from high installation and maintenance costs.

WIM sensors

A completely reliable sensor is not yet commercially available. Durability, accuracy, ease of handling, on-road installation and maintenance, calibration needs and frequency, and cost are among varying factors that distinguish sensors. Following is a current list of sensor types and their published advantages and disadvantages[19].

1. Bending plate:
    - Advantages:
        - Designed for traffic data collection and weigh estimation use
        - High accuracy (more so than piezoelectric systems) and low cost (lower than load cell systems)
        - Minimal maintenance with required refurbishing after four to five years
    - Disadvantages:
        - Less accurate than load cells
        - More expensive than piezoceramic
2. Piezoceramic
    - Advantages:

    - High speed ranges (10 to 70 miles per hour) tolerance
    - Monitors up to four lanes
    - One piezoceramic
    - Least expensive
  - Disadvantages:
    - Less accurate than load cells and bending plate
    - Sensitive to temperature and speed variations
    - Replacement required within three years of deployment
3. BL (Brass Linguni) Piezoceramic
  - Advantages:
    - In addition to those listed above for piezoceramic, BL piezoceramic sensors are extremely flexible, which is significantly beneficial during installation
  - Disadvantages:
    - In addition to those listed above for peizoceramic, high output voltages (up to 35V) are generated
4. Piezoquartz (partially piezoelectric but with newer technology)
  - Advantages:
    - Negligible temperature effect enables immunity to age or fatigue
    - Accuracy and cost within load cells range
  - Disadvantages:
    - Inoperative for portable WIM application
    - More expensive than other piezoceramic technologies
5. Hydraulic Load cell
  - Advantages:
    - Most accurate
    - Inoperative for traffic data collection and weight estimation
  - Disadvantages
    - Inoperative for portable WIM applications
    - Most expensive
    - Highest maintenance cost
    - Replacement required five years after deployment
6. Capacitive Mat
  - Advantages:
    - Functional for portable WIM applications
    - Monitors up to four lanes
  - Disadvantages
    - Less accurate than load cells, bending plates, or piezoquartz WIM devices
    - Trucks easily avoid driving on the mats
    - Trucks easily damage them when applying breaks atop them
    - High equipment and installation cost are similar to those for load cell
7. Fiber-optic based
  - Advantages:
    - Light-weight
    - Immune to electromagnetic interference
    - Hostile environment insertion
    - High bandwidth capability
    - Lower cost
    - Time-saving installation
    - Low power requirements
  - Disadvantages

  - Inaccurate weight measurements when using long fibers
  - Fragile
  - Limited availability—only one known device available in the marketplace
  - Underdeveloped technology

Current portable WIM systems

Several commercial, low-speed portable WIM systems, including DAW300 PC from IRD [20], are currently available. This particular system uses portable bending plates that weigh vehicles up to 40,000lbs per axle at speeds up to 40 mph. The manufacturer claims an accuracy of ±3% at speeds < 8 mph, and ±4% for speeds between 8 and 15 mph. Hence, accuracy is inversely proportional to the speed of the vehicle.

A more precise, low-speed portable WIM system that operates for vehicle speeds of 5kph (around 3mph) is also commercially available. CAPTELS CET 10-4 SLIM [21] weighs vehicles up to 60,000lbs per axle with a declared accuracy of ±2% for vehicles traveling at the recommended speed. This portable WIM system employs metal weight pads fashioned from strengthened aluminum that are covered with a special coating.

A highly accurate, slow-speed portable WIM developed by Oak Ridge National Laboratory (ORNL) [22] was originally designed for military use to control air force cargo loads. Advanced software features enable tracking and military vehicle location services, as well as calculating vehicle center-of-balance [23]. According to army specifications, two generations were developed: first generation (WIM Gen I) accuracy was ± 3%, and second generation (WIM Gen II) was less than ±1% [24].

Dr. Taek Kwon from the University of Minnesota, Duluth has developed a weigh-pad-based portable WIM system with easy-to-install road sensors. Similar to our design, his WIM uses a RoadTrax BL piezoelectric sensor. The sensor is placed between two convey belts for rapid road installations. Notably, this configuration will not support prolonged deployment. The design includes the development of software algorithms to calculate weights from signals obtained from piezoelectric sensors [25]. Alternatively, our design uses a commercially available WIM controller that requires no software development for weigh calculations.

Portable WIM programs within the US

The research team contacted a large number of departments of transportation across the nation and asked questions about their state's WIM program. Responses were gathered via email or telephone conversations. Two summary tables are presented in this section highlighting states that terminated their portable WIM program, as well as states that currently operate portable WIM systems. Reasons for program termination are summarized in the following table. Most states obtained an elevated amount of inaccurate when portable systems were employed. A complete narration of the survey, including questions and provided answers, is provided in Appendix A of this report.

Table 1.1. States with a terminated portable WIM program

State	Reasons provided for terminating portable WIM program.
Alaska	Weather conditions affected portable WIM.
California	Portable WIM data had too many errors.
Colorado	Portable WIM data was not accurate enough, and it was costly to calibrate.

Connecticut	Department Downsized
Florida	Poor Road Surfaces, Insufficient Personnel, High Traffic Volumes
Idaho	Portable WIM data was inaccurate.
Illinois	Portable WIM data was inaccurate. Portable WIM was not cost effective or practical.
Maine	Portable WIM data was inaccurate, and the equipment was not practical to set-up.
Maryland	Portable WIM data was inaccurate, and calibration was difficult.
Mississippi	Portable WIM data was inaccurate.
New Mexico	No one knew how to use the portable WIM data.
North Dakota	Portable WIM data was inconsistent, and the sensors were too temperature sensitive.
Ohio	Portable WIM data was inaccurate.
Rhode Island	Portable WIM data is unreliable, and it is a lot of work.
South Carolina	Weather conditions, Sensors being destroyed too quickly, and Unusable Data.
Tennessee	Safety Concerns for Employees, Hard to Calibrate and Set-Up, Costly, Out-dated Equipment, Hard to Convert Data to the Appropriate Format, Reduced Need for Data
Virginia	Portable WIM data was inaccurate, and portable WIM is hard to calibrate and set-up.

Table 1.2. States with active portable WIM program

State	Operating portable WIM for
Alabama	Traffic Weight Control
Arkansas	Targeting Bridge Traffic Control and Detecting Over-weight Trucks
Georgia	Collecting Data for other Businesses or Programs
Kansas	Collecting Data for FHWA
Kentucky	Collecting Weight Data from Bridges
Louisiana	Collecting Data
Michigan	Prescreening Weight for Law Enforcement
Montana	Prescreening Weight for Law Enforcement
Nebraska	Collecting Data used for Planning Pavement Design

Report organization

This report is organized as follows; the next chapter will illustrate the integration of the portable WIM system components. A full description of the newly developed portable WIM system and its deployment is detailed in Chapter IV. Deployment test results are presented in Chapter V. Deployment data analysis is exhibited in Chapter VI. This chapter also includes a case study comparing per vehicle records for portable and permanent WIM sites.

Chapter II

Construction of portable WIM system

This chapter presents a brief description of commercially available WIM controllers. It also describes the design of the trailer used to house and transport WIM electronics and components (e.g., power, communication, and IP-based camera systems) during deployments. PEEK Traffic ADR-1000, ECM-Hestia, and IRD iSINC Lite WIM controllers were examined for implementation in the portable WIM. Table 2.1 provides a list of specifications supplied by the vendors. Further and updated information can be found on vendor Websites.

The PI and research team selected IRD iSINC Lite as the WIM controller for the portable WIM system. Their reasons were twofold: 1) iSINC is Linux-based—the only controller equipped with an Ethernet port to support real-time monitoring and remote configuration; and 2) ODOT previously selected iSINC Lite as its WIM controller for monitoring and logging traffic vehicle information at 20 permanent ODOT WIM sites.

Table 2.1. Comparison among Commercial WIM Controllers

Devices	**Peek Traffic ADR-1000 Plus**	**ECM HESTIA**	**IRD iSINC Lite-WCU**
Specification			
Working temperature:	-40ºC to +70ºC.	-25°C and +65°C	-
Counting rate	Up to 200 counts/sec per input	Up to 4 inputs (lanes)	-
Available Interval	1, 2, 5, 6, 10, 15, 30, 60 m.	-	-
Screen	Has a screen allow him to be configured and armed.	Doesn't have a screen. Should be configured using a computer connected to it.	Doesn't have a screen. Should be configured using a computer connected to it.
Hardware Capabilities			
Onboard primary memory	256 KB(128 KB for Data Storage)	(User have a choice of 1 or 4 MB memory) 4 MB is implemented	32 MB RAM
Secondary memory	PCMCIA SRAM memory card up to 20 MB	-	32 MB Flash
Microprocessor/ Processor	Intel 80C186	Each lane card is equipped with a 16 bit microprocessor. The station is controlled by a central unit.	-
Power management			
Power consumption	10 amp-hour at 6 volt	<130 mA at 12 VDC	Power consumption varies with the options selected, but typically is in the range of 10 Watts
Power supply	120 VAC, 60 Hz	110/220 VAC, 50 or 60 Hz.	90/ 264 VAC, 47 or 63 Hz
Data Management			
Ability to fetch files without software from the manufacturing company.	No (Your application can grab data files using ActiveX DLLs provided from the manufacturing company.	No	Yes
Accuracy claimed by manufacturer	±1 count/record/second input One count per interval, or better than 10% at 95% confidence on gross weight, or better than ASTM standard 13-18.	Counting : ±1,5% Speed : ±5% Long/short vehicles classification : ±5%	-
Classification categories	FHWA and EEC, and programmable classification options	99 Category	FHWA

Devices	**Peek Traffic ADR-1000 Plus**	**ECM HESTIA**	**IRD iSINC Lite-WCU**
Standalone configurability	Yes	No	No
Connection Type			
FTP	No.	No	Yes.
RS-232 Serial communication	Yes.	Yes	Yes but as RJ45 connector
Network Communication	No.	Modem is available to connect to station through telephony line	Yes.
USB Communication	No.	No.	Yes.

WIM electronic controller systems overview

In general, WIM controllers analyze piezoelectric signals and generate vehicle information records, including time-stamp, lane number, speed, axle weight, gross weight, and classification of passing vehicles. The information can be provided either per vehicle or grouped in bins based on speed or classification. The following section provides a brief overview of WIM functionalities.

Preliminary evaluation and testing of two controllers—PEEK Traffic ADR1000 and ECM Hestia— were conducted at the University of Oklahoma-Tulsa campus. The objectives were to: evaluate controller setup and ease of use; document interruption to data recording; determine suitable sensors per controller; evaluate the consistency of obtained vehicle weights; and determine if vehicle weights are dependent upon vehicle velocity. The photographs shown in Figure 2.1 were taken during a campus field test. The piezoelectric sensors were deployed over the newly installed concrete slab for the purpose of this evaluation.

Figure 2. 1. WIM controllers and sensor layout

Test procedure

The research team used two vehicles during testing; each drove over the piezoelectric sensor at a predetermined, fixed speed. Initially a Ford club wagon drove over the sensors a total of 15 times: five times at 15mph, five at 20mph, and five at 25mph. Next, a Chevrolet 2500 truck drove over the sensors five times at 15mph and five times at 20mph. Table 2.1, gives brief description of vehicle curb weights for the purpose of the evaluation. Through the remainder of this report, the Chevrolet 2500 will be referred to as “truck,” and the Ford club wagon as “van.”

Table 2.2. Test vehicles specifications.

	Truck	Van
Curb weight (lbs)	3669	5121

Sensor's setup

A class 1, 12' BL piezoelectric sensor was used in the initial evaluation. Figure 2.2. illustrates the sensor layout—two sensors with 8 feet separating them.

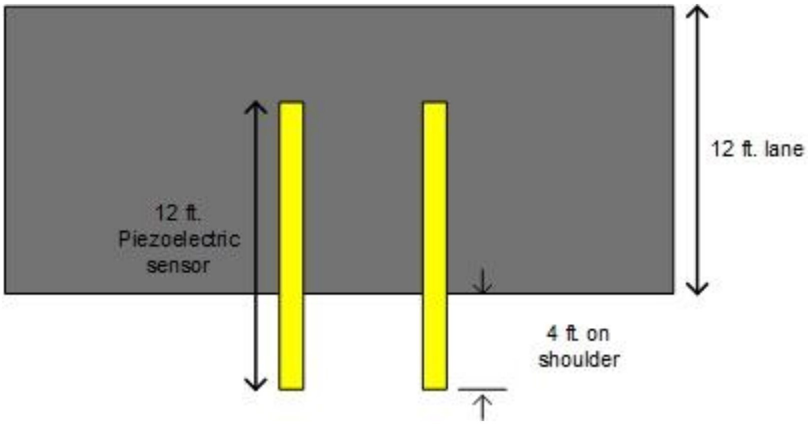


Figure 2. 2. piezoelectric sensor layout during evaluation

Micro Hestia WIM controller

Device configuration and setup is cause for concern. Although the research team evaluated station configuration/setup as easy to moderate, problems were encountered during setup. First, information pertinent to the sensors-to-station connection was lacking, primarily because configuration information was scattered throughout several manuals and documents. Second, connection-to-station was interrupted several times during configuration, although the number of disconnects decreased after setup was completed and testing commenced. Furthermore, the software packaged with the ECM controller was unable to provide per vehicle traffic information in real-time, requiring new firmware and a minor hardware modification on the device. Necessary firmware needed for us to complete our investigation was not provided by the ECM local vendor.

Test results

Test vehicle weight data was collected for five test runs at velocities of 15mph, 20mph, and 25mph. Data was consistent for both truck and van total weight and axle weight. The mean total weight of the truck was 7,010lbs; the mean for the van was 9,504lbs. Standard deviation values are 427lbs and 583lbs, respectively. Standard deviation for the truck is 6.0964% of total truck measurement mean; standard deviation for the van is 6.1378% of total van measurement mean. When compared with previous analyses, consistency among our test results is acceptable. Based on the mean and standard deviation for both truck and van, the research team concluded that weight measurements are roughly double the standard vehicle weight. Any difference was presumed to be the result of no calibration or a consequence of using a 12-

foot instead of eight-foot piezoelectric sensor. The research team believes that with proper calibration/scaling—in addition to considering the consistency of readings taken at different velocities for the same vehicle—the station output will be within acceptable boundaries. The mean for each of the aforementioned six categories—truck at 15-, 20-, and 25mph, and van at 15m-, 20-, and 25mph—was measured for comparison and to calculate actual total weights. Figures 2.3 and 2.4 show total weight output measurements and their mean for both truck and van at 15-, 20-, and 25mph. On each figure, red bars indicate total weight measurements when the driver is asked to proceed at 15mph. The mean of the five 15mph test runs is plotted on each bar. Speeds of 20mph are depicted in green and 25mph in blue. Figure 2.3 demonstrates a tendency for the truck's total weight mean to increase as the speed increases. However, this is not necessarily so for total weight mean of the van, as shown in Figure 2.4

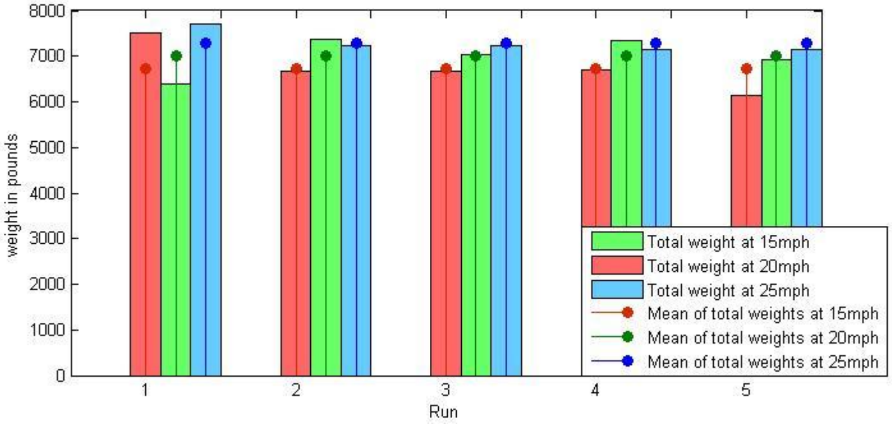


Figure 2. 3. Truck total weight data

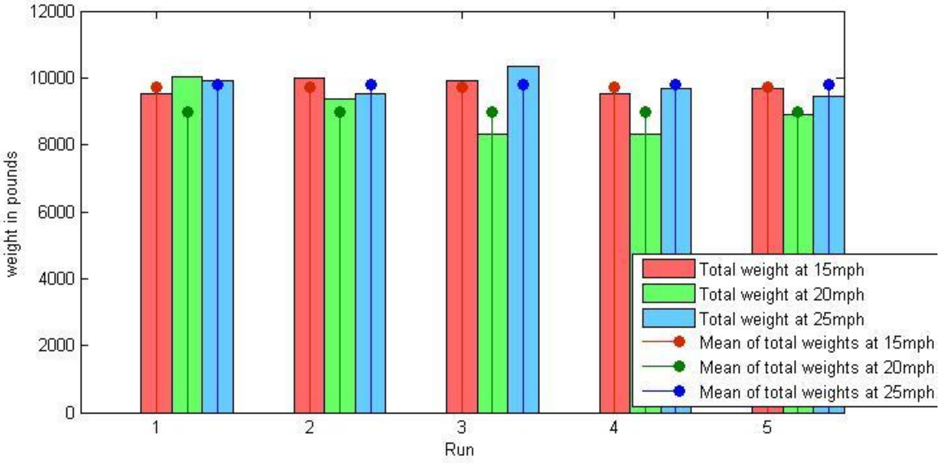


Figure 2. 4. Van total weight data

PEEK ADR-1000 WIM controller

This controller is easy to configure and use. It provides a keypad and an LCD panel to configure its parameters without the need of an external computer. It is capable of providing per vehicle records on its serial port. It will support real-time monitoring and weight measurements.

Test results

Data were collected five times for truck velocities at each speed of 15-, 20-, and 25mph. Statistically, standard deviation values based on all 15 total truck weight readings is 778lbs. The mean for each of the three speeds is measured and depicted for comparison in Figure 2.5. Using all 15 readings, the total weight mean is 4741lbs. Notably, actual truck weight is 3,669lbs. Discrepancies were attributed to lack of calibration. Figure 5 shows total truck weight readings and their mean at speeds of 15-, 20-, and 25mph..

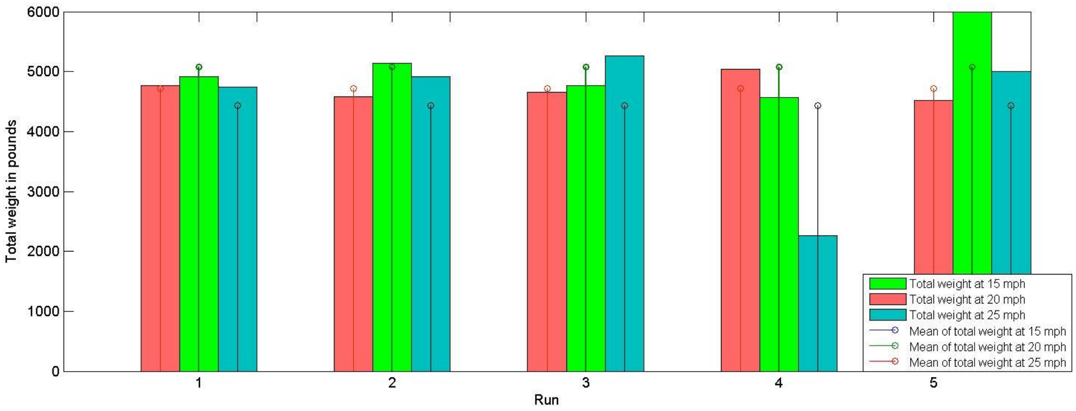


Figure 2. 5. Total truck weight

Portable WIM system design

This section describes the portable WIM system components—sensors and trailer components, including cabinet, batteries, wiring, solar panel controllers, REECE, and WIM electronic controller, among others. The overall portable WIM system logical architecture is shown in Figure 2.6.

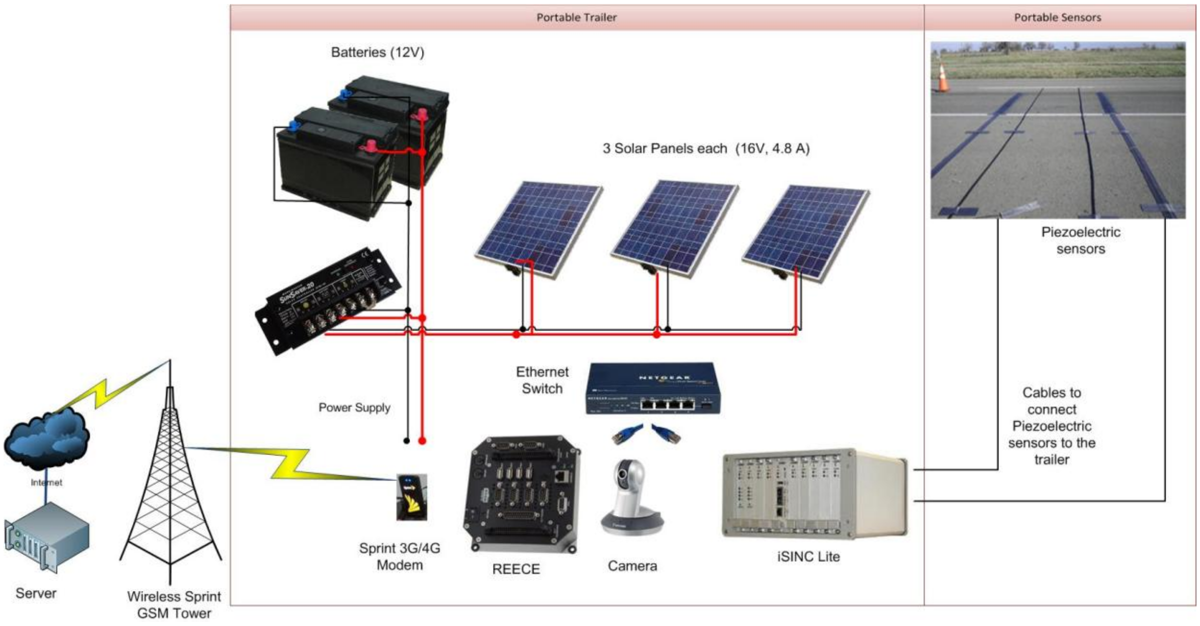


Figure 2. 6. Portable WIM system architecture

Sensors and sensors housing

Two 12-foot, class 1 piezoelectric Roadtrax BL sensors were employed in the portable WIM system. This technology has proven highly effective for traffic applications and weight measurements. The sensors are manufactured by Measurement Specialties and designed to withstand a substantial amount of weight. The sensors deliver well-shaped pulses when activated by passing vehicle axle loads. Although the sensor is relatively expensive, the special road surface deployment of the system requires this type of highly dependable and reliable sensor. See Figure 2.7. Two eight-foot metal steel fixtures were used to protect the sensors. Four inches of highly adhesive Bituthane tape with a one-inch pocket were attached to the metal plates and used to encase the sensor to protect them from direct exposure to vehicles tires. All materials can be rapidly installed on a road surface without prolonged traffic interruption.

Figure 2. 7. Measurement Specialties Roadtrax BL piezoelectric sensor

Housing trailer

ODOT supplied a trailer with cabinet for the research project. Figure 2.8 shows the trailer and cabinet prior to installing power system, WIM controller, and REECE.

Figure 2. 8. Portable WIM trailer before the installation of the power system, WIM controller and the REECE

The trailer power system was fabricated by wiring three solar panels—100 W/M2 Pro 4 JF from Siemens® Solar Industries. Maximum generated power is 75 Watts at over 4.4 Amp. Solar panels were interfaced with a Morningstar® SunSaver-20 voltage regulator to adjust and control battery current up to 20amps with 16volts for both solar and load current. Solar panels charge two 100Amp/hour deep cycle batteries, which were placed inside the trailer along with the selected WIM controller and REECE device.

IP camera

The portable WIM imaging device is critical for validating classification and facilitating enforcement implementation. Researchers used an in expensive MPEG-4 3GPP P/T Network Camera PT7135 from Vivotek® with the following features: motorized wide movement angles (Pan: +175° ~ -175°; Tilt: +90° ~ -35°); real-time MPEG-4 compression; 3GPP surveillance; and high performance in low light. The camera was controlled by a number of Application Programming Interface (API) methods.

Figure 2. 9. IP Camera

REECE and embedded software development

The REECE device is an embedded computer system with a Linux core operating system. REECE was first developed in 2005 by the PI and his research team with funds from the Oklahoma Transportation Center (OTC). Project objective was to enable remote wireless access to ODOT traffic automatic vehicle classifying (AVC) sites. Diamond Systems Prometheus was used for the embedded computing system.

A new generation Diamond Systems, namely Helios, evolved for improved functionality. The Helios 800 vortex86DX CPU processor is equipped with four USB ports, six serial RS-232 ports, PS/2 mouse and keyboard ports, 10/100 Ethernet port, and a VGA port. In addition to four analog outputs, the system has 40 digital manageable Input/Output (I/O) lines connected to a built-in Data Acquisition (DAQ) board.

Figure 2. 10. REECE device

WIM controller

Portable WIM deployment utilizes IRD iSINC Lite WIM electronic controller connected to the REECE through a crossover PC-PC Ethernet cable. This section explains the WIM system controller special configuration. The portable WIM deploys iSINC Lite to interface only with piezoelectric sensors. The following iSINC configuration is essential for appropriate portable WIM implementation:

1- Disable loops
2- Set a zero distance between axle sensors and loops
3- Interface sensors with accurate module

Subsequent mandatory configuration steps include creating a new site, configuring site parameters, and loading the classification scheme, as shown in **Figure 2.11**. Note that chosen settings and various menu factors, including the values for each menu and submenu in the settings, are illustrated below.

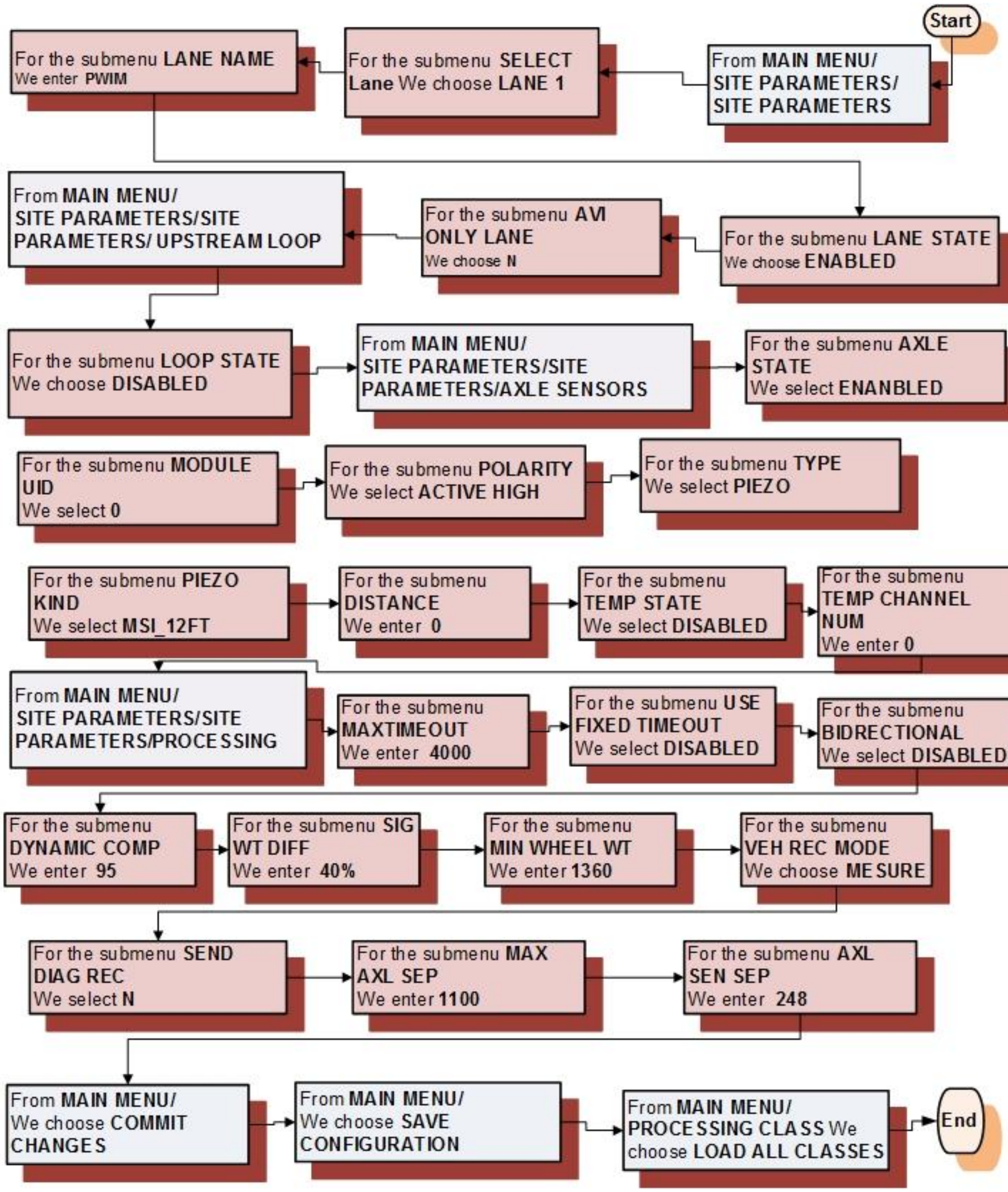


Figure 2. 11. Main steps for configuring the iSINC Lite as portable WIM station

Chapter III

Overweight vehicles detection for enforcement purposes

This chapter documents the design and implementation of a real-time system to aid law enforcement of overweight vehicles.

System overview

The newly developed portable WIM system is equipped with a video camera to capture images of all passing vehicles including overweight trucks in violation of highway regulations. The vehicle triggers the WIM controller as it comes into contact with the first sensor, setting in motion the process to determine its weight, speed, and classification. By adding a camera to the site, an overweight vehicle can be identified and reported to the proper law enforcement agency.

Each time the BL piezoelectric sensors are triggered, the WIM controller sends necessary information to the REECE via its serial port. The REECE then determines in real-time whether or not the vehicle's weight exceeds the acceptable road limit. The REECE triggers the video or image recording as the vehicle passes over the sensors. If the vehicle is overweight, the REECE sends the video/image file to the main server, along with vehicle classification, speed, GPS location, time of the detection, and weight.

Depending on the configuration of the controller, there are two methods for triggering the video/image recording. In the first scenario, the controller sends a signal to the REECE each time a sensor is triggered. In this set-up, the REECE device begins the video/image recording when the first sensor is triggered and ends when the second sensor triggered. Any type of video camera is acceptable for the system as long as start/stop recording is available on demand. In the second scenario, the controller sends the data to the REECE device only after the vehicle has passed the second sensor. In this case, the camera could be stationed pointing farther down the road

Regardless of method, video/image data of ample quality must be transmitted in real-time to the main server so an operator can precisely identify a vehicle. To achieve this, the REECE unit is connected to the Internet through a cellular network. We determined that the capacity of a single wireless broadband link was adequate to transmit video/image data in near real-time. Notably, wireless networks are heterogeneous, and wireless links may vary independently in time due to multipath.

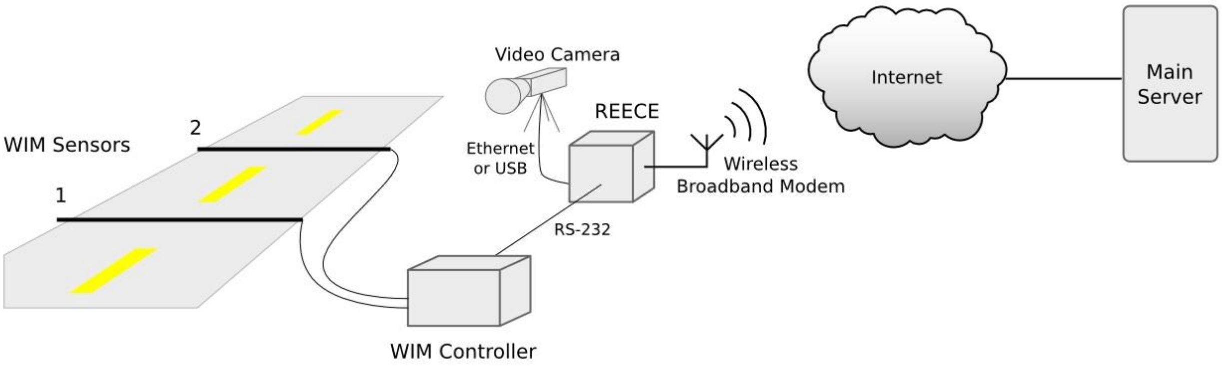


Figure 3. 1. Portable WIM system with video camera

Software design

Figure 3.2 illustrates an activity diagram of system software components. The diagram shows the interaction between the IRD iSINC Lite WIM controller, embedded software on the REECE, system camera, and visualization server. Communication from the portable WIM system to the server was secured with encryption keys. Transmitted images are securely uploaded to the server using a virtual private network (VPN) accessed only by computing entities knowledgeable of the encryption keys. This component of the system was specifically developed to alert law enforcement agencies about overweight vehicles. Real-time software was developed to capture an image of vehicles overpassing the piezoelectric sensors, and eventually show the captured image on a specially designed Website.

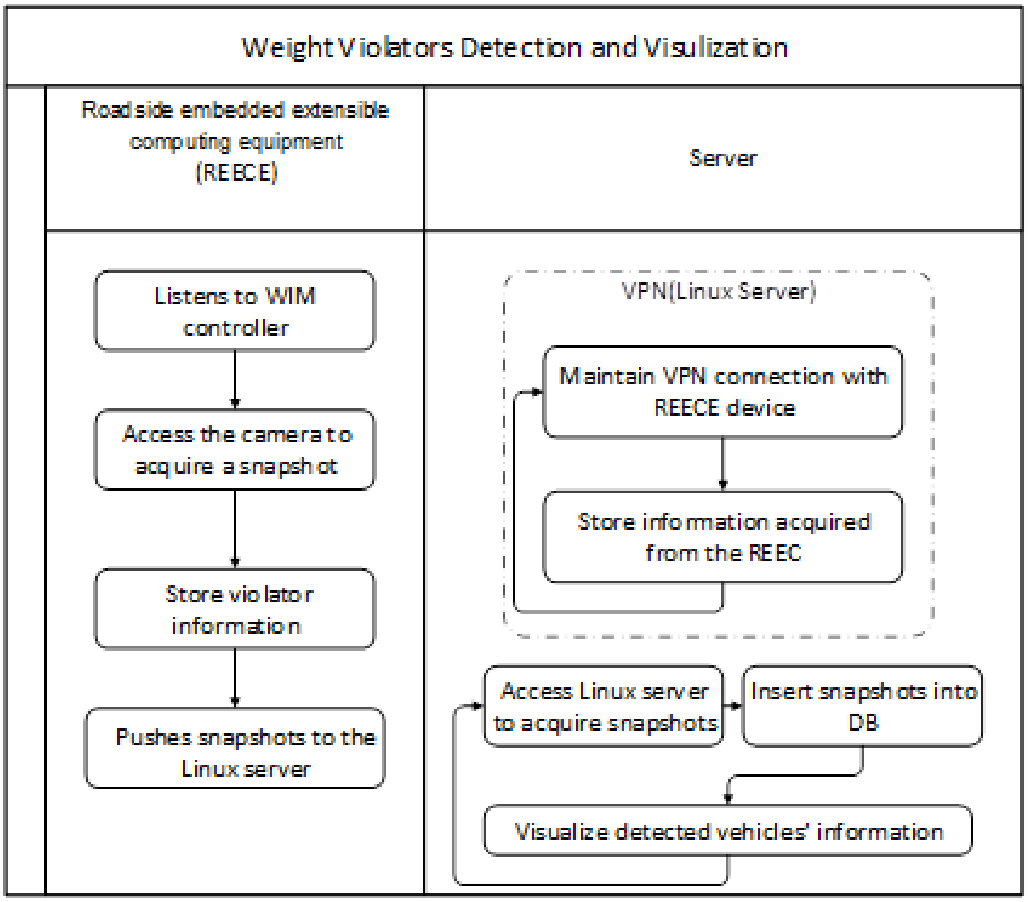


Figure 3. 2. Weight violators' detection and visualization in Unified Modeling Language (UML) activity diagram

WIM controller configuration

IRD iSINC generates a variety of real-time XML messages and sends them to a specific Transmission Control Protocol (TCP) port. Messages of this type are generated upon detection of a passing vehicle traveling on a particular lane.

Two approaches can be used for image capture of passing vehicles. One is configuring the iSINC device to generate "compliance" messages. This scheme is depicted in Figure 3.3. In this approach, the compliance option should be enabled for the iSINC unit to generate Compliance <cmpl> messages.

Various regulating settings or compliance types can be enabled to produce messages for each vehicle, e.g., maximum GVW, length, and number of axles. Vehicles that violate these predefined rules will be identified in generated compliance messages.

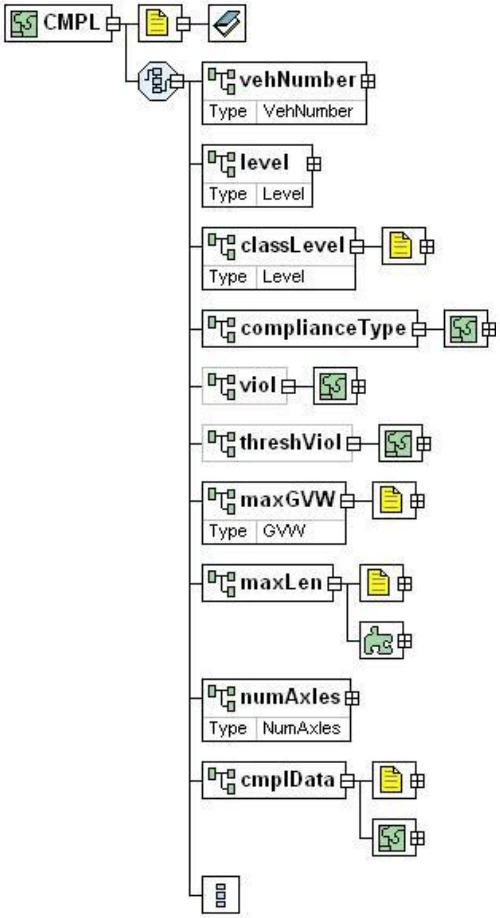


Figure 3. 3. Compliance message scheme, courtesy of IRD

The software the research team developed employs a second approach that relies on parsing the default <VehicleMesure> XML message output when a vehicle is detected. This message contains all detected vehicle parameters calculated by the WIM controller, including detection time, speed, axle spacing, and axle weight, as well as others. The embedded software verifies compliance with weight regulations based on received vehicle information. Figure 3.4 demonstrates the necessary steps for enabling the iSINC Lite to generate an XML message for each detected vehicle. Two iSINC settings, namely filter mask and filter code, can be adjusted to filter out events queued for transmission to the XML Ethernet port. With current settings in place, iSINC Lite generates an XML message for each event, e.g., time clock and vehicle detection, and many others.

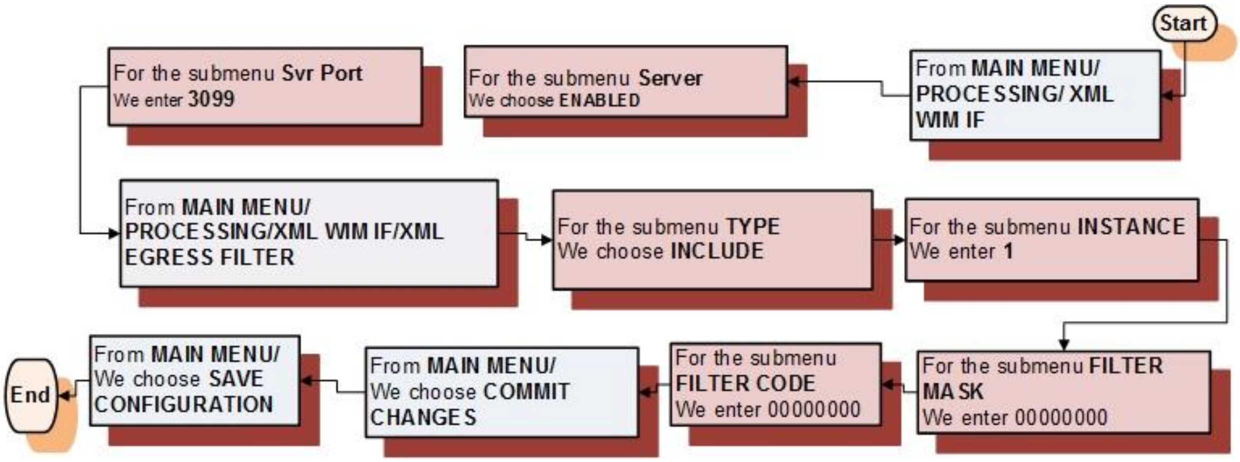


Figure 3. 4. Configuration steps to enable XML message generation

The embedded software

Design

The embedded software block diagram of implementation is described in Figure 3.5. Two software modules were developed to detect passing vehicles. The TCP Listener module listens to a specific port on the iSINC IP address, waiting for incoming XML messages. The XML Parser module processes XML message content, and then initiates a system call to the Camera Handler functionality for image capture when a vehicle is detected. Notably, this process can be configured to initiate the system call only if the XML messages indicate that the detected vehicle is overweight. Currently, this software option is not employed. Instead, the system captures images of all passing vehicles; these are continuously saved and synchronized with the server.

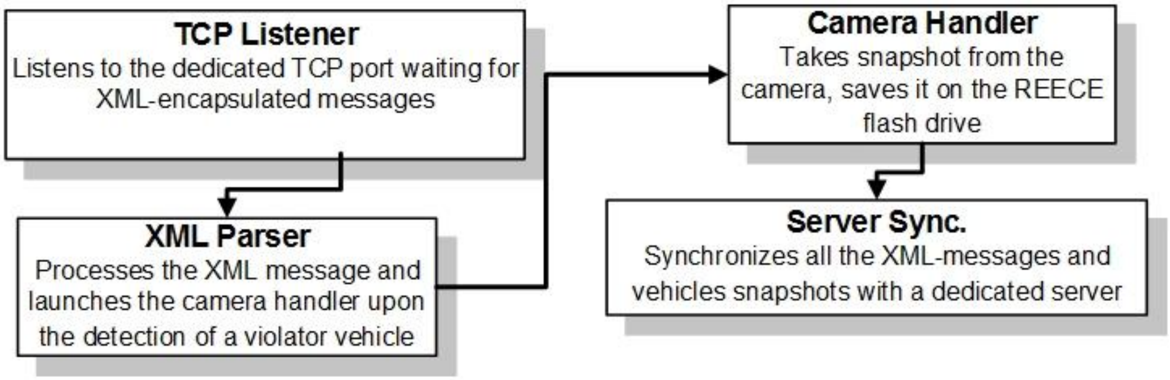


Figure 3. 5. Real-time embedded software modules

Implementation

The research team used Python programming language and Bash script for software implementation. Python library, i.e., *xml.etree.ElementTree*, is an open source solution for XML message processing of XML iSINC-generated documents. TCPListner.py is the python module developed for listening on the designated port of the iSINC IP address given any iSINC device-generated event. Following such an event, an XML message is generated by iSINC and sent to the communicating port. The TCPListner.py captures the message, and then calls XMLParser.py—a Python module for acquired XML message content processing. Upon vehicle detection, the XMLParser.py will initiate a call for Linux Camera

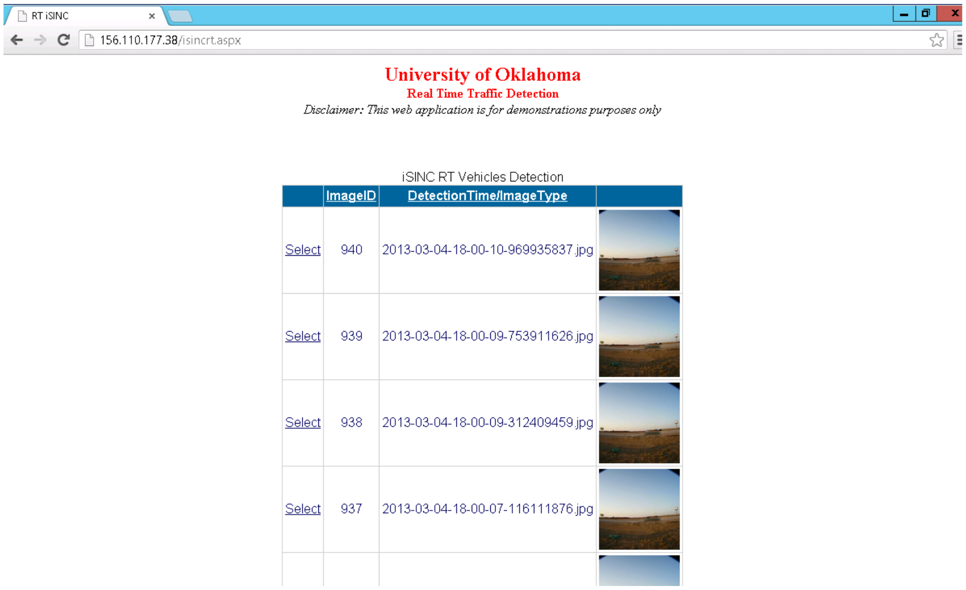
Handler, i.e., software responsible for image capture from IP-camera and data transmit to REECE via Ethernet port. The image will be saved on the REECE device flash drive under a name indicating the time at which the vehicle is detected. This procedure facilitates real-time or post processing of detected vehicle images and simplifies association with vehicle information calculated by the WIM controller.

The software executes in the background to upload vehicle images saved on the REECE to the server and manages server connection properties and status by tracking uploaded images—likewise for images not uploaded. The software is implemented in Bash script.

Visualization software

As aforementioned, the WIM controller is configured to communicate information for all passing vehicles to the REECE device software. This includes vehicle weight violation. Full design, implementation, and software testing has been reported. In addition, the portable WIM system was designed to maintain a real-time Virtual Private Network (VPN) connection with a Linux server. To facilitate weight law enforcement, the portable WIM system captures either an image or video of any detected overweight vehicle. This snapshot, along with other information about violator vehicles, is then pushed to the Linux server.

Windows Server 2012 was installed on the DELL workstation server along with Microsoft SQL Server 2008. Software was developed, and a database was setup to record and display an image of violator vehicles on a specially designed Website. Software was written in C#.Net to access the Linux server and fetch reported violator information. An open-source Secure Shell (SSH) library for .NET, namely SharpSSH, was utilized to periodically access the Linux server, fetch uploaded images, and insert them into a database. Basic conversion into stream of bytes is necessary to execute this process. An ASP.Net Website was developed to periodically present violator vehicles to law enforcement highway patrol personnel. Figure 3.6 presents a snapshot of the Web application visualization system.



University of Oklahoma

Real Time Traffic Detection

Disclaimer: This web application is for demonstrations purposes only

iSINC RT Vehicles Detection

	ImageID	DetectionTime/ImageType	
Select	940	2013-03-04-18-00-10-969935837.jpg	
Select	939	2013-03-04-18-00-09-753911626.jpg	
Select	938	2013-03-04-18-00-09-312409459.jpg	
Select	937	2013-03-04-18-00-07-116111876.jpg	

Figure 3. 6. Snapshot of the website available for local law enforcement forces

On-campus and highway field testing

System camera, REECE, Ethernet switch, and software were deployed for validation on campus and upon location at WIM05 on US69. An AC/DC power converter was used to power both Ethernet switch and camera. Figure 3.7 shows camera installation atop the cabinet for on-campus testing.

Figure 3. 7. Camera deployment

Figure 3.8 illustrates portable WIM system components housed inside the cabinet.

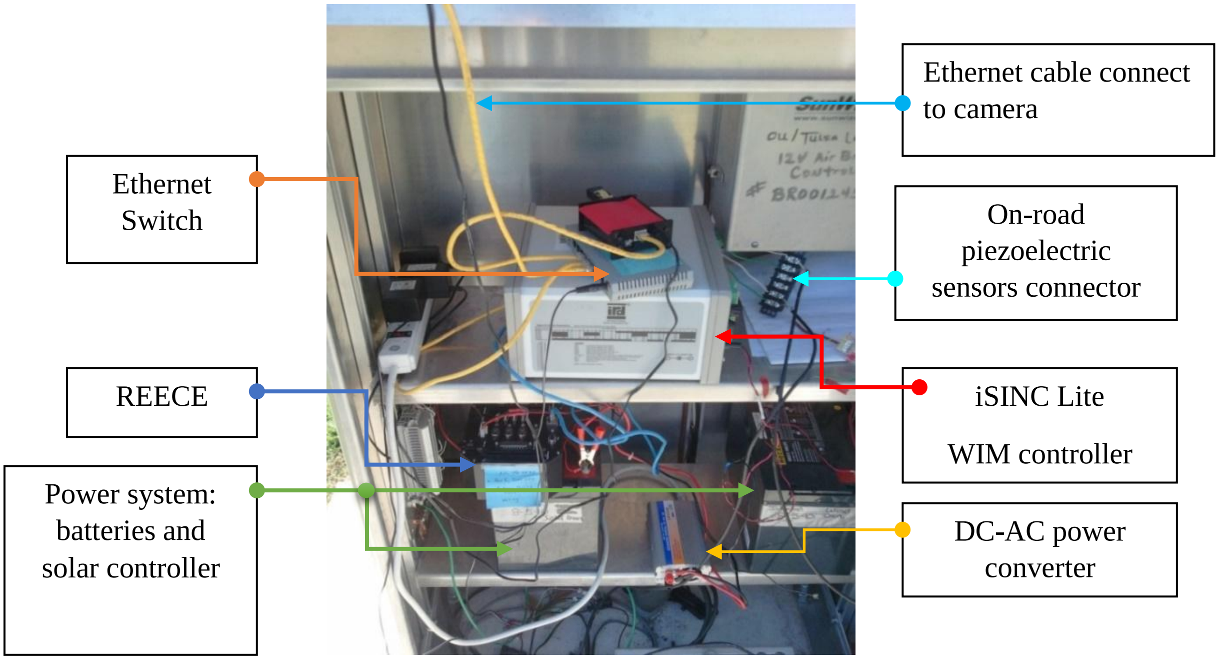


Figure 3. 8. System components with camera setup

Figure 3.9 shows sample images of vehicles captured when passing over the piezoelectric sensors. The camera detected and stored 95% of passing vehicles. Notably, it is possible that vehicles traveling at high speeds and in close proximity to one another will cause an error in detection.

Figure 3. 9. Sample images of vehicles captured in real-time using the developed software

Chapter IV

Installation and highway deployments

This chapter reports the different approaches investigated for sensor installation. The PI and his research team explored various sensors layouts, schematics, and affixing methods. Each method was characterized by a specific level of sensor vibration, number of signal ticks for each axle-tire impact, and number of undetected vehicles. Each layout and deployment required iSINC WIM controller configuration changes, including sensitivity thresholds and sensor timeouts. Results obtained from the deployments are presented in chapters V and VI.

Three sensor layouts were examined—one layout per field test deployment. The first two were deployed on pavement roadway of US69 within close approximation to the permanent WIM05 site. The third deployment was deployed on concrete roadway of US-412 approximate to permanent WIM16 site.

Sensors layouts

The three sensor layouts referenced above are detailed below:

1. Deployment one: 12-foot sensors on road surface with 8-foot section positioned in the lane area
2. Deployment two: 12-foot sensors with 6-foot section positioned on the lane area
3. Deployment three: 6-foot sensors covering 6-foot section positioned in the lane area

Initial deployments utilized a 12-foot, class-1 piezoelectric sensor to cover the majority of a standard 12-foot lane—more specifically 8 feet during deployment one and 6 feet during deployment two. A 4-foot section of the sensor was positioned on the road shoulder to protect the fragile sensor-cable connection. Sensor layout and lane coverage are shown in Figure 4.1.

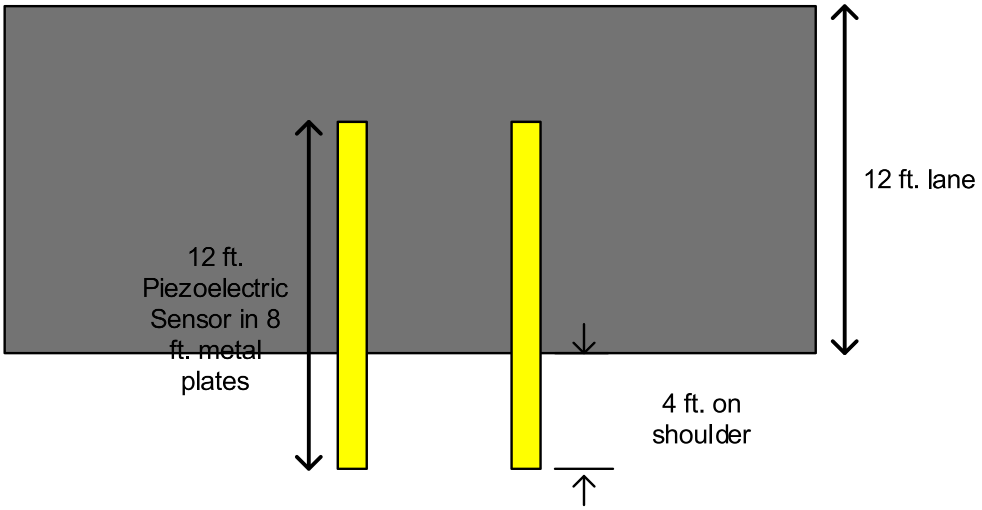


Figure 4. 1. Sensors layout in the initial deployment

After analyzing the performance of the system during deployment one and two, the team revised the layout depicted in Figure 4.1. To improve performance, the sensory area placed on the ground surface was reduced to a minimum—in this case the BL sensor length was reduced to 6 feet. Sensor signal quality from overpassing vehicles increased significantly when the 6-foot sensor was employed. The revised sensor layout is illustrated in Figure 4.2.

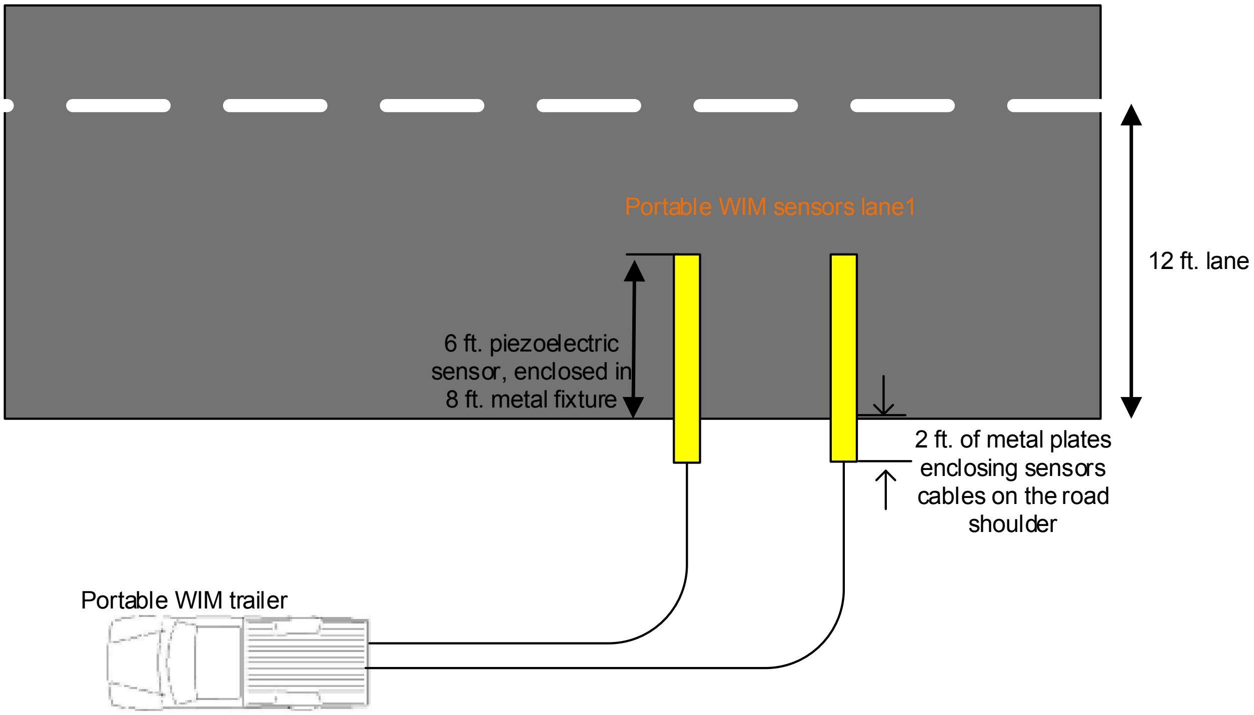


Figure 4. 2. Revised sensors layout

Performance improvement was based on minimizing propagated vibration caused by vehicle impact with either the sensors or the fixture on which the sensors are held. This was accomplished by reducing the 12-foot sensors to a more effective 6-foot length. Errant vehicle detection and classification were directly influenced by sensor vibration and number of ticks recognized by the WIM controller. A tick threshold is configured in the WIM controller to filter out noise from actual vehicles.

Sensors fixture affixing methods

As indicated earlier, sensor vibration increases errant vehicle detection. Hence, it is important that the fixture used to hold the sensors on the roadways is designed to limit vibration. The fixtures used in the deployments were made of a 22 gauge, 8-foot long sheet of steel metal cut in specific dimensions to accommodate a piece of Mar Mac tape inside which the sensor was placed. Fixture width is one foot, of which one inch on each side (edge) was folded. Nail/screw holes were made in the leading edge (that which faces traffic) every six inches and again every foot in the back edge. The center of the sheet is sanded to make it rough, and then heated to 90 degrees Celsius in order to attach the tape. Mar Mac tape was placed on the opposite side of the sheet (that which sits on the road) as a cushion between the fixture and the road. The fixture was outfitted with tape and sensor before road installation so that it could be rapidly installed on the road using a nails or screws.

To firmly affixed the sensor fixture on pavement roadway, 2.5 inch PK nails were used during deployment one; 3-inch bolt-anchors and 2.5-inch PK nails were used on pavement during deployment two; and 3-inch concrete screws were used on concrete roadway during deployment three.

Figure 4.3 presents two attempted methods for installing the metal fixtures: bolts-anchor and PK nails. The bolts-anchor method was used to examine the feasibility of preparing the road surface for portable WIM system sensor rotations. After installing the anchors, ODOT personnel would merely need to lay the metal fixtures on the road surface and screw in the bolts. The initial installation of bolts-anchors was very labor intensive and time consuming since it required drilling. For example, installing one anchor might take half an hour for inexperience installers. Also, the metal fixtures require at least 20 affixing points, making the installation of a single fixture extremely time consuming. The installation of the anchor in pavement was not successful. The fixture loosened when vehicles drove over the fixture to the point that vibration propagated to the sensor.

Consequently, the research team, switched to using PK nails. Initially the team used 1½-inch PK nails to affix the metal fixtures to road surface. Fixture vibration caused by the continuous interaction with truck tires made it necessary to replace the 1½-inch PK nails with 2½-inch PK nails.

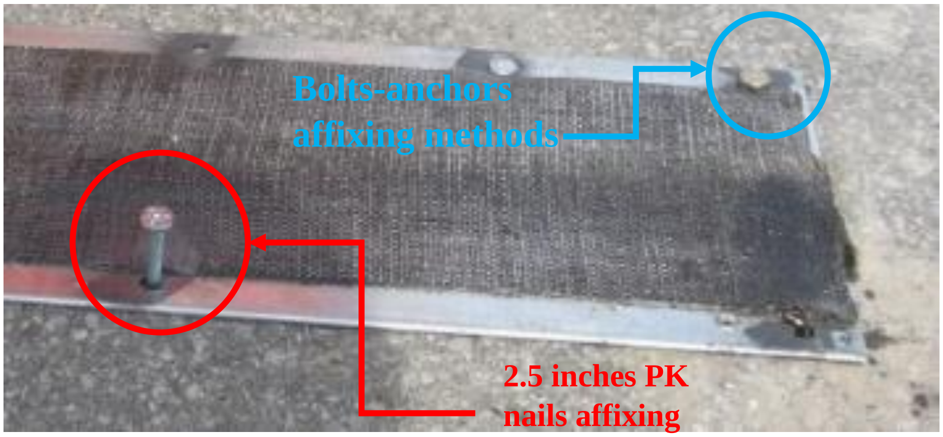


Figure 4. 3. PK nails and bolts-anchors affixing methods

Deployment three of the portable WIM system was on concrete. In this case, the research team employed 3-inch concert screws instead of the PK nails. The team drilled the concrete surface to a depth of 3-inches, and then fastened the concrete screws through the top of the fixtures. This installation limited sensor vibration tremendously and reduced the number of undetected and misclassified vehicle. Notably, each installation required an hour and a half for expert installers.

Deployment and sensor installation

The research team field-tested the newly developed portable WIM system three times, as detailed below. This section explains the selected site locations and required traffic conditions.

Deployment one

Site selection (quality, and traffic flow)

The portable WIM system was deployed on a highway section of US69 in Wagner, OK. See Figure 4.4. The site is 100-feet downstream from permanent ODOT WIM005 site. The proximity allowed a comparison of accuracy between the portable WIM and the permanent site. Vehicle flow, especially for trucks, at the selected site is extremely high. Approximate truck traffic ranges between 3,000 and 3,500 trucks/day.

Figure 4. 4. The portable WIM trailer deployed in Wagoner

Deployment steps

During deployment one, the right-most lane was instrumented with piezoelectric sensors. A number of nail types were tested and failed to firmly attach the fixture on the roadway. Metal fixtures were ultimately affixed using 2½-inch PK nails secured into the roadway using a 3lb hammer. (An attempt to use a nail gun to attach the sensor fixture was not successful, primarily because a nail gun is not designed for use with this type of nail; smaller nails would not firmly affix the fixture to the roadway.) The 2½-inch PK nails added more stability and vibration tolerance, rendering the system operable for several weeks. Prior to affixing the fixtures, piezoelectric sensors were lubricated and inserted into the pockets. Figure 4.5 shows the two installed fixtures separated by a distance of 8 feet. Two road tubes were also installed for additional measurements.

Figure 4. 5. Piezoelectric sensors and full length of the fixture covered most of the lane area

For deployment one, ODOT Division 8 provided traffic control during the four-hour installation. The following notes detail installation activities:

- Batteries were charged with an external power source prior to system deployment, primarily because when batteries lose their charge and voltage declines below 8 volts, the solar panel voltage regulator disconnects the load.
- For safety purposes, the power system was disconnected during transportation to the deployment location.
- Trailer wheels were removed after system deployment to discourage theft.
- One person hammered down the PK nails. Delegating this task to two persons would decrease installation time.

Deployment two

Site selection

The team positioned the WIM at the same site field tested in deployment one—100 feet downstream from the permanent ODOT WIM005 site in a highway section of US69 in Wagner, OK.

Deployment steps

The goal for the second deployment was to reduce the high number of undetected vehicles caused by a variable number of tires impacting the two sensors, as well as effects of sensor vibration. The team planned revisions to the first deployment accordingly, revising the layout to allow only 6 feet of the 12-foot sensor on the lane area, as shown in Figure 4.6.

Figure 4. 6. The initial piezoelectric sensors in the second deployment

Due to asphalt scraping on the road shoulder, it was mandatory that the team position 7 feet of the metal fixtures to cover the lane area. In an effort to speed up the installation process, the team enlarged the pocket tape to make inserting the sensor easier. Notably, enlarging the pocket tape negatively affected deployment. The increased space yielded the sensor ample wiggle room to increase vibration when impacted by a vehicle tire. The research team learned that in order to produce a high-quality signal, the encasing tape should be tight fitting and the metal fixtures should be tightly affixed to the roadway.

Deployment three

Site selection

ODOT permanent WIM016 site located on a concrete highway section of US-412 near Chateau, OK was selected for the third deployment. The portable WIM was located 75-feet downstream. The site is characterized by heavy traffic, although typically far fewer class 9 trucks and more passenger vehicles than travel past the WIM005 site.

Deployment steps

Best practices from the second deployment indicated the pocket tape should not be enlarged. Fishing-wire and a lubricant were used to pull the sensors from one side of the pocket tape to the other. Three-inch concrete screws were used to attach the metal fixtures to the road surface. Two portable Milwaukee battery-drills with hammering feature were initially used to drill a 3-inch hole in the concrete prior to inserting and firmly tightening the screws. Spare drill batteries and extra drill bits were carried on site for installation purposes. Single-lane deployment lasted approximately three hours and required at least two persons: one drilled the hole while another placed and fastened the fixture onto the roadway. Figure 4.7 shows the concrete installation of the fixture.

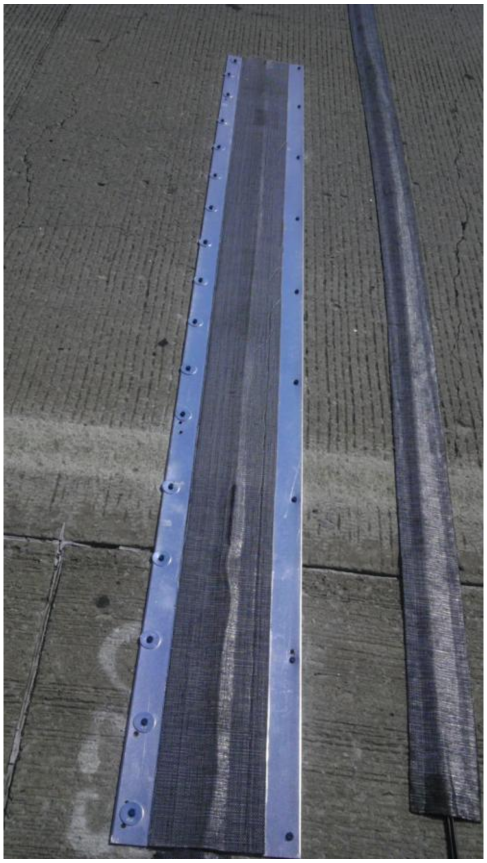


Figure 4. 7. The fixture affixing deployment three

Deployment durability

Procedures for affixing the sensors to the roadway rendered the deployed system operable for several weeks. Regardless if PK nails or concrete screws were used, the team projected that roadway installation would provide quality data for more than one month time. However, some PK nails loosened their tight grip on the metal fixture after only one week. Expected pocket-tape wear occurred, as indicated in Figure 4.8.

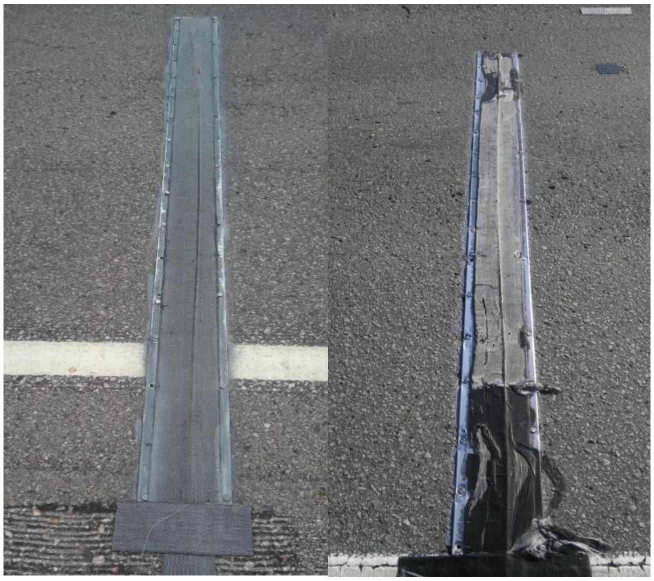


Figure 4. 8. Deployment durability sensors after 20-day deployment and then after 40 days

Chapter V

Calibration and testing

This chapter describes highway deployment and calibration procedures for the iSINC portable WIM controller. Calibration factors and configuration are utilized to achieve accurate WIM measurements. This chapter also presents results of WIM accuracy analyses conducted under a controlled environment in which a truck (hereafter known as test-truck) with known axle weight and dimension was used to evaluate system performance. Test-truck axle weight and spacing, speed, and classification performance parameters are reported in this chapter.

Portable WIM configuration

Sensors thresholds and bounce adjustments

During the first two deployments, the WIM IRD iSINC Lite controller required special configuration to overcome a significant amount of sensor vibration resulting from high-speed traffic. Additional sensor threshold-value settings were applied to the default iSINC settings at permanent WIM sites. The level of vehicle detection is highly correlated to threshold value. If set too high, the system fails to count axles; if set too low, the system falsely registers electronic noise as axle counts. Threshold range could be between 0 and 1,023. Portable WIM site threshold values proved to be significantly different from those at permanent sites, possibly due to added sensor vibration interference differences between portable sensors laid atop the road and permanent ones installed in the road. Although a threshold default value of 40 was set at permanent sites, values up to 150 were determined applicable for sensors experiencing a high number of ticks at portable sites. Sensors embedded and flush on highway surfaces typically experience between 20 and 30 ticks. Specifically for the test reported herein, the number of ticks exceeded 200 in some instances. As a result of enhanced configuration in sensor layout and concrete affixing methods used in deployment three, the system reported tick values within the range reported by the permanent WIM system. The new WIM default thresholds were then able to capture quality data.

Calibration method and special adjustments

Calibration is imperative for each deployment of every site. Results from deployment one proved that calibration factors used at permanent sites should not be employed at portable sites, as erroneous WIM measurements result. New calibration factors must be discovered using test-trucks. The portable WIM controller was successfully calibrated three times during the three highway deployments, i.e., weight measurements were accurate within acceptable error. Results were consistent and repeatable. More details are provided in the following sections.

An ODOT truckload of sand with known weight and length was used for testing. Test-truck speed at time of sensor overpass is an important factor for calculating truck weight. Hence, the WIM controller must accurately measure truck weight prior to the start of the calibration process. Minor sensor separation (distance between the two installed sensors on one lane) adjustments were performed until an acceptable speed measurement was achieved. WIM speed should match driver-reported test-truck speed. This method includes human factor error. Notably, radar technology could provide an alternative method for obtaining more accurate vehicle speed measurements. However, radar technology was not employed during calibration.

Next, front axle weight (FXW) and gross vehicle weight (GVW) were calibrated by driving the test-truck multiple times over the sensors, and then inputting average WIM readings into the following calibration factor equation:

$$New\ CF = \frac{Actuall\ GVW}{Average\ WIM\ GVW} * \text{Current CF}$$

During weight calibration, both FXW and GVW parameters can be adjusted. A tradeoff between these two exists, as the former may adversely impact overall GVW, and the latter may adversely influence FXW. Accordingly, balance between these two parameters was achieved by adaptively adjusting the parameters during calibration. Calibration factors were determined for each speed bin (e.g., 10mph) to obtain improved WIM measurements. Although the same factors could be used for all speed bins, it is important to know that WIM measurements will deviate from their true values.

The equation used to calibrate GVW can also be used to calibrate FXW. This procedure is required to obtain accurate overall weight measurements. The diagram in Figure 5.1 depicts calibration methodology.

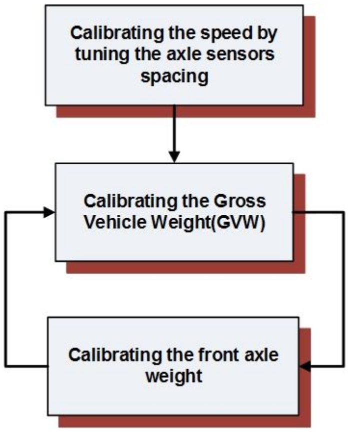


Figure 5. 1. Calibration Methodology

A second calibration method can be achieved by configuring one piezoelectric sensor as class-1 and the other as class two. As such, the latter was used only for speed calculation and was excluded from weight calculation. This methodology is recommended when results from one of the two sensors is inaccurate. Calibration steps using iSINC menus are described in Figure 5.2. Portable WIM calibration factors are significantly different from default values at permanent sites. IRD ships iSINC with default calibration factors of 4,000 for the first three speed bins. ODOT configured the permanent sites for calibration factors of 10,500. After calibration, a setting of 1,800 was used during the first and second deployments of the portable WIM controller to obtain acceptable GVW for the first four speed bins. A setting of 1,660 was used for all speed bins for the third calibration.

Field testing using test-trucks

This section describes deployment results and observations for drive tests conducted with an ODOT class 6 sand truck. Results were used to evaluate the developed portable WIM system and its ability to accurately measure weight. An evaluation of the accuracy and inconsistency of weight measurements follows.

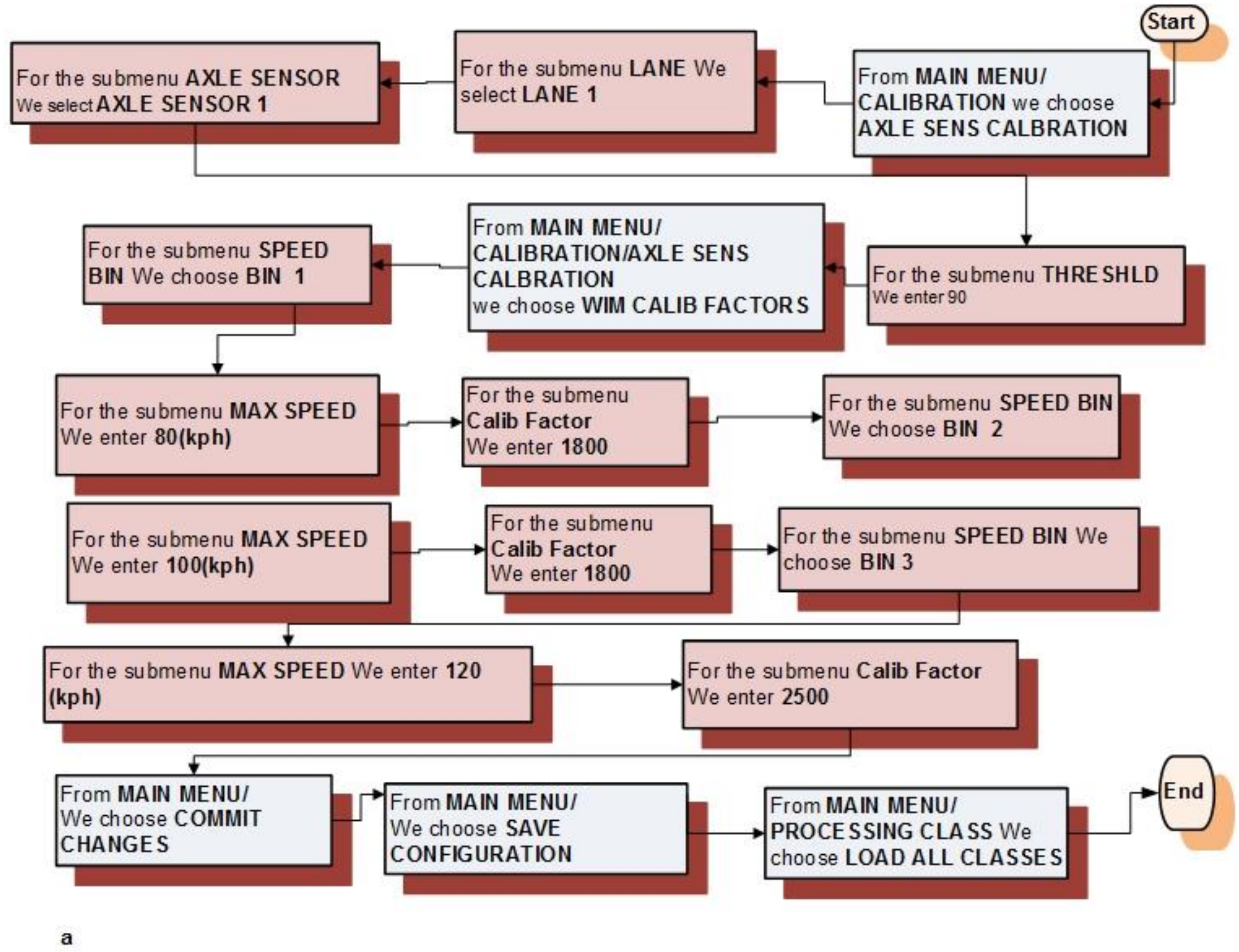


Figure 5. 2. iSINC calibration steps for one sensor in the first lane

On-site data observation

In the first two deployments, significant data errors were observed during testing:

1. *Unequal axle error*— ghost axle, wherein one axle sensor records more axles than the other. The downstream axle sensor will typically count a ghost axle.
2. *Slow vehicle error*—ghost axle detected by the first sensor and device time out before the next axle was recorded.

As previously mentioned, most errors were recorded because sensor coverage across an entire lane permitted drivers to pass over the axle sensors differently. However, the third round of testing utilized 6-foot sensors judiciously placed to permit crossing by one side of vehicles tires. This reduced errors considerably.

Data analysis for the weight recorded by portable WIM system

During this deployment a series of five calibrations and tests were conducted using a 1996 ODOT class 6, International-4900 series dt466, 10-wheel sand truck. For each drive test, the truck bed was filled with sand and weighed using a state-certified scale.

First round of drive test experiments

The first round of testing was conducted during deployment one and included 19 drive tests using an ODOT test-truck. Weight measurements collected during the first round of testing were inaccurate, and portable WIM system performance was poor. Inaccuracies were later attributed to using inappropriate factors and thresholds for system configuration. Initial factors matching those programmed in permanent/continuous WIM systems were entered into the portable WIM controller and found unsuitable for current testing given that sensors used in the portable system are positioned atop of the roadway. (Permanent system sensors are embedded in the roadway.) First round portable WIM system measurements reported excessive truck weight and did not match weight measurements reported by the permanent WIM system. As a result, excessive weight measurements caused inaccurate vehicle classification. Measurements are not included as part of this report due to significant inconsistencies and inaccuracies. Lessons learned subsequent to first round testing were critical for procedure corrections.

Second round of drive test experiments

The second round of testing included 19 drive tests using the same ODOT test-truck from round one. For some tests two vehicle wheels from each axle passed over the senor; for others only one wheel passed over the sensor. Of interest was whether or not a shorter sensor—less expensive, easier to install, and installation with fewer nails—could be calibrated so results were similar to those obtained using sensors typically longer in length. Updated initial factors and thresholds more suitable for on-ground sensor installation were selected for the second series of testing to improve weight measurements. Updated factors affected both calibration and dynamic compensation. The test-truck was again scaled using a state-certified static scale. Reported front axle truck weight was 10,400lbs; second axle weight was 29,280lbs; and third axle weight was 0 lbs. Due to scale limitations, the second and third axle weight was combined into one and reported as second axle weight only, leaving the weight of the third axle at 0lbs. Additional modifications were made to improve weight measurement accuracy. These are listed in Table 5.1 and include two sensor separation adjustments to improve speed measurements and the configurations of two new calibration factors. Measurement results and analyses are presented in Table 5.2.

Table 5.1. Modifications made to the system factors and thresholds

Run	Configuration Made During Testing.
5	Sensor separation increased by 2cm
8	Sensor separation increased by 2cm
10	New calibration factors*
11	*Dynamic compensation= 90% instead of 80%*
13	New calibration factors*
14	*Dynamic compensation= 94% instead of 90%*

Average GVW measured by the portable system was 44,171lbs with an error of 11% when compared to actual test-truck GVW. Standard deviation of the first axle weight was 1,081lbs with average error of 6%. Standard deviation for the second and third axles was 3,558lbs. Notably, the portable WIM accurately classified the test-truck during all drive tests. Table 5.3 summarizes results obtained from the second round of drive tests. Front axle spacing is the distance between the front and second axles, while second axle spacing is the distance between the second and third axles.

Table 5.2. Portable WIM second test campaign

Run	FAS (inches)	SAS	Length (inches)	Speed (mph)	1st axle Weight (lbs)	2nd axle Weight (lbs)	3rd axle Weight (lbs)	GVW (lbs)
1	Not Detected (Vehicle Too Slow- Unequal Axle Count on Sensors)							
2	Not Detected (Vehicle Too Slow- Unequal Axle Count on Sensors)							
3	137	59	196	56	8,073	16,636	19,154	43,863
4	150	50	201	55	12,641	20,146	19,903	52,690
5	137	52	189	55	10,199	18,357	20,357	48,913
6	140	48	189	56	8,580	18,607	23,640	50,827
7	138	49	187	55	8,824	17,356	20,322	46,502
8	144	54	197	58	9,865	16,454	14,969	41,288
9	146	52	198	58	9,110	17,796	16,297	43,203
10	141	50	191	57	9,493	17,421	16,707	43,621
11	141	52	194	57	9,330	17,478	17,090	43,898
12	145	54	198	58	10,341	18,341	16,414	45,096
13	141	52	192	57	10,185	17,011	15,882	43,078
14	146	51	196	57	10,137	16,310	15,432	41,879
15	137	53	189	57	10,040	16,451	15,745	42,236
16	145	52	197	60	9,392	15,450	15,626	40,468
17	139	53	191	54	10,088	14,983	15,106	40,181
18	142	53	194	54	10,763	14,884	15,206	40,853
19	139	54	193	57	10,419	16,592	15,296	42,307
Mean	142	52	194	57	9,852	17,075	16,286	44,171
SD	4	2	4	2	1,018	1,358	4,735	3,620
Actual Weight of the test-Truck					**10,480**	**29,280**	**0**	**39,760**

Table 5.3. Portable WIM second test campaign results summary.

	Gross vehicle weight	**First axle weight**	**First axle spacing**	**Second axle spacing**
Actual	39,760 lbs	10,480 lbs	145 inches	53 inches
Mean	44,171 lbs	9,852 lbs	142 inches	52 inches
Standard Deviation	3,620 lbs	1,018 lbs	3.8 inches	2.4 inches
Average Error	**11%**	**6%**	**2%**	**1.9%**

The driver of the test-truck was asked to pass the sensors at various speeds in order to examine a relationship between GVW and the speed at which the truck impacts the sensor. Figure 5.3 compares the truck’s measured total weight with its actual weight as a function of speed. Measured average truck weight was 4,000lbs heavier than actual weight. Standard deviation was 3,620lbs. Hence, achieved accuracy of weight measurement was limited to less than 12%.

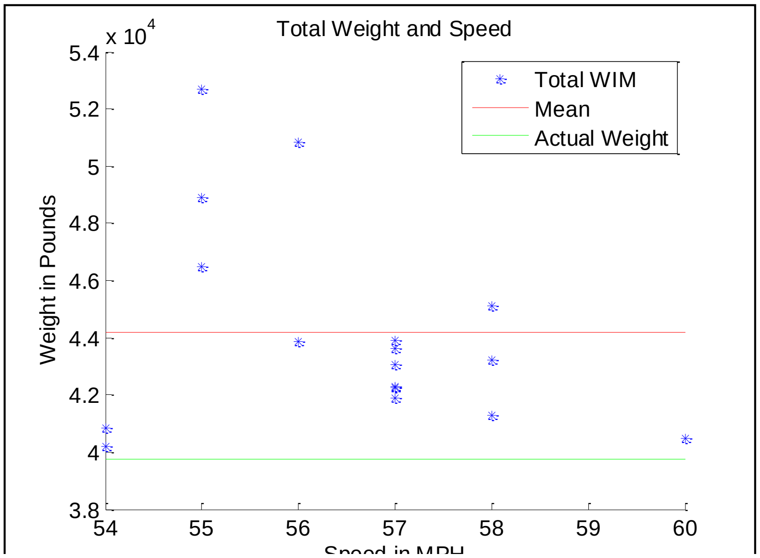


Figure 5. 3. Truck WIM versus speed during round II drive test

Observed weight measurement was speed dependent, i.e., as speed increases truck weight is lower. Further investigation is needed to confirm this phenomenon.

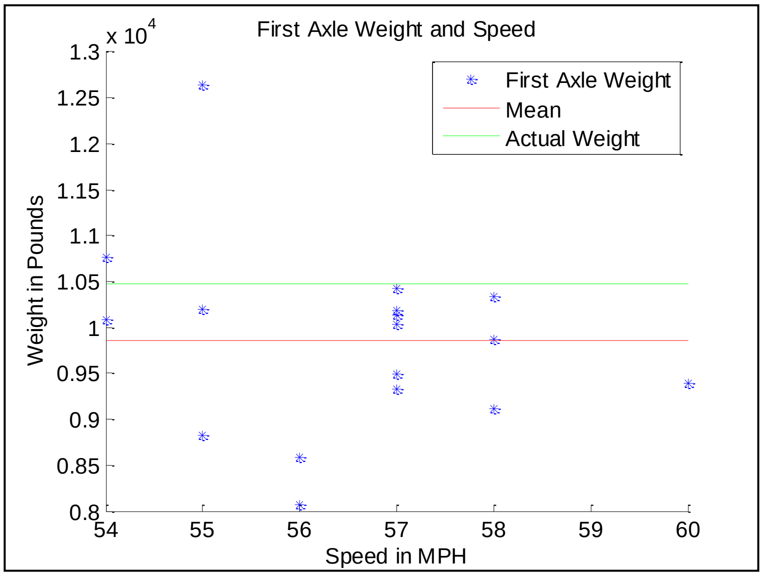


Figure 5. 4. Front axle weight versus speed during round II rive test

Third round of drive test experiments

The third series of drive tests included 13 runs using the ODOT test-truck loaded with a sand weight different from previous tests. Tests were conducted during deployment two. System calibration factors were adjusted following the sixth run. During one test drive the truck's front passenger tire became flat. Tire replacement affected weight measurements and required a factor modification for improved accuracy. Weight measurements reported by the portable WIM system are listed in the following table.

Table 5.4. Portable WIM third drive test round

Run	*1st Axle Spacing (inches)*	*2nd Axle Spacing (inches)*	*Length (inches)*	*Speed (mph)*	*1st axle (lbs)*	*2nd axle (lbs)*	*3rd axle (lbs)*	*GVW (lbs)*
1	153	52	205	60	9,318	13,353	11,911	34,582
2	144	54	198	58	8,454	14,174	12,405	35,033
3	153	51	204	58	9,592	13,574	11,171	34,337
4	156	54	210	58	10077	10,774	11,594	32,445
5	154	52	206	58	10,628	13,503	11,025	35,156
6	150	54	203	58	10,284	13,054	11,109	34,447
7	150	52	202	59	10,394	13,838	11,969	36,201
8	145	52	197	57	10,487	14,553	11,792	36,832
9	146	51	197	56	11,336	12,818	11,058	35,212
10	150	53	203	57	10,844	14,350	11,193	36,387
11	146	49	195	57	11,605	13,673	11,080	36,358
12	152	52	204	58	10,659	12,983	11,365	35,007
13	153	41	204	58	10,364	13,371	11,290	35,025
Mean	150	51	202	58	10,311	13,386	11,459	35,156
SD	4	3	4	1	831	943	437	1,146
Actual Weight of Test-Truck					**12,340**	**26,360**	**0**	**38,700**

Weight measurement accuracy improved during the third test drive experiments. GVW average error was limited to 9%. The difference between actual truck weight and the figure reported by the portable WIM system narrowed when compared with second round testing. Table 5.5 summarizes third round test results. Standard deviation of the first axle weight was 831lbs. Standard deviation for the second and third axles was 3,558lbs. Standard deviation for third round testing was lower than that of the second round. Consistent results were achieved.

Table 5.5. Portable WIM third test campaign results summary

	Gross vehicle weight	First axle weight	First axle spacing	Second axle spacing
Actual	38,700 lbs	12,340 lbs	145.00 inches	53.0 inches
Mean	35,156 lbs	10,311 lbs	150.00 inches	51.0 inches
Standard Deviation	1,146 lbs	831 lbs	3.80 inches	3.4 inches
Average Error	**9%**	**16%**	**3%**	**3.7%**

Figure 5.5 and .6 shows total weight measured as a function of test-truck speed as it impacted the sensor. Impact speed was reported by the driver.

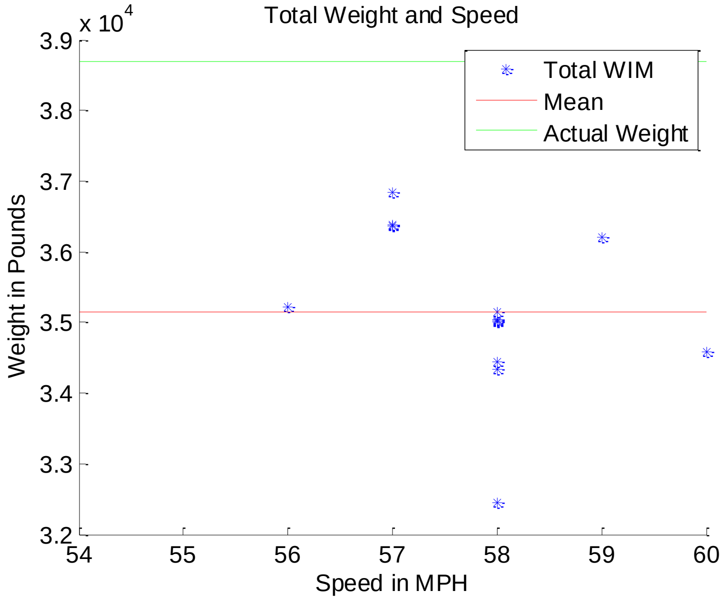


Figure 5. 5. Total truck weight versus actual as a function of speed

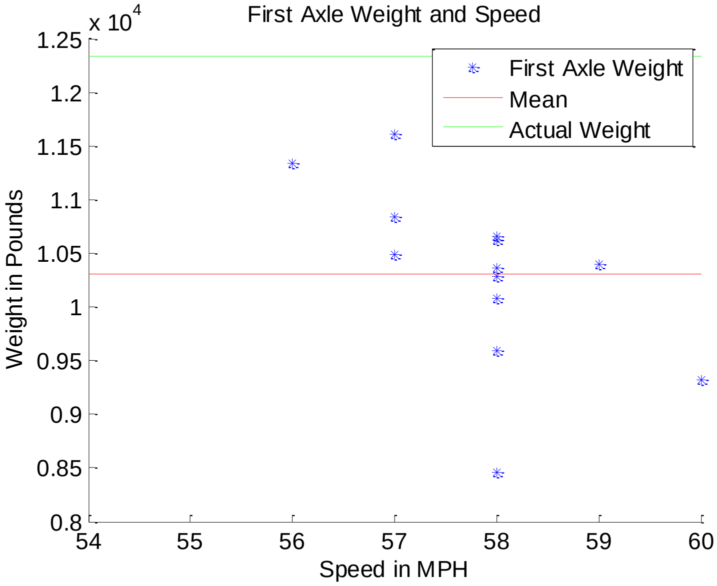


Figure 5. 6. Front axle weight and actual weight versus speed

Significant improvements were deemed likely given that the portable WIM system was calibrated immediately prior to the drive test. These results emphasize the need for regularly scheduled calibration.

Fourth round of drive test experiments

Using the ODOT test-truck filled with non-shifting sand, the research team conducted the fourth series of test drives, including 20 runs—four of which were erroneous as indicated in the table below. The drive tests were conducted during deployment three. Calibration was conducted, and system calibration factors were tuned two days prior to testing. No adjustments or further configuration changes were made during this round of testing. The average GVW error was limited to less than 7% while FXW was limited to less than 1.5%. Portable reported weight measurements, axle spacing and weights, and calculated mean and standard deviation, as well as average errors, are listed in Table 5.6.

Table 5.6. The results of the portable WIM fourth round of test drives during the third deployment

Run	FAS (inches)	SAS (inches)	Speed (mph)	FAW (lbs)	SAW (lbs)	TAW (lbs)	GVW (lbs)	Length (ft)
1	170	56	55	14,178	14,760	15,805	44,743	18
2	170	56	55	13,825	15,532	16,701	46,058	18
3	170	56	55	14,090	15,708	17,768	47,566	18
4	171	56	55	16,074	15,342	17,314	48,730	18
5	172	56	55	14,747	15,404	15,051	45,202	18
6	171	57	57	14,438	14,981	16,551	45,970	18
7	173	56	55	12,758	14,844	16,440	44,042	19
8	171	55	56	15,382	15,170	17,649	48,201	18
9	ERROR: Vehicle Too Slow STATUS: Unequal Axles Detected							
10	170	54	54	14,888	15,267	16,992	47,147	18
11	171	56	57	13,693	14,028	16,361	44,082	18
12	173	56	57	13,402	14,280	14,385	42,067	18
13	ERROR: Vehicle Too Slow STATUS: Unequal Axles Detected							
14	171	56	55	13,905	14,994	16,586	45,485	18
15	171	55	55	13,151	14,862	15,744	43,757	18
16	170	55	55	14,090	14,130	16,679	44,899	18
17	170	55	55	13,984	14,862	14,235	43,081	18
18	173	56	55	13,111	15,029	14,562	42,702	19
19	ERROR: Vehicle Too Slow STATUS: Unequal Axles Detected							
20	ERROR: Vehicle Too Slow STATUS: Unequal Axles Detected							
Mean	171	56	55	14,107	14,950	16,176	45,233	18
SD	1	1	1	810	451	1,051	1,843	0
Actual	166	54	-	14,320	34,260	0	48,580	18
Average Error	**3.0%**	**3.1%**	**-**	**1.5%**	**9.1%**	**-**	**6.9%**	**1.0%**

Careful assessment of the first two deployments was vital for setting adjustments to the WIM controller, optimizing sensors layout, and determining the method for attaching the fixture to the roadway. These refinements enhanced the results obtained during the fourth set of test drives.

In order to compare the portable WIM measurements to those measured by the permanent during deployment three, the PI and his research team also recorded WIM measurements of the test-truck obtained from the permanent WIM system located approximate to the portable WIM site. Notably, the permanent site was calibrated two weeks prior to portable WIM deployment. Table 5.7 shows permanent WIM site measurements. The permanent site was able to achieve zero percent error in front axle weight measurements.

Table 5.7. The results of the permanent WIM fourth round of test drives during the third deployment

Run	FAS (inches)	SAS (inches)	Speed (mph)	FAW (lbs)	2nd AW (lbs)	3rd AW (lbs)	GVW (lbs)	Length (ft)
1	176	56	57	14,284	14,747	15,801	44,832	27
2	176	56	57	12,723	14,019	14,050	40,792	26
3	175	56	57	14,593	15,607	14,509	44,709	27
4	175	56	55	12,013	12,529	11,814	36,356	26
5	176	56	57	15,029	17,115	15,510	47,654	26
6	175	56	58	15,620	16,044	15,761	47,425	26
7	176	56	57	15,691	16,048	15,938	47,677	26
8	176	56	57	14,249	14,725	14,187	43,161	27
9	175	56	57	14,174	13,376	15,095	42,645	27
10	176	57	57	15,501	17,243	16,414	49,158	27
11	176	56	58	12476	14628	14094	41,198	27
12	176	56	58	12,965	14,937	13,971	41,873	26
13	176	56	57	15,338	15,528	15,043	45,909	27
14	175	56	57	15,250	14,619	14,945	44,814	27
15	175	56	56	14,654	16,105	17,018	47,777	26
16	176	57	57	15,334	16,445	15,461	47,240	27
17	176	56	57	14,249	15,078	13,587	42,914	26
18	176	56	55	13,852	14,350	14,443	42,645	26
19	175	56	57	14,606	14,760	15,316	44,682	26
20	175	55	56	13,803	16,158	14,063	44,024	26
Mean	176	56	57	14,320	15,203	14,851	44,374	26
SD	0.47	0.37	0.77	1,030	1,129	1,098	2,926	0
Actual	166	54	-	14,320	34,260	0	48,580	18
Average Error	**5.8%**	**3.8%**	**-**	**0%**	**12.3%**	**-**	**8.7%**	**44.3%**

Table 5.8 summarizes results obtained from permanent and portable WIM systems during fourth round of drive testing. When compared to results from deployment one and two testing, third deployment results demonstrated improved accuracy. The fourth set of experiments indicated less average error in GVW measurements, as reported by the developed portable WIM system. Aside from first axle weight measurements, test results illustrate that results from the portable WIM test outperform permanent WIM in consistency (i.e., lower standard deviation) and average error. The improvement of accuracy could be contributed to the deployment site being concrete instead of asphalt and the affixation of sensor using concrete screws instead of PK nails.

Table 5.8. Portable WIM fourth test campaign results summary

	GVW (lbs)	**FXW (lbs)**	**FAS (inches)**	**SAS (inches)**
Actual	**48,580**	**14,320**	**166**	**54**
Portable Mean	35,156	14,107	171	55
Permanent Mean	44,375	14,321	176	56
Portable Standard Deviation	1,146	810	1	1
Permanent Standard Deviation	2,926	1,030	0.24	0.15
Portable System Error	**6.9%**	**1.5%**	**3.0%**	**3.1%**
Permanent System Error	**8.7%**	**0%**	**5.8%**	**3.8%**

The portable WIM system reported consistent measurements, as did the permanent WIM system. GVW measurement errors were limited to 6.9% in portable WIM—superior than 8.7% error reported for the permanent WIM. Portable WIM front and second axle spacing measurements were superior to permanent site measurements, as well. Only front axle weight reported by the permanent WIM was characterized more accurate than those reported by the portable WIM.

Chapter VI

Classification and weight accuracy

This chapter presents a comprehensive examination and comparison of WIM data collected at the portable and permanent sites during the three deployments. While Chapter V presented a comparison study of portable and permanent WIM systems using test-trucks with known weights during testing periods that lasted up to three hours, this chapter presents a comparison between the two systems for time periods of 22-days for deployments one and two and 18-days for deployment three. Vehicle statistical distributions in relation to first axle weight (FXW), gross vehicle weight (GVW), vehicle classification, speed, and first axle spacing (FAS) are presented in this chapter. It is important to stress that the permanent WIM site is assumed to provide accurate weight measurements. However, this assumption may not hold or apply if the permanent site is not calibrated, configured properly, and/or the site's sensors are damaged.

In addition to investigating the data as lump sum (aggregate data without matching vehicle records), the research team conducted a case study that included a small portion of the WIM data in which they analyzed the accuracy of the portable WIM data with its matching permanent WIM per vehicle record. Although the portable and permanent sites were time synchronized upon deployment, matching vehicle records between the two sites proved challenging for the following reasons: 1) Number of passing vehicles is large; 2) Portable site is placed 100 feet downstream from the permanent site; 3) Vehicle processing time varies based on the number of instrumented traffic lanes (portable WIM was deployed on one lane); 4) Portable WIM system is not triggered by inductive loop, and, most importantly, 5) Unequal number of undetected vehicles.

Vehicle count statistical distribution analysis

This section presents detected vehicle distributions calculated in terms of FXW, GVW, classification, speed, and FAS i.e., the distance between the first and the second axles. Since the focus of this project was to track overweight trucks, the distributions presented in this chapter focus on class 9 vehicles—trucks with five axles and a single trailer. Furthermore, class 9 vehicle detection is important because FXW is typically used for automatic calibration of weight measurements. Most electronic WIM controllers ship with specific software procedures to perform automatic calibration based on Class 9 vehicle first axle weight.

Class 9- First Axle Weight (FXW) Distribution

Prior to data presentation, WIM data was conditioned by removing all records in which an error occurred during vehicle detection. Vehicle count distributions of class 9 FXW during all three deployments are shown in Figure 6.1. Class 9 FXW is roughly standardized at weight equal to 10,000lbs. The figure confirms that the percentage of undetected vehicles during the first two deployments was extremely high, unlike deployment three. The reason for the elevated errant vehicle detection was due to improper road sensor installation, which caused excessive piezosensor vibration that was explained in Chapter IV and V.

The mean FXW value of the portable WIM system was close to 10,000lbs in all deployments, while standard deviation is wider, as shown in the figure. Figure 6.1 confirms that the permanent ODOT WIM05 was out of calibration during deployment two. Excessive first axle weights were also reported. The figure also shows that portable WIM system performance improved tremendously during deployment three due to revised sensor setup, installation, and concrete roadways.

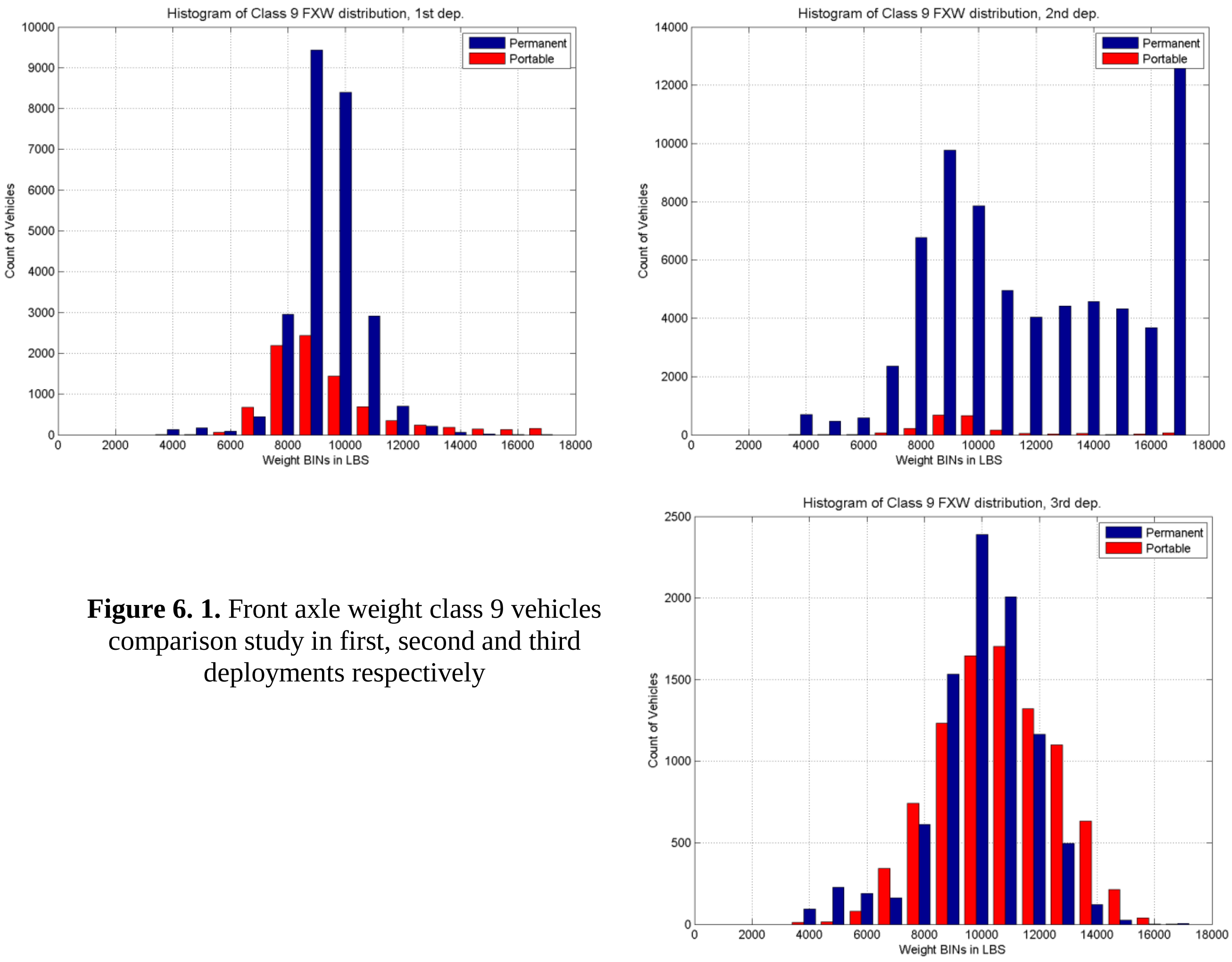


Figure 6. 1. Front axle weight class 9 vehicles comparison study in first, second and third deployments respectively

Table 6.1 presents the calculated mean and standard deviation of the FXW measurements obtained by the portable and permanent WIM systems. On average, the portable WIM system provided a good estimate of first axle weight; however, its standard deviation is wider than its permanent count, except during the second deployment.

Table 6. 1. Class 9 FXW mean and standard deviation measured during deployment I, II, and III

	FXW			
	Portable		Permanent	
	Mean (lbs)	SD (lbs)	Mean(lbs)	SD(lbs)
1st deployment (22 days)	9,626	2,462	9,480	1,190
2nd deployment (22 days)	10,171	3,348	12,616	4,459
3rd deployment (18 days)	10,806	2,005	10,092	1,858

Class 9- Gross Vehicle Weight (GVW) Distribution

GVW measurement accuracy is an important WIM system performance factor. Its vehicle count distribution for a calibrated WIM site should exhibit two (possibly three) bell shaped curves. The first bell (far left below) shaped curve highlights the trucks carrying no loads, while the second (far right below) highlights the trucks carrying a full load. Figure 6.2 shows the vehicle distributions in relation to GVW for vehicles detected as class 9 vehicles by the two systems. Vehicle count distribution during deployment three exhibits two bell shaped curves. This may be related to the fact that ODOT WIM16 permanent site was calibrated two weeks prior to the research team deployment. On the other hand, portable WIM GVW distribution exhibited such distribution to a lesser degree, e.g., its two peaks are less pronounced than those produced by the permanent site. However, this may be beneficial to quarantining detection of overweight vehicle. Vehicles that are detected as overweight are guaranteed to be overweight and error in detecting overweight vehicles is minimized when using the portable GVW distribution.

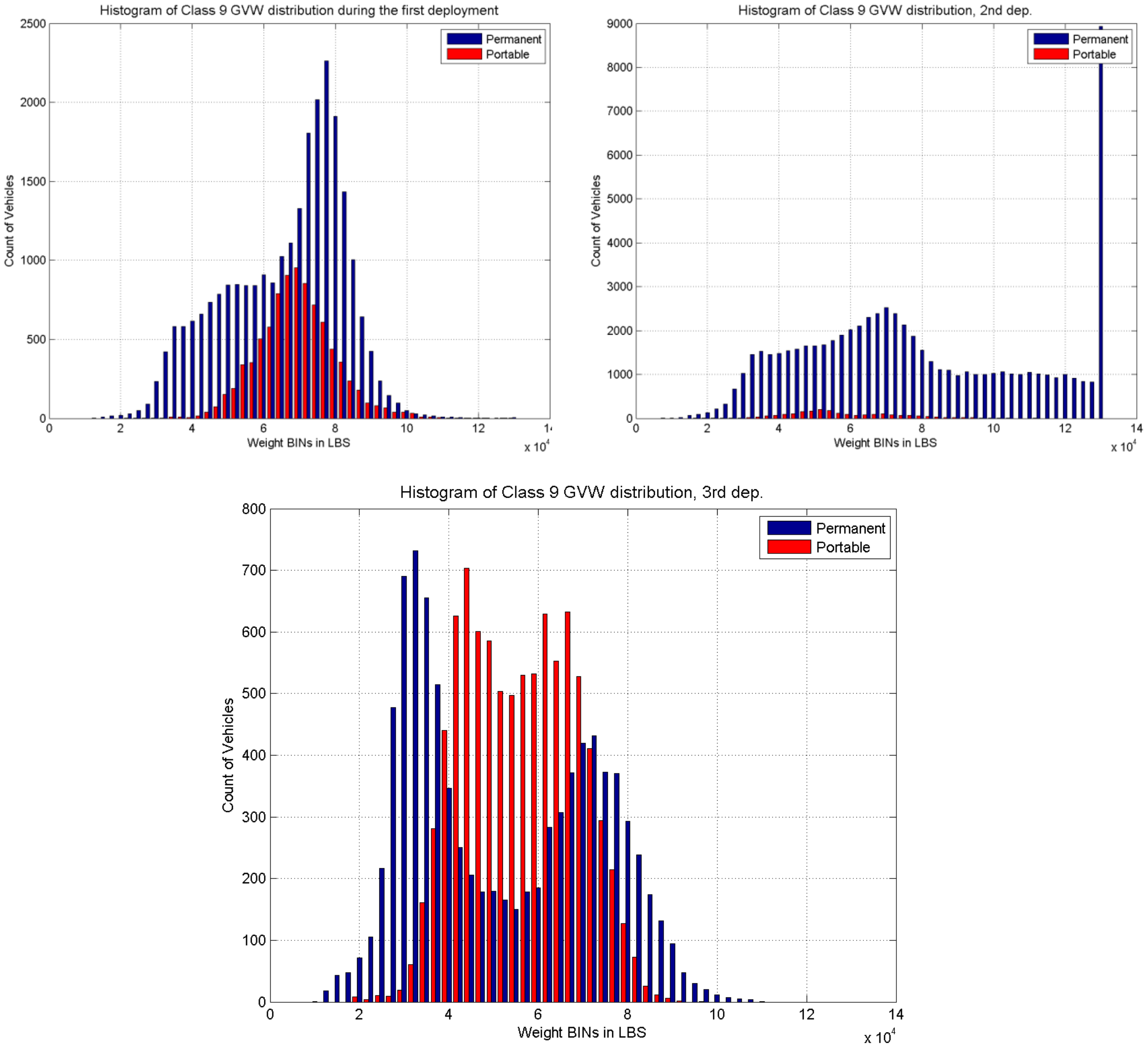


Figure 6. 2. GVW comparison study, first, second and third deployments respectively

Vehicle Classification

Vehicle classification distributions are presented in Figure 6.3. The classes investigated were large vehicles, including those in classes 6 to 13, since the focus of this project was to develop portable WIM to monitor overweight trucks. Figure 6.3 confirms the inaccurate classification of class 9 vehicles during the first two deployments. However, the third deployment shows accurate classification distribution. Shortening the sensor length and lane area coverage to 6 feet in deployment three limited vibration and improved the quality of the collected portable WIM data. Table 6.2 shows that the number of vehicles classified as class 9 improved. The percentage of error between the portable and permanent systems is 3.5%.

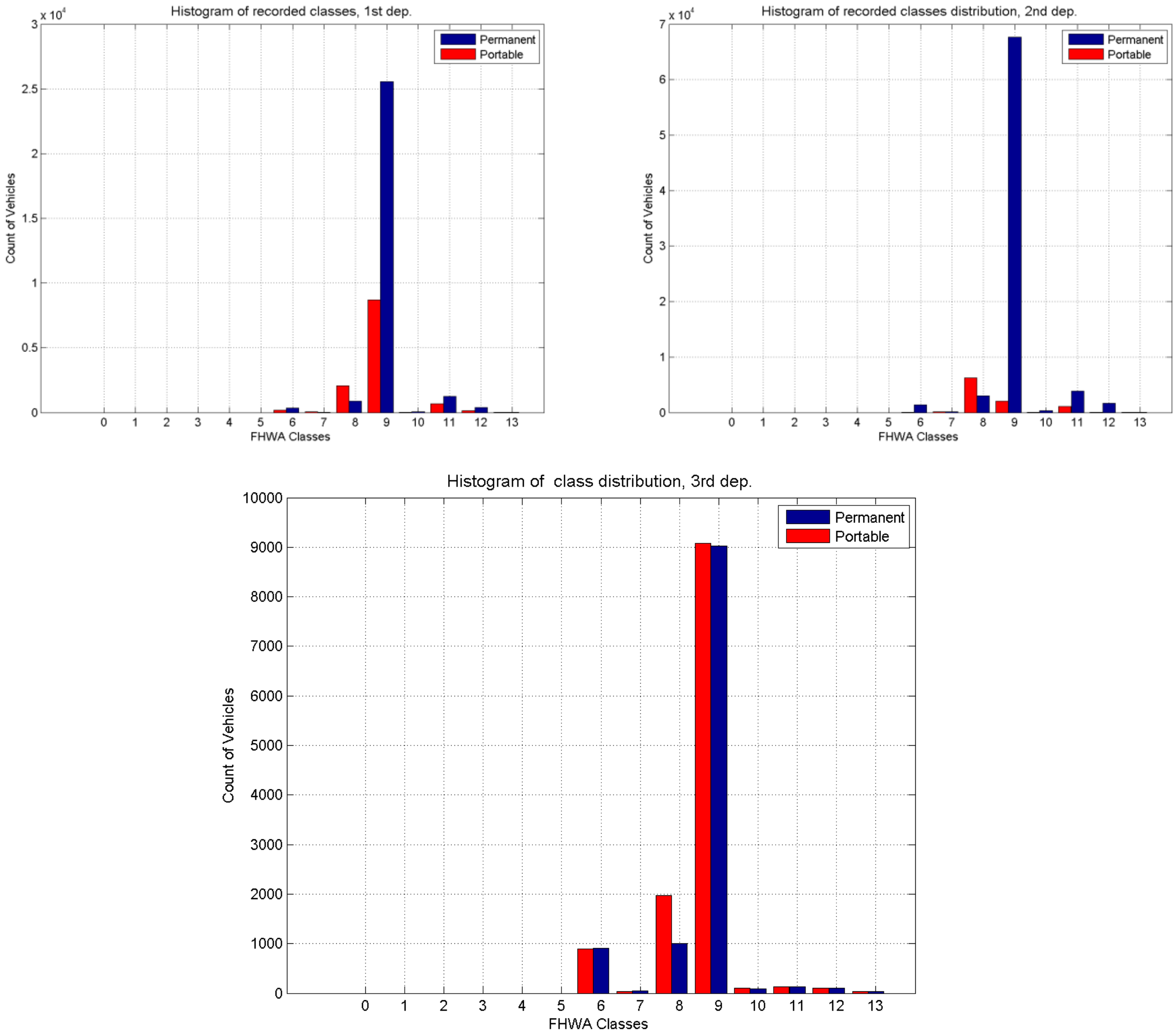


Figure 6. 3. Vehicle classes comparison study first, second and third deployments respectively

In the first two deployments, the portable WIM system experienced what it is referred to as a "vehicle-splitting problem," causing high number of mismatched class 9 vehicles when comparing the portable and permanent systems. Figure 6.4 illustrates examples of this problem. A class 9 vehicle is mistakenly classified as a class 5 due to a miscount of an equal number of tires on the remaining vehicle axles. This event causes an error. Likewise, a vehicle could easily be tagged class 5 if the WIM controller correctly detects only the first two axles, as was predominant in the portable WIM data collected. This explains the large number of class 5 vehicles recorded during the deployments.

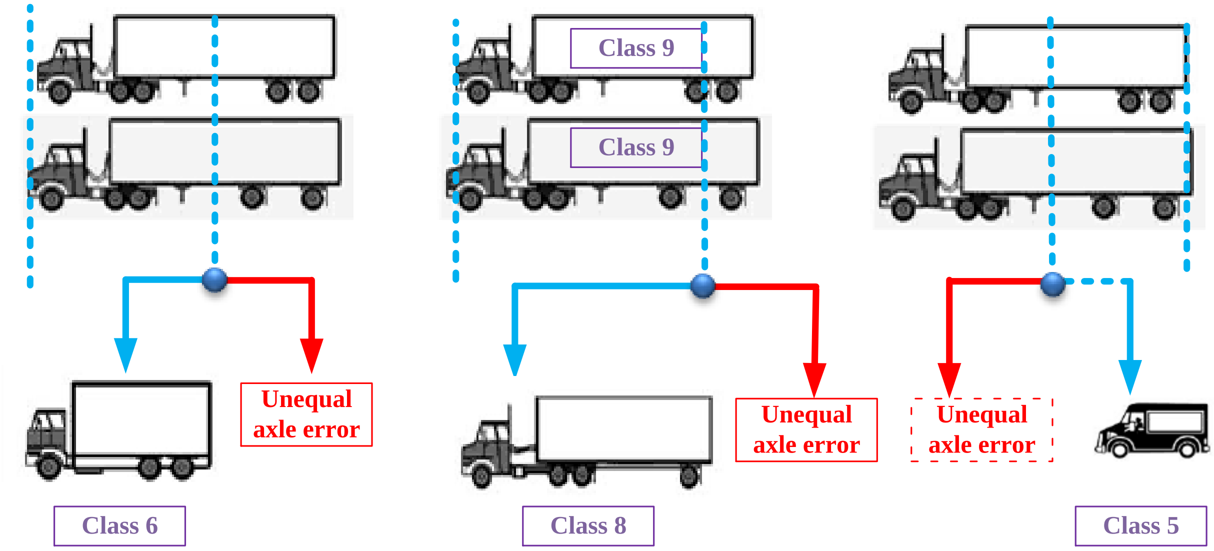


Figure 6. 4. Portable WIM vehicles splitting problem

A great improvement in the accuracy of detecting class 9 vehicles was achieved during deployment three. Table 6.2 compares the number of vehicles per class detected by the portable and permanent systems. Only heavy vehicles in classes 6 to 13 are presented in the table. During deployment three the percentage of difference between the number of vehicles detected as class 9 between the two systems is less than 1%. Portable WIM data quality also improved during the third deployment as a result of 1) Shortening lane coverage, which forced only one tire per axle to overpass sensors; and 2) Firmly affixing the sensor housing on the road surface.

Table 6. 2. Classification errors between portable and permanent sites

Class	Portable Vehicle Count	Permanent Vehicle Count	Difference
6	891	903	1.33%
7	34	43	20.93%
8	3,164	1,006	214.51%
9	9,052	8,999	0.59%
10	103	93	10.75%
11	133	128	3.91%
12	96	103	6.80%
13	30	29	3.45%

Class 9 Vehicle Speed Distribution

Detecting accurate speed is important for calculating axle weight. Since different calibration factors are assigned to different speed bins, accurate speed determination is tightly connected to accurate vehicle weight calculation. The calculation of speed depends on accurate configuration of the distance separating

the two sensors. As indicated in Chapter V, the research team adjusted the separation distance to match the speed reported by the driver of the calibration truck. In hindsight, data could have been more accurate if the research team used radar technology to acquire a more precise measurement of speed.
Figure 6.5 illustrates speed distributions for all three deployments. Again, speed calculations of deployment three prevailed as more accurate and better matched with the permanent site counterpart.

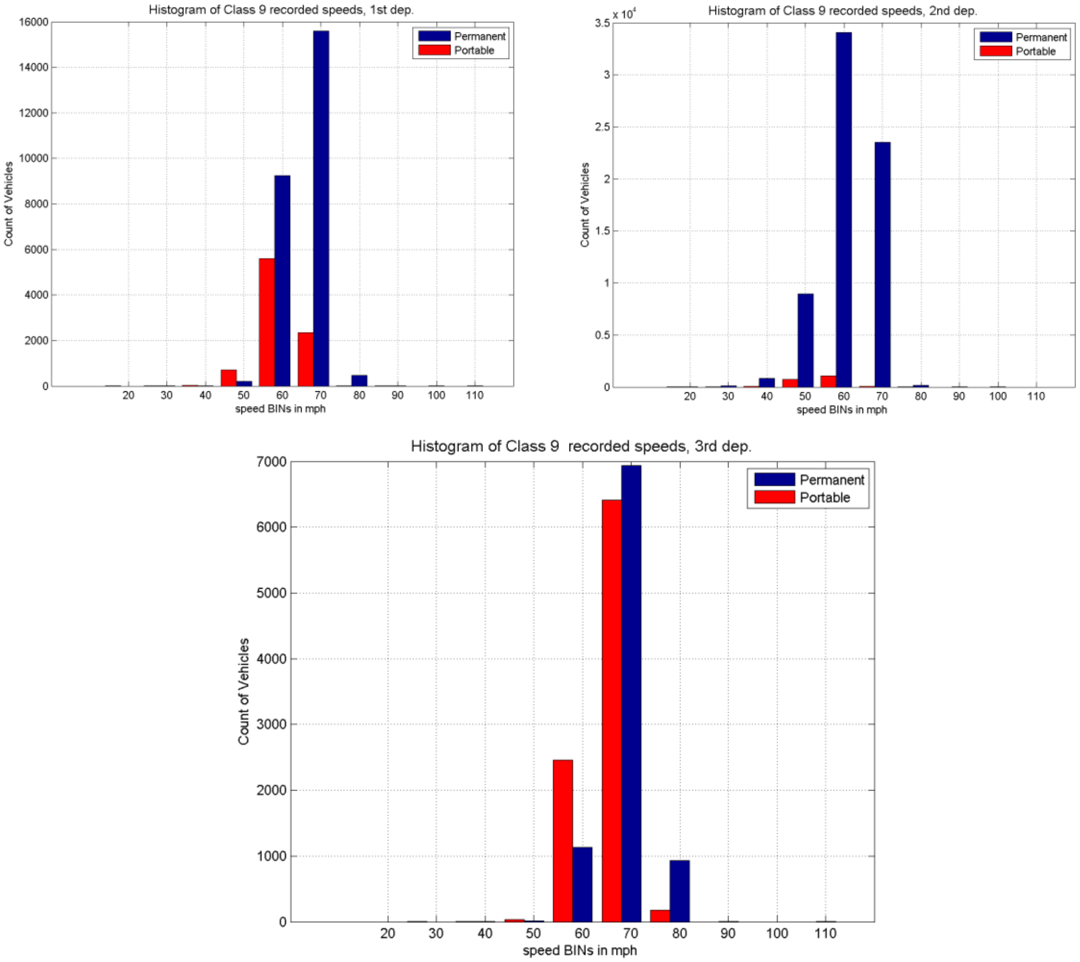


Figure 6. 5. Speed comparison study

Table 6.3 presents the calculated mean and standard deviation of the speed measurements obtained by the portable and permanent WIM systems for class 9 vehicles.

Table 6. 3. Speed mean and standard deviation for class 9 vehicles in deployment I, II, and III

	Speed			
	Portable		Permanent	
	Mean (mph)	SD (mph)	Mean (mph)	SD (mph)
1st deployment (22 days)	62.6	5.0	66.5	4.1
2nd deployment (22 days)	55.5	7.7	62.4	6.1
3rd Deployment (18 days)	67.8	4.0	70.4	4.4

Class 9 First Axle Spacing Distribution

First Axle spacing in class 9 vehicles is standardized and fixed. Hence, it becomes another performance parameter that could be monitored, collected, and analyzed. Figure 6.6 presents class 9 first axle spacing distribution for all three deployments. Again, more accurate spacing calculations were achieved by the portable WIM system during deployment three.

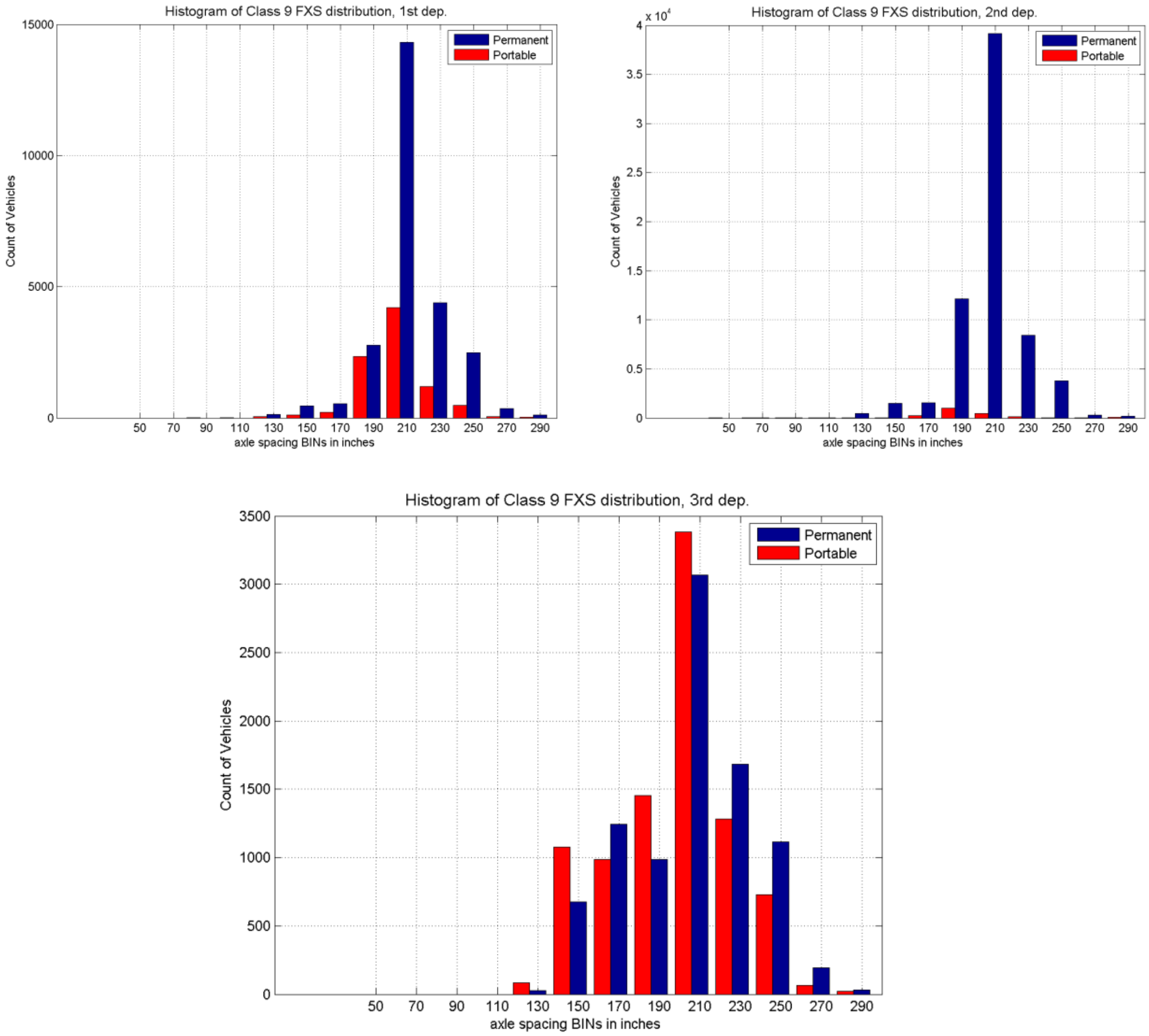


Figure 6. 6. First axels spacing (FXS) comparison study

Table 6.4 presents the calculated mean and standard deviation of the FXS measurements obtained by the portable and permanent WIM systems for class 9 vehicles.

Table 6. 4. FXS mean and standard deviation for class 9 vehicles in deployment I, II, and III

	Portable		Permanent	
	Mean (inches)	**SD (inches)**	**Mean (inches)**	**SD (inches)**
First deployment (22 days)	208.4	20.6	214.7	20.9
Second deployment (22 days)	199.7	37.9	208.9	20.2

	Portable		Permanent	
	Mean (inches)	**SD (inches)**	**Mean (inches)**	**SD (inches)**
Third Deployment (18 days)	201.9	29.0	209.1	30.6

Regression analysis of WIM data during deployment three

This section presents linear regression analysis on data acquired during deployment three. It is comparing the GVW for class 9 vehicles collected from the portable WIM data against that collected from the permanent WIM data. The fact that both systems were deployed within close approximation implies that the relationship between outcomes of the two should be linear, $y = x$ ideally (where y represents the portable WIM data and x represents the permanent WIM data). The research team applied a simple binning scheme. GVW data was binned into 52 different weight bins. The chosen range of weights was between 5,000 and 130,000lbs with a step size of 2,500lbs for each successive bin.

Consequently, a simple linear regression model was built based on Eq. (6.1) to approximate day-by-day the relationship between the two sets of portable and permanent binned GVW data, and then determine the accuracy of the newly developed system depending on how close the linear model was to the ideal case ($y = x$)

$$y_\iota = \beta_0 + \beta_1 x_i \tag{6.1}$$

Where: β_0 is the y-intercept of the relationship.

β_1 is the slope of the relationship.

Coefficients β_0 and β_1 are determined using the Ordinary Least Squares method [1]

Another coefficient R is a statistical measure of how well the regression line approximates the real data points; it is calculated using the formula in Eq.(6.2) [1]. A high R value indicates that the portable and permanent site data are highly correlated.

$$R = \overline{1 - \frac{(y_i - y_\iota)^2}{(y_i - y)^2}} \quad \text{where} \qquad 0 < R < 1 \tag{6.2}$$

The results of applying linear regression analysis on the aggregate data collected throughout the 18-day deployment is shown in Figure 6.7. Each circle indicates the number of vehicles whose GVW is detected by the portable and permanent systems. A circle on the diagonal $y = x$ line means that an equal number of vehicles of equal GVW were detected by both systems. As the circles depart from the diagonal line, an error is indicated due to an unequal number of detected vehicles.

The quality the GVW was monitored daily for detection signs of any system performance degradation during the 18-day deployment. It was expected that as more vehicles traveled the portable site, the performance of the system would deteriorate. On the contrary, results showed that system performance was improved during the few days following sensor road installation.

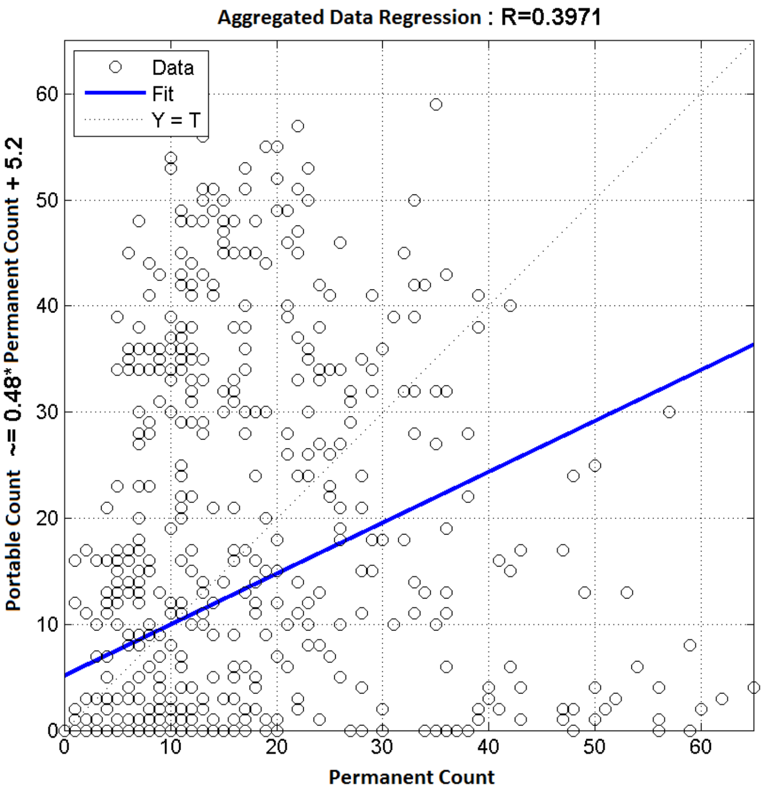


Figure 6. 7. Linear regression analysis on the aggregate data collected throughout the 18-day deployment

As shown in Figure 6.8, the quality or “goodness fit” (R values) of the portable system improved during the first three days of deployment. The figure also shows that on the 7th day, system performance was poor. To further investigate the reason for this phenomenon, the research team examined vehicle count and its distribution on that particular day, as shown in Figure 6.9. Results show a large discrepancy between class 9 GVW collected by the portable and permanent sites. No apparent reason was found to explain the large discrepancy.

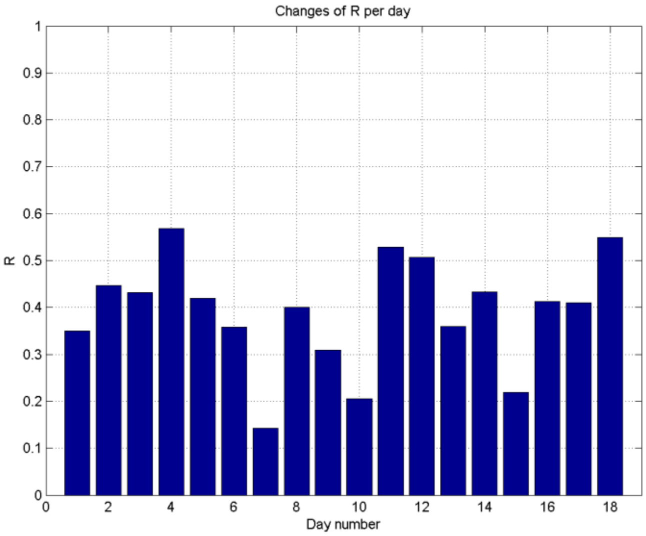


Figure 6. 8. R^2 changes throughout the 18-day deployment.

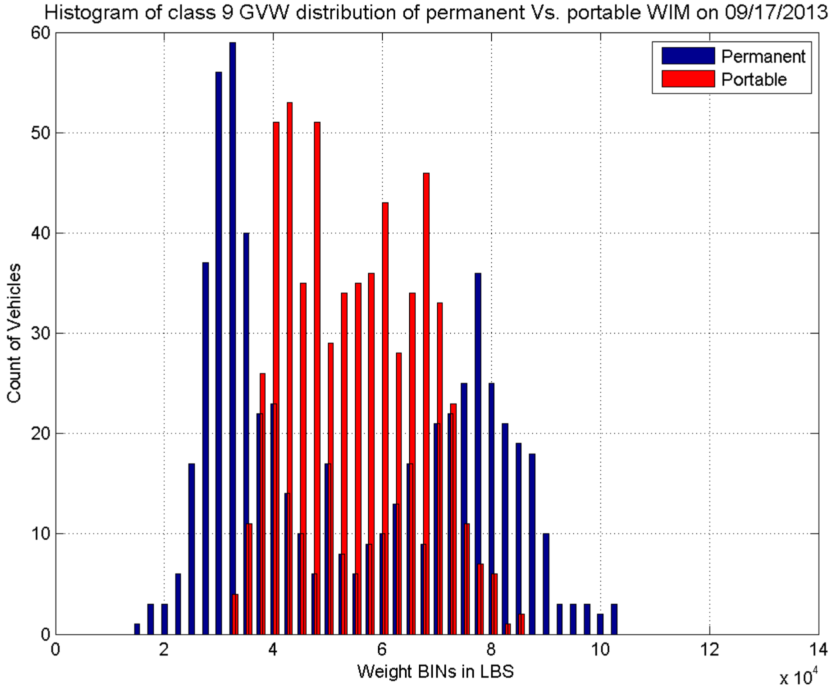


Figure 6. 9. Vehicle count distribution on the 7th day of deployment

Temperature and portable WIM data

The research team investigated the effect of temperature on the performance of the portable WIM system. IRD iSINC WIM controller used in the portable system applies temperature factors to the calculation of weight; however, a temperature probe must be connected to the controller to obtain current temperature readings. In the portable system, temperature factors and compensation was disabled. Figure 6.10 shows regression results of class 9 GVW. It confirms that the system performed better during PM periods rather than AM periods. The "goodness fit" factor improved by 37% during PM periods. Air temperature during the 10 days deployment period varied from 67^{o} F to 103^{o} F.

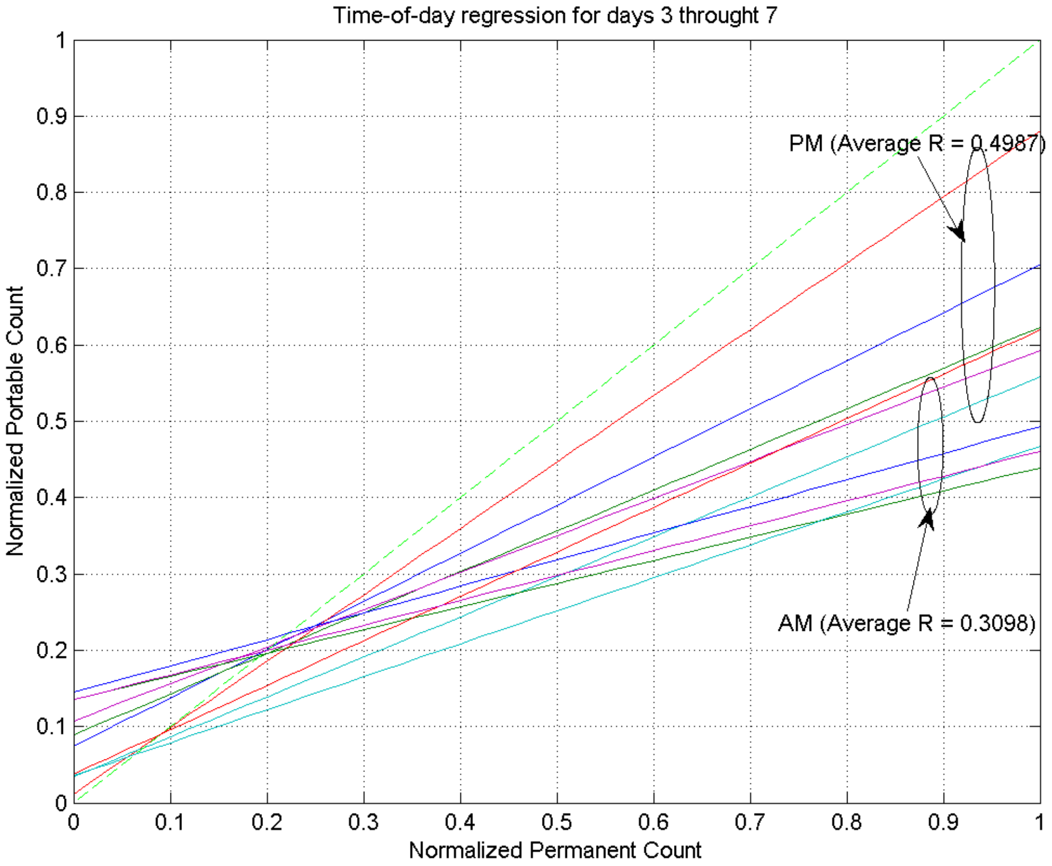


Figure 6. 10. Regression plot to detect temperature trends in permanent and portable WIM systems

Case study—Per vehicle comparison

This section presents a vehicle-by-vehicle comparison between permanent and portable WIM site data. The analysis presumes permanent WIM data is completely accurate and is considered as a reference. This assumption, in fact, is not true because errors might and most likely will occur even at a newly calibrated permanent WIM site, as exemplified by WIM05 next to which our portable WIM was placed during deployment two. System accuracy could be verifiable with the use of static scales; however, this was prohibitive for our purposes due to the excessive amount of vehicles we used to test our system. Ultimately, the research team would like to develop a statistical understanding of portable WIM data quality.

The research team developed an algorithm (the description of which is outside the scope of this report) to allow match-per-vehicle records to be collected by the permanent and portable WIM systems. As indicated earlier, time synchronization is not sufficient to facilitate per vehicle record matching between the two systems. Time drifts occur between the portable and permanent sites due to unequal processing times. Furthermore, as earlier results showed, vehicles could be undetected for a variety of reasons by either permanent or portable WIM site systems. Hence, it is extremely difficult to separate and match vehicle records, especially for highly traveled roadways.

To facilitate the matching of vehicles detected by the portable and permanent systems, time synchronization between the two systems was implemented using Network Time Protocol (NTP) servers. This process requires continuous Internet connectivity, which was accomplished via cellular modems installed in the REECE devices. Hence, time correction was continuously applied to the portable and permanent system clocks. The research team later developed a vehicle record alignment algorithm that uses passing vehicle time detection information. The algorithm was applied on data collected on four randomly selected days during deployment testing. 2,048 out of 2,162 class 6 to 13 vehicle records were matched from the portable and permanent sites. Unmatched vehicles were eliminated from the study.

To measure deviation of portable WIM data when compared to permanent site data, several statistical tools were employed: Root Mean Square Error (RMSE) given in Eq. (6.3), Normalized RMSE or NRMSE given in either Eq. (6.4), and correlation coefficient given in Eq. (6.5), along with its R^2. RMSE calculates the deviation or error between the portable and permanent WIM data per vehicle record. NRMSE calculates the percent error. These tools were used to characterize deviation as well as correlation in classification, GVW, FXW, FAS (defined as the distance between the first and second axles), and speed.

$$RMSE = \overline{\frac{{}_{i=1}^{n}(y_i-x_i)^2}{n}} \qquad (6.3)$$

where y_i represents the portable WIM data and x_i represents the permanent WIM data

$$NRMSE = \frac{RMSE}{y_{max} - y_{min}}$$

$$NRMSE = \frac{RMSE}{average(y)} \qquad (6.4)$$

where y_{max} is the maximum observed portable WIM data and y_{min} is the minimum observed permanent WIM data.

$$Correlation\ (x, y) = \frac{cov(x,y)}{\sigma_x \sigma_y} \qquad (6.5)$$

where $cov\ x, y$ is the covariance between the portable and permanent measurements; σ_x is standard deviation of x, namely the permanent WIM data; and σ_y is the standard deviation of y, namely the portable WIM data.

Correlation coefficient varies between [0,1], where 1 indicates strong correlation and 0 indicates no correlation. Correlation coefficient values of 90% or higher indicates high linear correlation between portable and permanent WIM data. The coefficient of determination, namely R^2, is calculated. Its value represents a statistical measure of how well the regression line approximates the scattered data points. Table 6.3 summarizes the calculated NRMSE and correlation, . The correlation coefficient exhibits strong correlation between portable and permanent WIM data. The correlated WIM information is first axle weight followed by the GVW data. The best correlated WIM information is the speed, followed by vehicle type classification. However, The error exhibited in GVW was 26%, which was the highest calculated error.

Table 6. 5. NRMSE, Correlation between portable and permanent WIM systems.

Parameter	NRMSE	Correlation Coefficient
Classification	0. 0295 (3%)	0.9668
GVW	0.2577 (26%)	0.8103
First Axle Weight	0.2364 (24%)	0.3856
First Axle Spacing	0.0456 (4%)	0.9819
Speed	0.0408 (4%)	0.9720

Regression results and R^2 values of classification, GVW, FXW, FXS, and speed are respectively presented in Figure 6. 11 through Figure 6. 14 Figure 6.11 shows 0.96 correlation in vehicle classification between portable and permanent system. Although the figure might not clearly demonstrate the strong correlation, Table 6.6 indicates that 98% of detected vehicles classification matched between the systems. Only 2% of vehicles were incorrectly mismatched its classification.

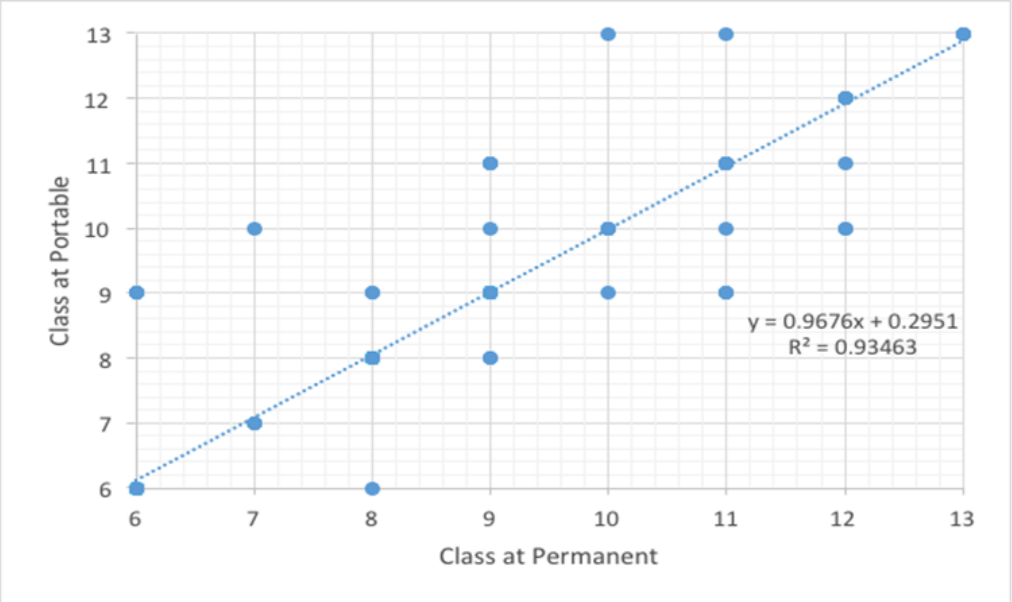


Figure 6. 11. Linear regression for permanent to portable classification comparison

Table 6. 6. Classification matching results between portable and permanent WIM systems.

Status	Number of Occurrences	Pecentage of Occurrences
Permanent and portable reported the same vehicle class matching.	2017	98.49%
1 Classes difference (e.g. site reported class 8, while the other reported 9)	8	0.39%
2 Classes difference (e.g. one reported class 6 , while the other reported 8)	16	0.78%
3 Classes difference (e.g. one reported class 6 , while the other reported 9)	7	0.34%

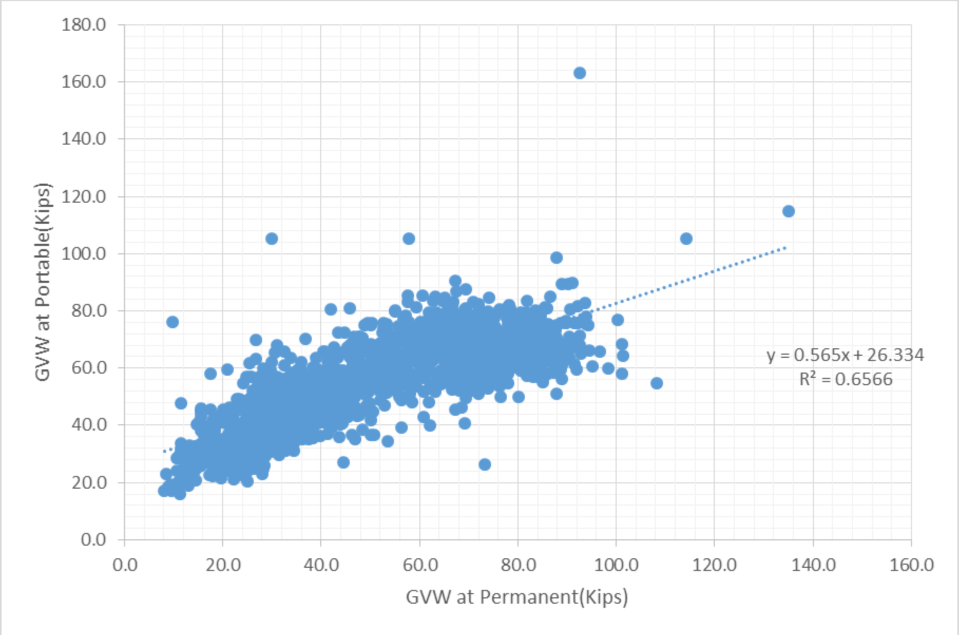


Figure 6. 12. Linear regression for permanent to portable GVW comparison

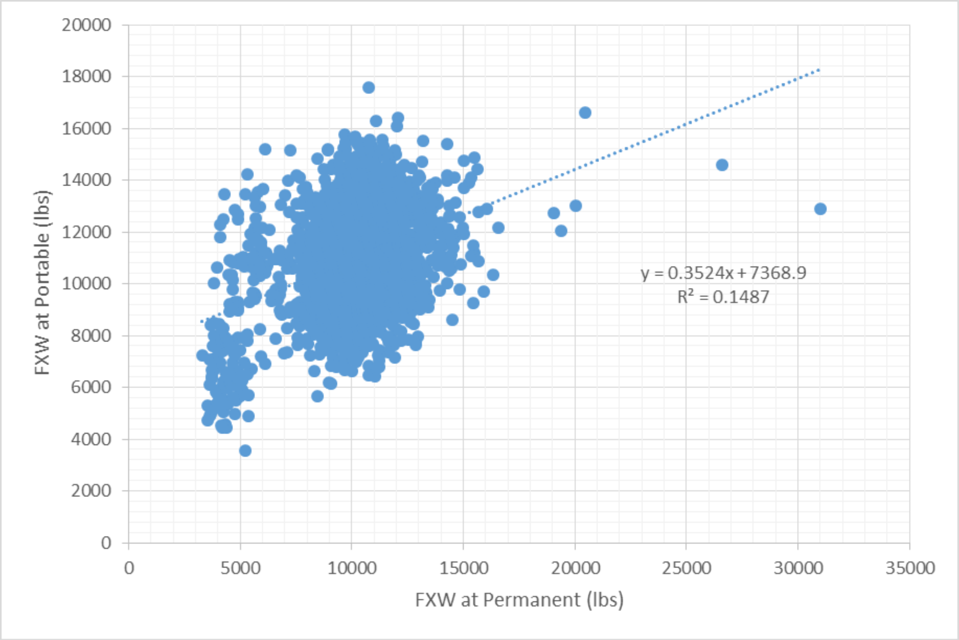


Figure 6. 13. Linear regression for permanent to portable GVW comparison

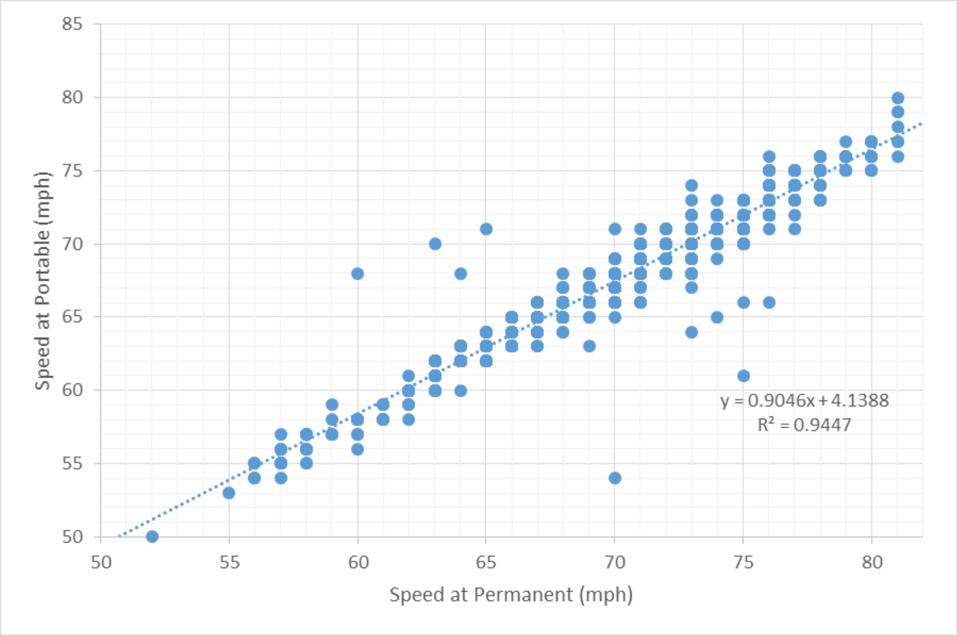


Figure 6. 14. Linear regression for permanent to portable speed comparison

The overall error exhibited in GVW was 26% on average. However, given that GVW data was further examined to provide details of the percentage of vehicles with a specific error, we found that 37% of vehicles had GVW error of less than 10%, 22% of vehicles had GVW error of less than 20%, and 21% of vehicles had GVW error of less than 30%. The complete analysis results are presented in Figure 6.15.

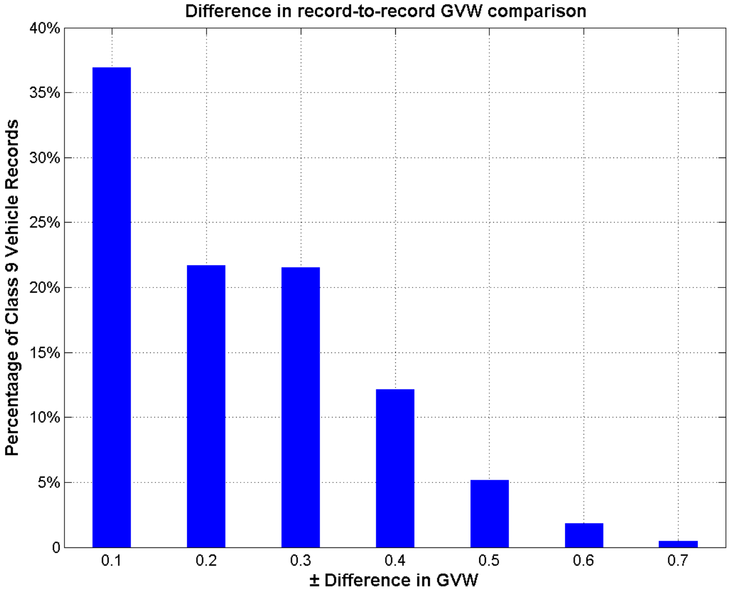


Figure 6. 15. GVW error histogram

Conclusion

This report presents results of a newly developed portable WIM system that uses off-the-shelf components and commercially available WIM controllers. The commercial WIM controller used in this project was IRD iSINC Lite. The fabricated portable system could be promoted as an alternative WIM monitoring solution to permanent WIM systems and/or static scale stations, both of which are extremely expensive to install on highways. The portable WIM uses RoadTrax BL piezoelectric class-1 sensors, galvanized metal fixtures equipped with pocket tapes to house the sensors, and a trailer with cabinet to house WIM electronics, batteries, and REECE device for real-time monitoring. The system is solar powered with three 100-Watt panels. Total cost of system is roughly $20,000.

Piezoelectric BL sensor vibration was determined to be the primary factor for undetected vehicles. Improper installation of the sensor was suspected to allow the sensor to vibrate within its pocket when a vehicle axle impacted it. In turn, the WIM controller detects and registers a large number of ticks due to one axle impact. This results in either over counting or misdetection, depending on the WIM configuration—in particular, the tick filtering threshold. A method to firmly affix the sensor onto the ground was developed and proved successful. Another approach to limit vibration is to reduce the size of the piezoelectric strip (thus reducing its sensing capacity) and position the sensor to cover part of the lane area so only one tire impacts it. Six-foot sensors were found suitable for low vibration deployment.

Default calibration factors used for sensors embedded in the roadway are not suitable for on-ground sensor installation used for portable WIM setups. Doing so causes significant weight error and inaccurate vehicle classification. Hence, portable WIM systems should be calibrated at deployment site. A new calibration is required each time the portable WIM site is changed. It is advised to use calibration factors per speed bin to increase weight accuracy.

The portable WIM system was deployed three times at two locations: US69 highway with pavement-type roadway and US412 with concrete-type roadway. Duration of deployment exceeded 20 days per site. System performance showed acceptable WIM measurement results with only slight variation throughout deployment periods. Portable WIM data was compared to permanent WIM data collected at co-located sites. Error and regression analyses were carried out. Root mean square errors and correlation coefficient were calculated for GVW, speed, classification, FXW, and FXS for each vehicle type. Results indicated a significant error of 26% when comparing portable and permanent GVW. Correlation coefficients were found above 81% for most studied system performance parameters, indicating that portable WIM data is highly correlated with permanent site data.

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Appendix A

The research team contacted a large number of departments of transportation across the nation and asked questions about their state's WIM program. The responses were gathered via emails or telephone conversations. Some departments were brief in their responses. The research team complied responses in this appendix. Following are the questions asked and the responses offered. These are listed in alphabetical order according to state name.

1. a. Does the state have a portable WIM (Weigh-In-Motion) program?
   b. If not, has the state ever used portable WIM? If so, when? Why did the state stop using it? What were the difficulties in using portable WIM?
2. Does the state have a permanent WIM program? How many permanent location sites?
3. What resources (financial) does the state use to support the portable WIM program?
4. What technology does the state use for the portable WIM program?
5. What sensors do the state use for the portable WIM program?
6. Sensor/recorder Housing. During deployment, how does the state house the sensor for the portable WIM device? Where does the state place the data sensor/recorder?
7. How does the state deploy the sensors?
8. How does the state select a deployment site for the portable WIM device?
9. What period of the year does the state perform the portable WIM system?
10. What does the state do to calibrate?
11. How often does the state calibrate the portable WIM device and why?
12. How does the state retrieve the data from the portable WIM device?
13. Does the state use the portable WIM data for law enforcement?
14. a. What data does the state process/analyze and store with the portable WIM device?
    b. What departments use this data?
    c. How accurate has the data been?
15. What difficulties has the state had in using the portable WIM device?

Alabama:

Randy Braden
(334) 242-6474

1) Alabama has a portable WIM program for traffic weight control.

Alaska:

MaryAnn Dierckman, Transportation Planner
(907) 465-6993
maryann.dierckman@alaska.gov

1) Alaska no longer uses a portable WIM program. Alaska has not used portable WIM since 1987 because of weather conditions.
2) Alaska only has a permanent WIM program. Also, Alaska sometimes uses a portable jump scale for weight enforcement.

Arkansas:

Jared Wiley
(501) 569-2110

1) Arkansas has a portable WIM program. This program has recently started about two months ago.
2) Arkansas has a permanent WIM program.
4) The portable WIM program has two complete systems. The WIM controller is ADR 2000.
5) The sensors are BL piezoelectric. The sensors are expensive. The cost of these sensors is between $700 to $800. The sensors need to be replaced often, since they are deployed on the road and not in the road. The sensor is used once for every deployment.
7) The configuration is piezo-loop-piezo. The sensors are taped on the road. The lead wires are put in a pipe to cross to the adjacent lane. It is a good bump when a vehicle hits the pipe. There is no specific crew devoted to portable WIM deployment. It is a part of the classifier/WIM group, which consists of five people.
8) Deployments are targeted for bridge traffic to detect overweight trucks and for Fayetteville Shell Facility to get an idea on trucks' weights. A site with a hard spot in the pavement is selected, which is tested with a deflectometer for accuracy. This is proven by calibration or deployment in tandem with the calibrated permanent site.
11) Annual calibration is done for permanent sites.
12) The data is picked up from the system manually.
13) The data is not used for law enforcement.

14) The data has been very accurate. It is better than the manufacturer's suggested thirty percent accuracy. The data has been used to target bridge traffic and to detect overweight trucks. Also, it has been used by Fayetteville Shell Facility to get an estimate of trucks' weights.

California:

Stan Norikane
California Department of Transportation
(916) 654-5651
Scott Philips
(407) 310-0708

1) California does not use a portable WIM program and has not used one for about fifteen years. No one in the California Department of Transportation office has worked with portable WIM. California stopped the program due to the fact that the data generated from a portable WIM device is rather poor compared to a permanent WIM device. They found that the data from the portable WIM devices is beyond their acceptable data error limits.
2) California has determined that a permanent WIM program will be their only type of WIM program. California has a permanent WIM program with 107 Data WIM locations and 27 weigh station bypass WIM systems.

Colorado:

Mehdi Bazair,
Manager
(303) 757-9047

1) Colorado Department of Transportation (CDOT) ran a portable WIM program for at least five years, but the program was terminated two years ago due to the lack of accuracy in the collected data. CDOT surveyed other states before deciding to terminate the program.
2) Colorado has thirteen permanent WIM sites.
4) The WIM controller was an ECM.
5) The sensors were BL piezoelectric sensors. The configuration was a piezo-6ft-piezo.
7) Deployment was only done on the right lane, and no lead wires would cross the lane. Two people were assigned to portable WIM data collection and field deployment.
8) There were thirty different portable sites every cycle. One cycle was completed in one year.
9) Portable WIM data was collected in forty-eight hours during June to September intervals. Data was collected at the end of the forty-eight hours.
10) The portable WIM system was not calibrated. It was programmed for self-calibration. It was very costly to calibrate.
14) Portable classification data was only used. No portable WIM data was used. Portable WIM data was sent to the FHWA.
15) The data was not accurate, and it was costly to calibrate.

Connecticut:

Donna Weaber
(860) 594-2334
Connecticut Department of Transportation (WIM program)

1) Connecticut does not use a portable WIM program anymore. CDOT has not used a portable WIM program in about eight to ten years. Donna Weaber is one of the few people working in this department. She believes that CDOT does not have a portable WIM program anymore because the department has downsized. Now, they have fewer workers to do everything, and it would be hard to set up a portable WIM system on some of the constant busy roads. CDOT is trying to make everything more automatic.
2) The rest of this section explains three of the CDOT's programs. CDOT has a permanent WIM program, TMS (Transportation Management System), and an ATR (automatic traffic recorder) program. For permanent WIM sites, they mainly use two loops and two piezoelectric (loop-piezo-loop-piezo), and they are looking to transfer each site over to two loops and two piezoelectric. Some sites have a loop-piezo-loop configuration. For permanent WIM, they use two lanes going in opposite directions, and they collect data for forty-eight hours, and during this time, they have a counter counting the traffic. They have one field staff worker that goes around to check the permanent WIM devices and to collect the data. The data taken from the TMS program is given to the federal level. The data sampling taken by the ATR is sent to the office computer automatically to be processed. Some difficulties with the permanent WIM are that the piezo does not survive the winter due to the payment cracking. Due to financial restrictions, the sensors do not get repaired right away.

Florida:

Richard L. Reel, Jr., P.E.
Transportation Statistics Office
(850) 414-4709
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1) Florida Department of Transportation no longer has a portable WIM program. FDOT took a close look at the Golden River Capacitance Mat WIM system in the late 1980's and early 1990's. FDOT's intention was to install the capacitance mats on roads where they planned major construction, in order to get site-specific truck weight data. As they got into the testing, they realized that all the roads with scheduled projects were worn out with deep ruts in the wheel paths and severe cracking. Most of the roads also had a rough ride. They learned quickly that they needed smooth, level pavement to have any chance of acquiring reasonable truck weights, and these roads just did not have the qualities needed. They really needed to weigh trucks on these

roads before the roads got tore up. Additionally, by 1990, traffic had grown so heavy on most of the roads that the equipment could not be safely installed without a lane closure. Since their original concept was a single person crew to install the WIM, which was similar to what was used to collect routine traffic counts, this was not going to work. In previous times, FDOT could call upon district maintenance to provide crews to perform lane closures, but at about the same time they were investigating portable WIM, the maintenance office was downsizing. Trying to obtain district assistance was problematic. So, all these factors – poor road surfaces, insufficient personnel, high traffic volumes—resulted in the decision to abandon portable WIM in favor of permanent WIM, which was installed in new, smooth pavement.

2) Florida has more than thirty permanent WIM sites.

Georgia:

Scott Susten
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1) Georgia has a portable WIM program. Georgia is expanding the program as the budget allows in order to help other programs.
4) The contractors have the equipment.
7) A contract company is used to deploy the portable WIM program and is used to collect data.
10) The contractors calibrate the portable WIM program.

13) The portable WIM data is not used for law enforcement

14) Georgia's Department of Transportation collects the data and provides it to other business units and programs that do road, freight, etc. analysis. For example, GDOT sends data to the FHWA. The department personally does not use the data for anything. Also, the Public Safety Department has their own portable WIM program.

Hawaii:

Napoleon Agraan
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1) Hawaii's Department of Transportation does not have a portable WIM program.
2) HDOT has twelve permanent WIM stations.

Idaho:

Glenda Fuller
Roadway Data Manager
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1) Idaho does not use a portable WIM program. Idaho used to use a portable WIM program about ten to fifteen years ago, but Idaho decided to stop using it due to the fact it was not giving accurate data.
2) Idaho has twenty-five permanent WIM sites.

Illinois:

Richard Telford
(217) 782-7416

1) Illinois does not have a portable WIM program. Illinois tried to use portable WIM about ten to fifteen years ago, but in testing, Illinois found out that the data was not accurate, the deployments and moving equipment was not practical, and it was not cost effective.
2) Illinois has thirty-seven permanent WIM sites, which are used for truck weight enforcement.

Indiana:

Jim Poe
Duty Commissioner of Indiana's Department of Revenue
(317) 232-8257

1) Indiana does not and has not ever had a portable WIM program.
2) Indiana has five permanent WIM sites.

Kansas:

Bill Hughes
(785) 296-6863

1) Kansas has used portable WIM for data collection for the last twenty-three years.
2) Kansas has eight permanent WIM sites.
4) The system uses a capacitance mat with TDL500 controller by Aviar Inc. (Truvelo Manufacturers Ltd.—South Africa). The configuration is loop-configuration-loop.
7) The loops are taped down to the road, and the capacitance is taped down in the middle and nailed down on the edge. Portable WIM is deployed on the right lanes, which is where the trucks are

supposed to be. Portable WIM is not deployed on the center lanes. In the summer, two people are assigned to collect portable WIM data.

8) The program cycles through a hundred predetermined sites over a three-year-cycle. Each year, thirty-three sites are surveyed. Deployment sites are selected based on 2000/2001 traffic monitoring guide (TMG).
9) Portable WIM data is collected during the summer, which is the warm and dry season.
10) Calibration is conducted at the beginning of the summer to all the systems at a scale house.
11) For every deployment site, the system is calibrated. No data is collected for the first one to two hours of deployment. Afterward, data is collected for forty-eight hours. At the end of the forty-eight hours, a weight check is performed with a district three-axle-dump truck, not a class 9, for data validation.
13) There is not really any real-time enforcement. At the end of each year, the statistical weight data is provided to public safety for enforcement for the next year.
14) Portable WIM data is sent to the FHWA.

Kentucky:

Jadie Thomlinson
Transportation Branch Manager
Division of Planning
(502) 782-5087

1) Kentucky does not have a portable WIM program, but Kentucky uses one portable WIM device to collect data on a need data basis, which is a rare occasion. This rare occasion is when they need data to see how much weight is put on bridges. Kentucky used to use portable WIM more often, but once they switched over to permanent WIM, there was not much of a need for portable WIM anymore, and permanent WIM is more reliable.
2) Kentucky has twelve working permanent WIM sites. Permanent WIM is where Kentucky collects most of its data.
14) Kentucky uses its one portable WIM device for weight enforcement of bridges.

Louisiana:

James C. Porter
Planning Support Engineer
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1) Louisiana uses a portable WIM system and is looking to switching over to installing a permanent WIM system in the next couple years.
2) Louisiana is looking to switch over to permanent WIM. They do not see much interest in portable WIM in next 10 years. After permanent WIM is installed, they would only use portable WIM for special program counts in the middle of nowhere.
4) Louisiana has one portable WIM system with one recorder and 2 pairs of calibrated cable sensors, where they use 1 pair of calibrated cable sensors for deployment.
5) The sensors are BL (Brass Linguini) piezoelectric sensors.
6) Louisiana leaves the recorder about twenty to twenty-five feet away from the road as the data is being collected. They chain the recorder to a telephone post.
7) The crew consists of two people. When they deploy, the pair of calibrated cable sensors are placed eleven feet apart and taped down with pocket tape. Each car is weighed twice with the sensors.
8) There are one-hundred non-changing WIM sites. They do thirty-three sites per year and collecting data from each site is over a three-year-period.
9) Data collection is only done in the summer months, because the pocket tape that tapes down the sensor only works during the summer months. The other months are either too cold or too wet for the pocket tape to work on the pavement.
10) Calibration used to be done only in the spring, but they switched over to an automatic weigh station.
11) This station calibrates after every ten to fifteen vehicles that cross the sensors. The station calibrates by weighing the cars' steering axle, averaging the cars' weight, and then, makes an assumption for the calibration. This system is from International Road Dynamics Inc. (http://www.irdinc.com/systems/wim/wim_system_applications/aws.php). It is the only automated weigh station produced by IRD. Louisiana switched over to this automated weigh station due to the fact that Louisiana's temperatures and humidity vary so much throughout the day. This automated weigh station is supposed to correct the error caused by temperature variation in the piezoelectric sensor.
12) Data is collected two ways: by a laptop and a PCM card for classification. They plug the laptop into the recorder once the data is collected.
14) The data is supposed to be accurate. The BL sensors are temperature sensitive, but the automatic weigh station is supposed to help in correcting that error. They were thinking about using heat sensors to correct temperature error before the automatic weigh station. They process and store data (research grade data: weight of every axle) according to DASL Isle recording standards. This processed data goes to the payment design program, which is mostly computerized. Louisiana gives FHWH weigh-in-motion data once a year.
15) Difficulties: manufacturing program—the software for portable WIM programs is not designed for the BL sensor. The signal generated with the BL sensor is not correct. It gives a different signal in calibration. They calibrate it to one point, but everything above or below that point is off. The automatic weigh station is supposed to help with this problem along with the temperature problem.

<u>Maine</u>:

Deborah Morgan
Traffic Monitoring Manager
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1) Maine does not use a portable WIM program anymore. MDOT has not used portable WIM in about twenty to twenty-five years. The portable WIM program was cumbersome, heavy, and took a lot of time to set up. Maine tried researching portable WIM again about 15 years ago, and the data results were inaccurate. Maine moved on from using portable WIM.
2) Maine has sixteen permanent WIM sites.

<u>Maryland:</u>

Karl Hess
Manager-Traffic Monitoring System
(410) 545-5523
KHess@sha.state.md.us
Barry Balzanna
ATR data
(410) 545-5509

1) Maryland does not have a portable WIM program. Maryland tried using a portable WIM program in the 1990s, but it was not very successful at getting good data. Maryland also had problems with calibration.
2) Maryland used to have one permanent WIM site, but they decided to cut it from the budget. Now, Maryland uses a virtual weigh-in-motion program, which is permanent and cannot be moved. It is used, ran, and maintained by the motor carrier division. This data goes to the pavement design division.

<u>Michigan:</u>

Randy Coplin
Inspector
(517) 241-0479

1) Michigan does have a portable WIM program that has three to four portable WIM devices.
2) Michigan has fifty permanent WIM sites with some having weight scales. Their permanent WIM sites use Kistler Quartz piezos, and the data is put on the server or software at the weigh station facility.
5) The portable WIM uses Haenni load pads as its sensor.
7) This Haenni load pad is set up in a rest area. On the road, signs tell commercial vehicles to go to the rest area. Commercial vehicles have to pull over into the rest area. The Haenni pad is connected to a laptop, and then, an officer reads the real timing weight as the truck drives over the pad to see if the truck's axle reading is normal. The officer reads the weighing numbers and does not store them. If the axle reading is high, the truck has to go over a portable scale to measure the

correct weight. The portable WIM is used for sorting purposes for violations only. A team of 4-6 with a sergeant inspects the commercial vehicles and checks the lane. A team is always with the equipment.

9) Portable WIM is only used a hand full of times throughout May to October.
10) Michigan does not calibrate portable WIM because they do not use the data for law enforcement. They use the portable WIM for sorting over-weight commercial vehicles.
13) Portable WIM is used in helping with law enforcement.
14) Michigan sends statistics of their data to FHWA for highway annual certification.

Minnesota:

Gene Hicks
Principal Engineer
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1) Minnesota is in research mode for using a portable WIM program. They have been looking at portable WIM for a couple years, and hopefully by next year, they will know if a portable WIM program is useful and if it is what they are looking for in collecting data. Their portable WIM prototype is not on the market, since they are still in research mode.
2) Minnesota uses about fifteen plus permanent WIM sites.

Mississippi:

Trung Trinh
Planning Division
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1) Mississippi does not have a portable WIM program. Mississippi used to have a portable WIM program, but it gave unreliable data. They had a consultant deploy it for them.
2) Mississippi has twenty-six permanent WIM sites.

Missouri:

Jim Kramer
(517) 322-1716

1) Missouri does not have a portable WIM program.
2) Missouri has sixty permanent WIM sites.

Montana:

Tedd Little
Weigh In Motion Analyst
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1) Montana has a portable WIM program.
2) Montana has forty permanent WIM sites.
4) Montana has a portable WIM program that uses an ECM unit (Electric Control Measure) and two BL sensors.
5) The sensors are BL (Brass Linguine) sensors.
6-7) The two BL sensors, which are placed six feet apart, are housed by metal plates that have fabricated pockets. The recorder is a Hestia unit that is chained to a pole during deployment. This equipment is monitored several times a day during deployment.
8) Deployment sites are chosen by coordinating with Motor Carrier Services and seeing which site they need data from. Deployments last about five to seven days at a time.
9) Montana deploys from May to September in a three week cycle: pre-enforcement, enforcement, and post-enforcement. Pre-enforcement, enforcement, and post-enforcement are each one-week-long of deployment. Data is collected from each week. The pre-enforcement time period is the week before the officer is there. The enforcement time period is the week when the officer is there by the sensor. The post-enforcement time period is the week after the officer leaves. They collect a base line when an enforcement officer is there and is not there. They compare data from each week. Montana does this three week cycle at each of the deployment sites.
10) The sensors are calibrated when a class 9 (78,000 pound vehicle) drives over the sensors.
11) Calibration for the sensors is done in the spring once a year. It is only done once a year, because calibration takes too much time.
12) Once a deployment is done, the data is downloaded onto a lab top.
13-14) The base line data collected during deployment is taken to Motor Carrier Services, where it is used for law enforcement.
15) There are difficulties in errors in using portable WIM. For example, vehicles try to avoid it, and there are errors in the data that are not easily improved.

Nebraska:

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Steve Stroud
WIM Equipment/Deployment
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1) Nebraska has a portable WIM program in their planning division for the FHWA in determining the payment thickness of the roads using W (weight) tables.
2) There are no permanent WIM sites with the planning program.
3) Nebraska gets funding from their planning division program from FHWA to install and buy equipment.

4-5) The portable WIM program uses six-feet-piezoelectrics ($735/piezoelectric) for their sensors and Peek ADR 1000 ($7,500) for collecting data. Nebraska calls the Peek ADR 1000 their counter. IRD (International Road Dynamics) equipment is used for recording.

6) Nebraska chains the recorder to a pole on the side of the road.

7) For deployment for one lane, two piezoelectrics are placed and taped to the road with pocket tape. The piezoelectrics take up about half of the lane. Classification data is collected by two piezoelectrics weighing the traffic. They deploy by direction by lane with piezoelectric cables to detect vehicles in a lane. The cable is directly on the payment. They use two cables, which are bought brand-new every spring. Deployments are at least forty-eight hours. The types of deployment sites range from 2 lane highways—where sensors are on both lanes of traffic, to 4-lane-interstate—where sensors are on 2 lanes of traffic both ways.

During deployment, Nebraska deploys at two to three sites at a time. They will set up and calibrate one site and then go to the next site. Depending on how far apart the deployment sites are, they will check on the deployment sites a couple times a day by driving in a loop from one site to the other.

8) Nebraska has fifty-three portable sites, where twenty-three sites are deployed every year and thirty sites are deployed on a three year cycle. Nebraska deploys at thirty-three sites annually.

9) Deployment is done during the middle of May to the middle of October because the pocket tape only sticks to the payment in warm weather.

10-11) Calibration depends on location and the traffic volume. For low traffic volume, calibration is done by putting sensors on the road and having a truck drive over them. This truck’s weight is known and controlled. This means they know what values they should be receiving for the calibration with this truck’s weight. If the sensors give the correct weight of the truck, calibration is set. If the peek calibration is not correct after doing this with this truck, they will force the peek system to re-calibrate according to this truck. The calibrations vary according to variations in temperature and the amount of times a piezo is used. For high traffic volume, calibration is done by watching vehicles go over the sensors and looking at the weights. They wait for a class nine to go over the sensors and check that weight with the peek machine. If it is close, they calibrate it with this vehicle. Also, they check to see if other classes' weight line up with the appropriate weight. If they cannot get it to calibrate correctly, they will force the peek machine to recalibrate by doing a "force recalibration," which causes the peek machine to go through another vehicle and weigh it. In order to calibrate it correctly, they keep watching traffic go over the sensors until the peek machine receives accurate weights.

12) At the end of a deployment, Nebraska downloads the data from the peek machine to the laptop. The data is downloaded to the network, which allows the Planning and Project Development department to be able to access the data. They have software that looks at each vehicle, and they check to see if the data looks correct. They check to see if the data's weight matches the type of car and if the signal matches the car's weight.

13) Nebraska does not use portable WIM data for law enforcement. Nebraska has one permanent WIM site for law enforcement.

14) They submit the data to FHWA and use the data to find the appropriate W (Weight) tables and single axle values to use for determining payment thicknesses.

Nevada:

Ryan Mccurdy
(775) 888-7502
Ben Cry
(775) 888-7536

1) Nevada no longer has a portable WIM program. Nevada abandoned it several years ago.
2) Nevada uses permanent WIM.

New Hampshire:

Subramanian N. Sharma
Chief of Research and Engineering
(603) 271-1625

1) New Hampshire does not have a portable WIM program and has never used a portable WIM program.
2) New Hampshire has about three to five permanent WIM sites.

New Mexico:

Josh McClenahan
Supervisor
(505) 827-5137

1) New Mexico no longer uses portable WIM. It was terminated three years ago. The program was active for only one year (2007-2008).
2) Dialup is currently used with permanent sites. New Mexico has 130 data classifier sites. Also, New Mexico has fourteen permanent WIM sites. Eleven of the sites use piezo and three of the sites use a bending plate. The bending plate gets better data. WIM controllers are IRD for the bending plate.
4) The configuration is loop-piezo-loop-piezo deployment.
5) The sensors are BL piezoelectric sensors, which are from measurement specialists.
7) The portable system was deployed for forty-eight hours. One person was responsible for the portable unit deployment, calibration, and data collection.
10) Calibration is performed by waiting for a flat-bed, class 9, and empty (visually guessing) vehicle to cross the sensors.
11) Calibration is performed twice a year on the bending plate and once a year on the piezo sites.
13) New Mexico does not apply this data to law enforcement, although the state is still planning on implementing an enforcement program with WIM sites.
15) No one knew how to use the portable WIM data.

New York:

Kurt Matias
Supervisor, Traffic Monitoring Section
(518) 457-2815
Kurt.Matias@dot.ny.gov

1) NYSDOT does not have a portable WIM program and has never used a portable WIM program.
2) New York has twenty-two permanent WIM sites.

North Dakota:

Terry Woehl
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twoehl@nd.gov

1) North Dakota does not have a portable WIM program. North Dakota did portable WIM testing about ten years ago, and North Dakota had problems with inconsistent data and various errors that would come up in the data. A lot of problems were due to the sensors being temperature sensitive. The BL (brass linguine) sensors changed too much depending on the temperature.
2) North Dakota has thirteen permanent sites, which some are being repaired and installed, but by the end of 2013, North Dakota will have thirteen permanent sites working.

Ohio:

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Weigh-In-Motion Program Manager, Ohio DOT
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Dave Gardner
Manager, Traffic Monitoring Section
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1) At this time, Ohio's DOT does not have a portable WIM program, though Ohio has done some investigating, testing, and research in the past. Ohio tried portable WIM once, and Ohio did not like the results. Ohio never tried it again.
2) Ohio has about forty permanent WIM sites situated around the state, though not all of them are currently collecting data. Ohio is migrating all of its sites to PEEK 2000 ADR's. Many of its sites are equipped with Kistler Quartz piezos. The rest are standard BL piezos. Ohio has field personnel to perform light maintenance and repairs at the site. Ohio utilizes a service contract with an outside vendor for sensor installation, trenching, installation of pull boxes, cabinet and pole erections, etc. The sites are polled daily from a computer in their central office utilizing a mixture of cellular and hard line modems. Almost all the sites are self-powered with solar panels. They hope to eventually switch to IP modems when the PEEK software is developed to support it.

Oregon:

David Fifer
(503) 378-6054

1) Oregon does not have a portable WIM program, and Oregon has never used a portable WIM program.
2) Oregon has twenty-four permanent WIM sites. The permanent WIM data is used by several different departments. The Motor Carrier Transportation Department includes the Traffic Data Unit Division and the Highway Division. The Traffic Data Unit Division creates traffic volume

tables from the permanent WIM data to be able to determine peek times of travel and car classification. This data is used by the Highway Division for figuring out payment thickness and other factors related to building roads. This year, Oregon is in the process of building two virtual permanent WIM sites, which will be sites twenty-five and twenty-six. These sites will mostly be used for data collection. The first twenty-four permanent WIM sites are placed in the highway ahead of enforcement weigh stations. The commercial vehicles drive over the permanent WIM, which signals if the driver has to pull over at the up-coming weigh station. Permanent WIM is used to help enforce and regulate regulations/laws. Oregon only has portable static Haenni scales used to weigh commercial vehicles.

Pennsylvania:

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Transportation Planning Manager
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josharp@pa.gov
Andrea Bahoric
Planning Division Manager
Phone: (717) 705-2382

1) Pennsylvania's DOT does not have a portable WIM program. They never used a portable WIM program.
2) Pennsylvania's DOT currently has thirteen permanent WIM sites. All of their sites are instrumented with International Road Dynamics (IRD) products and maintained and calibrated by IRD on an annual basis. The calibration occurs in the spring and the maintenance in the fall.

Rhode Island:

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Traffic Operations/ Traffic Research/ Contract Management
(401) 222-5826 Ext. 4119
philip.dercole@dot.ri.gov

1) Rhode Island does not use portable WIM. Portable WIM has been unreliable and a lot of work.
2) Rhode Island uses permanent WIM.

South Carolina:

Stacy Eargle
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earglesa@scdot.org

1) SCDOT decided this year (2013) to temporarily suspend its portable WIM data collection. Portable WIM data collection was collected prior to Stacy Eargle's employment in the traffic data collection office beginning in 1995. All employees prior to Stacy Eargle's employment have since retired so she is not sure when the start of portable WIM data collection actually began. SCDOT temporarily suspended portable WIM data collection in 2013 after a review of the data being collected as well as limited resources. SCDOT only had one employee assigned to collect portable WIM data for the entire state of South Carolina. They had issues with the portable sensors being destroyed multiple times at locations without being able to collect any useful data. Most of the data they collected was considered unusable after review. They have a short window of good weather for deploying portable sensors and often found that they were unable to collect data in that time frame.

2) SCDOT uses permanent WIM, and SCDOT has seventeen permanent WIM sensor locations. However, due to pavement conditions and the small life cycle of WIM sensors only four are currently collecting usable data.

3) The WIM program is funded by Federal Highway Administration funds under the State Planning and Research Work Program (SPR).

4-5) Since 2000, they have used the Roadtrax BL Sensor (piezoelectric traffic sensor/Brass linguini) for both portable and permanent WIM data collection. Prior to 2000, they used PAT America WIM data collection sensors. Due to resources and safety issues, they discontinued the PAT sensors. The bending plates for several permanent site locations began separating from the surrounding concrete/asphalt causing serious safety issues as some were completely torn from the roadway surface. They use Peek Traffic ADR counters and the proprietary software (TOPS) for data files and reporting.

13) SCDOT does not use portable WIM data for law enforcement. They share truck volumes with the SC Transport Police who handle enforcement.

14) Data per vehicle records are stored for class 4 and above. Primarily, they have only provided this data to the Federal Highway Administration. Truck volumes from classification data has been shared with the SC Transport Police.

South Dakota:

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Engineering Supervisor
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1) SDDOT does not have a portable WIM program and has never used a portable WIM program.
2) South Dakota has fifteen permanent WIM sites.

Tennessee:

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Travel Data Office
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1) Tennessee does not have a portable WIM program. Tennessee discontinued their Weigh-In-Motion collection program in December 2007. They did so due to the safety concerns of their work staff and various mechanical reasons.

   Reasons include:

   a. The use of portable scales posed great safety concerns for their workforce. The workforce was locating equipment on high volume – high speed roadway at considerable risk.
   b. The equipment was cumbersome to use, hard to calibrate, and the data collected was not easily downloaded and compiled into the *.TMG format as it was requested by the receiving party.
   c. Their equipment had exceeded its performance lifespan, and it was costly to keep in working order.
   d. The data that was collected was not used by the TDOT office, and the Pavement Design Office had additional ways to ascertain their required data demands.
   e. A Proof-of-Concept was developed to see if the Transportation Department could retrieve the weigh data from the weigh stations operated by the Department of Safety. While the concept did show some promise, problems arose involving the security and communication of the requested data. The expenditure of our reduced funding and additional equipment demands were not something they wished to engage at this time.

   Due to the demands of our finances, reduced workforce, and the reduced need of this data within the Department, this program was discontinued.

3) TDOT does not have a permanent WIM program. Permanent scales are located in the weigh stations manned by their Department of Safety.. The Department of Safety is currently used primarily in the realm of enforcement. TDOT does not receive the Department of Safety's data. There are a few LTPP (Long-Term Pavement Performance) sites across the state, but the Planning Division, Traffic Data Office does not collect nor maintain any files of the LTPP data. Tennessee's coordinator for the LTPP program is James Maxwell (James.M.Maxwell@tn.gov).

Texas:

Catherine Wolff
(512) 467-3940
Catherine.wolff@texdot.gov

1) Texas does not use a portable WIM program.

2) Texas has twenty-seven permanent WIM sites. Texas uses IRD Isinc Equipment. They use a bending plate but are converting to Kistler sensors. The Kistler sensor has a much better accuracy than the bending plate.

Virginia:

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Program Manager
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Hamilin Williams
(804) 786-7763

1) Virginia's DOT does not have a portable WIM program. Virginia has not used portable WIM for production in the last twenty years. Virginia has done some testing and research with portable WIM in the last twenty years, but Virginia has come to the conclusion that it is not accurate or suitable enough to meet its needs. Virginia has had several difficulties in trying to use a portable WIM program. A portable WIM program is hard to calibrate and takes a lot of time to set up and deploy. The portable WIM sensors are temperature sensitive, which causes errors in the calibration. This means the sensors have to be calibrated again once the temperature increases or decreases throughout the day.
2) Virginia's DOT has thirteen permanent WIM sites. DOT gives this data to the pavement designers for research purposes. The Department of Motor Vehicles has some permanent WIM sites that are used for prescreening trucks. If the truck is over-weight, the DMV uses an actual weighing scale to further law enforcement.

Washington:

Angela Ranger
Washington DOT: Commercial Vehicle Services
(888) 877-8567

1) Washington does not have a portable WIM program.
2) Washington has twelve permanent WIM sites.

West Virginia:

Gary Garley
Project studies unit leader (Civil Engineer)
(304) 558-9510

1) West Virginia does not have a portable WIM program and has never used it before.
2) West Virginia has more than fifty permanent WIM sites. Also, West Virginia uses portable scales.