SPR-731 JULY 2017

Successful Practices in Weigh-in-Motion Data Quality with WIM Guidebook

Volume 1

Arizona Department of Transportation Research Center

Successful Practices in Weigh-in-Motion Data Quality with WIM Guidebook

SPR-731
Volume 1
July 2017

Prepared by:
Olga Selezneva and Dean Wolf
Applied Research Associates
Transportation – Mid-Atlantic Division
7184 Troy Hill Drive, Suite N
Elkridge, MD 21075

Published by:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, AZ 85007
In cooperation with
Federal Highway Administration
U.S. Department of Transportation

Disclaimer

This report was funded in part through grants from the Federal Highway Administration, U.S. Department of Transportation. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data, and for the use or adaptation of previously published material, presented herein. The contents do not necessarily reflect the official views or policies of the Arizona Department of Transportation or the Federal Highway Administration, U.S. Department of Transportation. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names that may appear herein are cited only because they are considered essential to the objectives of the report. The U.S. government and the State of Arizona do not endorse products or manufacturers.

This report is subject to the provisions of 23 USC § 409. Any intentional or inadvertent release of this material, or any data derived from its use, does not constitute a waiver of privilege pursuant to 23 USC § 409, which reads as follows:

> **23 USC § 409 — Discovery and admission as evidence of certain reports and surveys**
>
> Notwithstanding any other provision of law, reports, surveys, schedules, lists, or data compiled or collected for the purpose of identifying, evaluating, or planning the safety enhancement of potential accident sites, hazardous roadway conditions, or railway-highway crossings, pursuant to sections 130, 144, and 148 of this title or for the purpose of developing any highway safety construction improvement project which may be implemented utilizing Federal-aid highway funds shall not be subject to discovery or admitted into evidence in a Federal or State court proceeding or considered for other purposes in any action for damages arising from any occurrence at a location mentioned or addressed in such reports, surveys, schedules, lists, or data.

.

Technical Report Documentation Page

1. Report No. FHWA-AZ-17-731	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Successful Practices in Weigh-in-Motion Data Quality with WIM Guidebook		**5. Report Date** July 2017 **6. Performing Organization Code**
7. Author(s) Olga Selezneva and Dean Wolf		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Applied Research Associates Transportation – Mid-Atlantic Division 7184 Troy Hill Drive, Suite N Elkridge, MD 21075		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** SPR-000 1(184) 731
12. Sponsoring Agency Name and Address Arizona Department of Transportation 206 South 17th Avenue Phoenix, AZ 85007		**13. Type of Report and Period Covered** Final Report (Volume 1) **14. Sponsoring Agency Code**

15. Supplementary Notes

Project performed in cooperation with the Federal Highway Administration

16. Abstract

The Arizona Department of Transportation (ADOT) plans to install new weigh-in-motion (WIM) stations with either piezo-polymer or piezo-quartz sensors. Recognizing some limitations of WIM sensor technologies, ADOT sponsored this study to ensure the accuracy of the future WIM data collection. The project tasks included (1) reviewing other highway agencies' practices related to WIM data quality assurance through literature review and a survey; (2) developing a guidebook of clear recommendations for managing WIM installation, calibration, maintenance, and data quality assurance; and (3) developing a research report with recommendations on how to achieve successful implementation of a WIM program.

Through reviewing available literature and surveying selected highway agencies, the project team determined that the piezo-quartz sensors perform much better than the piezo-polymer sensors due to their consistent reliability, reduced calibration requirements, and relative temperature insensitivity. With proper installation, piezo-quartz WIM sensors should provide accurate axle and truck weight measurements in Arizona.

Findings also indicated that piezo-polymer sensors should perform well in Arizona for vehicle classification, traffic volume, and speed studies, but not for weight data collection. This is due to the temperature sensitivity of piezo-polymer sensors and to the limitations of auto-calibration and temperature compensation technologies in environments where pavements undergo rapid day-to-night temperature changes and are subjected to high seasonal temperatures. Piezo-polymer sensor use with an auto-calibration feature for weight measurements should be evaluated on a case-by-case basis.

Using findings from the literature review and the successful WIM practices survey, the research team developed a guidebook with recommendations and procedures for WIM site selection and qualification, installation, calibration, maintenance, data quality assurance, and personnel needed to support ADOT's WIM program. These recommendations are specific to WIM systems that use piezo-quartz sensors and piezo-polymer sensors. The guidebook is included as Chapter 4 of this final report.

17. Key Words Weigh in motion, Weigh in motion scales, Piezoelectricity, Piezoelectric Materials, Sensors, Calibration		**18. Distribution Statement** This document is available to the US public through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 154	**22. Price**

FORM DOT F 1700.7 (8-72) **REPRODUCTION OF COMPLETED PAGE AUTHORIZED**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

CONTENTS

EXECUTIVE SUMMARY 1
Literature Search Findings 1
State WIM Practices Survey 1
WIM Guidebook 2
Conclusions and Recommendations 2
CHAPTER 1. INTRODUCTION 3
Background 3
Objective 3
Methodology 3
CHAPTER 2. LITERATURE REVIEW 7
Review of WIM Systems with Piezo-Polymer Sensors 8
Review of WIM Systems with Piezo-Quartz Sensors 17
Alternative WIM Sensor Options Offering Comparable Cost and Accuracy 22
Procedures to Provide Sustainable, Long-Term WIM System Reliability 23
Data Quality Assurance Activities Necessary to Maintain WIM System Accuracy 26
Strategies to Manage WIM Installation Costs and Long-Term Costs 28
Conclusions from the Literature Review 29
CHAPTER 3. SURVEY OF STATE WIM PRACTICES 31
Survey Purpose 31
Survey Participants 31
WIM System Types Used by Agencies 32
Types of Data Collected by WIM Systems 41
WIM Data Customers 42
WIM Program Management 43
WIM Site Qualification and Construction Practices 47
WIM Equipment Installation Practices 49
WIM Equipment Maintenance Practices 49
WIM Equipment Calibration Practices 52
WIM Data Accuracy and Quality Assurance (WIM Data QA-QC Program) 56
WIM Data Sharing Between State Transportation and Weight Enforcement Agencies 61

Recommendations Obtained from the Survey for WIM System Type and System Components 63
WIM Technology Testing Using Test Beds/Facilities 64
Supporting Documentation 64
Conclusions Based on Survey Responses 65
CHAPTER 4. GUIDEBOOK FOR WEIGH-IN-MOTION INSTALLATION, CALIBRATION, MAINTENANCE, AND DATA QUALITY ASSURANCE 71
Overview 71
Section 1 – WIM Site Location Selection and Assessment 72
Section 2 – WIM System Installation 85
Section 3 – WIM System Calibration 96
Section 4 – WIM Equipment Maintenance 113
Section 5 – WIM Data Quality Assurance and Analysis 123
Section 6 – WIM Program Support Staff 127
CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS 131
Summary 131
Conclusions 131
Recommendations 138
REFERENCES 143
APPENDICES: SEE SPR-731 VOLUME 2
APPENDIX A – COMPLETED SURVEY FORMS .... Vol 2
APPENDIX B – FHWA LTPP SITE EVALUATION FORM (CA SPS-2) .... Vol 2
APPENDIX C – WIM SYSTEM INSTALLATION SAMPLE DOCUMENTS AND FORMS .... Vol 2
APPENDIX D – WIM SYSTEM CALIBRATION DOCUMENTS AND SAMPLE FORMS AND TOOLS .... Vol 2
APPENDIX E – WIM EQUIPMENT MAINTENANCE DOCUMENTS AND SAMPLE FORMS .... Vol 2
APPENDIX F – WIM DATA QUALITY ASSURANCE AND ANALYSIS SAMPLES .... Vol 2

LIST OF FIGURES

Figure 1. Weight Data in 2001: Histogram of Gross Weights of Class 9 Trucks as Measured with Piezo-Ceramic Sensors 9

Figure 2. Weight Data in 2005: Histogram of Gross Weights of Class 9 Trucks as Measured with Piezo-Quartz Sensors 10

Figure 3. GVW Estimation Error by Temperature at the New Mexico SPS-5 LTPP WIM Site (Selezneva et al. 2016) 20

LIST OF TABLES

Table 1. ASTM Active Standard E1318-09 Type I WIM Systems Requirements 8
Table 2. LTPP Data Comparison 10
Table 3. Comparison of Axle Weight Measurements by TDC/BL and iSINC/BP Sites in Arizona 11
Table 4. Overall Maryland SPS-5 Site Results (Source: FHWA 2002) 12
Table 5. Overall Florida Piezo-Polymer WIM Site Results (Source: FHWA 2002) 13
Table 6. Average Weight Measurement Error Due to Equipment Precision Observed at LTPP SPS Sites with Different WIM Sensors 19
Table 7. Performance and Cost of WIM Equipment Sensors 29
Table 8. Survey Participants 32
Table 9. Agency WIM Equipment 33
Table 10. Controller Types and Quantities Represented in Survey 34
Table 11. Sensor Technologies and Quantities Represented in Survey 34
Table 12. ASTM Sensor Types and Quantities Represented in Survey 35
Table 13. Pavement Types and Quantities Represented in Survey 35
Table 14. Controller-Sensor Combinations Represented in Survey 35
Table 15. Temperature Compensation Methods Used by the Surveyed States for the Represented Controller-Sensor Combinations 37
Table 16. Sensor-Pavement Type Combinations Represented in Survey 37
Table 17. Sensor-ASTM Type Combinations Represented in Survey 38
Table 18. Installation Combinations Represented in Survey 39
Table 19. Count of WIM Systems Used by DOTs to Collect Data for Customers, Sorted by Sensor Type 42
Table 20. WIM Program Staffing 43
Table 21. Outsourced WIM Program Support Activities by Respondent – Equipment 43
Table 22. WIM Installation Quality Assurance Staff 45
Table 23. WIM Maintenance and Calibration Staff 45
Table 24. Qualified WIM Calibration Staff 46
Table 25. On-Site WIM Calibration Staff 46
Table 26. WIM Maintenance Staff 46
Table 27. Site Qualification Criteria Ranking 48
Table 28. Site Selection Documentation 48
Table 29. WIM Installation Documentation 49
Table 30. WIM Maintenance Documentation 50

Table 31. WIM Preventive Maintenance Frequency 50
Table 32. WIM System Maintenance Assessment 51
Table 33. WIM Repair Response Time 51
Table 34. WIM Calibration Documentation 52
Table 35. WIM Calibration Frequency and Effort Assessment 52
Table 36. Acceptable GVW Mean Error and Range in Error by Agency – Piezo-Polymer 54
Table 37. Acceptable GVW Mean Error and Range in Error by Agency – Piezo-Quartz 55
Table 38. WIM Measurement Bias and Error Tolerance Table – Weight Enforcement 56
Table 39. WIM Measurement Bias and Error Tolerance Table – Planning 56
Table 40. WIM Measurement Bias and Error Tolerance Table – Research 57
Table 41. WIM Measurement Bias and Error Tolerance Table – Environmental 57
Table 42. WIM Measurement Bias and Error Tolerance Table – Safety 57
Table 43. WIM Measurement Bias and Error Tolerance Table – Design 58
Table 44. WIM Measurement Bias and Error Tolerance Table – Asset Management 58
Table 45. WIM Data QA-QC Checks Performed 59
Table 46. Assessment of Relationship with Weight Enforcement Agency 62
Table 47. WIM Program Documentation Available for ADOT Program Development 65
Table 48. Recommended WIM Smoothness Index Thresholds 76
Table 49. Recommended Sensor Channel and Homerun Slot Depths 91
Table 50. Functional Performance Requirements for WIM Systems per ASTM E1318-09 97
Table 51. Recommended WIM Smoothness Index Thresholds 102

LIST OF ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
AC	alternating current
ADOT	Arizona Department of Transportation
ARA	Applied Research Associates
ASTM	American Society for Testing and Materials
BL	Brass Linguini®
BP	bending-plate
CDS	comparison data set
ConnDOT	Connecticut DOT
CPATT	Centre for Pavement and Transportation Technology
DOT	Department of Transportation
DMV	Department of Motor Vehicles
F	Fahrenheit
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
ft	feet
GDOT	Georgia Department of Transportation
GFCI	ground fault circuit interrupter
GRS	galvanized rigid steel
GUI	graphical user interface
GVW	gross vehicle weight
ISWIM	International Society for Weigh-In-Motion
IRD	International Road Dynamics, Inc.
IRI	International Roughness Index
kips	kilopounds
lb	pounds
LDOTD	Louisiana Department of Transportation and Development
LRI	long-range index
LTAS	LTPP traffic analysis software
LTPP	Long-Term Pavement Performance (program name)
MEPDG	*Mechanistic Empirical Pavement Design Guide*
MnDOT	Minnesota DOT
MPD	Multimodal Planning Division
NATMEC	North American Travel Monitoring Exhibition and Conference
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NCR	Non-compliance report
OHPI	Office of Highway Policy Information
OWL	Optimal WIM Locator

PCC	portland cement concrete
PVC	polyvinyl chloride
PVDF	piezoelectric polyvinylidene fluoride
QA	quality assurance
QC	quality control
RMC	rigid metal conduit
SPS	Specific Pavement Studies
SRI	Short-Range Index
TMAS	Travel Monitoring Analysis System
TPAS	Traffic Polling and Analysis System
TRB	Transportation Research Board
TTI	Texas Transportation Institute
VTRIS	Vehicle Travel Information System
WIM	weigh-in-motion

EXECUTIVE SUMMARY

The Arizona Department of Transportation (ADOT) plans to install approximately 60 weigh-in-motion (WIM) stations. These stations will collect vehicle weight, classification, and speed data. The collected data can be used to aid in pavement design, weight violation enforcement, and freight travel demand modeling. These WIM stations will have either piezo-polymer or piezo-quartz sensors. Recognizing some limitations of WIM sensor technologies and the effect that the environment, traffic speed and volume, pavement roughness, and physical site characteristics can have on WIM measurement precision, ADOT sponsored this study to ensure the accuracy of its future WIM data collection. The project tasks included (1) reviewing other highway agencies' practices related to WIM data quality assurance (QA) through literature review and a survey; (2) developing a guidebook of clear recommendations for managing WIM installation, calibration, maintenance, and data quality assurance; and (3) developing a research report for ADOT with recommendations on how to implement its WIM program successfully.

LITERATURE SEARCH FINDINGS

The project team reviewed available literature and determined that piezo-quartz sensors outperform piezo-polymer sensors because of their consistent reliability, reduced calibration requirements, and relative temperature insensitivity. Piezo-quartz WIM sensors should provide accurate axle and truck weight measurements in Arizona and could be installed in both asphalt and concrete pavements. To achieve sensor longevity, special attention should be given to proper installation and site location selection, including selection of pavement that provides sufficient structural support and is not susceptible to changes in stiffness due to fluctuations in ambient temperature.

Findings also indicated that using piezo-polymer sensors to consistently collect accurate axle and truck weight data in Arizona may be very challenging. This is primarily due to a known temperature sensitivity issue of piezo-polymer sensors and limitations of auto-calibration and temperature compensation technologies in environments where pavements undergo rapid day-to-night temperature changes and are subjected to high seasonal temperatures. These sensors are not recommended for applications that require accurate weight data collection. Piezo-polymer sensors should perform well in Arizona for vehicle classification, traffic volume, and speed studies because these data are obtained using a different data-processing algorithm that is not related to weight data.

In addition, the literature search identified several critical elements of WIM system installation, maintenance, and data quality assurance programs that must be considered. These findings were further investigated and summarized in the survey task. Literature review findings are presented in Chapter 2 of this report.

STATE WIM PRACTICES SURVEY

The project team surveyed successful WIM practices in several state and federal highway agencies that use similar WIM system technologies and obtained inputs from industry experts representing the Transportation Research Board (TRB), North American Travel Monitoring Exhibition and Conference

(NATMEC), and the International Society for Weigh-In-Motion (ISWIM). Special attention was given to the experiences of agencies with WIM sites installed under climatic conditions similar to Arizona.

Based on the mail-in survey responses, the project team identified WIM practices beneficial to ADOT's WIM program. These practices include: (1) selection of WIM technology that satisfies user needs and budget, (2) selection of a WIM site location that supports accurate weight measurement, (3) use of certified WIM installers and independent (from contractor) QA inspectors for WIM installation, (4) regular preventive and timely corrective WIM maintenance, (5) continuous or frequent remote monitoring of WIM data quality and operational performance, (6) regular calibration with frequency determined by sensor type and site characteristics, (7) comprehensive and ongoing data quality assurance and quality control (QA-QC) process, and (8) availability of trained staff and sufficient budget to provide continuous operation of WIM sites within specified performance requirements. Details on the survey questionnaire's contents and the survey results are provided in Chapter 3 of this report.

WIM GUIDEBOOK

Using findings from the literature search and the successful WIM practices survey, the research team developed a guidebook with recommendations and procedures for WIM site selection and qualification, installation, calibration, maintenance, data quality assurance, and personnel needed to support ADOT's WIM program. The guidebook includes recommendations specific to WIM systems that use piezo-quartz sensors and piezo-polymer sensors. It could serve as an implementation and management plan for ADOT's WIM program. The guidebook is presented as Chapter 4 in this final report.

CONCLUSIONS AND RECOMMENDATIONS

The last chapter of the final report contains conclusions based on the findings from the review of WIM practices implemented by other highway agencies for collecting quality data from WIM systems equipped with piezo-quartz sensors and piezo-polymer sensors. It summarizes the applicability and limitations of these WIM systems and provides recommendations for technology selection and for implementation of a WIM program that would meet ADOT's needs for quality WIM data. These recommendations include (1) using the procedures and recommendations in the guidebook included in Chapter 4, (2) developing a *WIM Technician's Field Operations Manual* with supporting tools and reporting documentation templates, and (3) developing and/or implementing computer-aided tools to perform WIM calibration, data processing, and data quality assurance functions.

CHAPTER 1. INTRODUCTION

BACKGROUND

The Arizona Department of Transportation (ADOT) plans to install new weigh-in-motion (WIM) stations to collect vehicle weight, classification, and speed data. These data will aid in pavement design, weight violation enforcement, and freight travel demand modeling. These WIM stations will have either piezoelectric polyvinylidene fluoride (PVDF) Brass Linguini® (BL) sensors manufactured by Measurement Specialties, Inc., or piezoelectric quartz sensors manufactured by Kistler Instrument Corporation. The BL sensor belongs to the piezo-polymer type of sensor and the Kistler sensor belongs to the piezo-quartz type of sensor. Because sites will be chosen according to various customer needs, it will not be possible to avoid locations with adverse climatic conditions, such as significant temperature variations, or very high or very low traffic volumes.

WIM technology has evolved over the past 20 years, but some measurement accuracy limitations still remain. The accuracy of WIM measurements can be diminished by factors such as the performance limitations of WIM sensors, the environment (especially temperature differentials during the day and over the year), traffic speed and volume, pavement roughness, and physical site characteristics. The effects of these factors can be minimized through proper WIM sensor installation, equipment maintenance, calibration, and data quality assurance practices.

OBJECTIVE

ADOT sponsored this study to ensure the accuracy of WIM data collection. The project tasks include reviewing other agencies' successful and failed practices related to WIM data quality assurance through a literature search and a mail-in survey, and developing a guidebook of clear recommendations for managing WIM installation, calibration, maintenance, and data quality assurance.

METHODOLOGY

Literature Search Approach

The literature search focused on collecting and reviewing past studies of successful and failed practices in WIM data quality assurance, particularly those practices concerned with correcting the effects of temperature variations on traffic classification, speed, and axle weight data collected using piezo-polymer and piezo-quartz sensors. Throughout the search, the research team placed special emphasis on evaluating WIM performance under climatic conditions similar to those found in regions within Arizona. Through the literature review, the project team summarized the advantages and limitations of piezo-polymer and piezo-quartz, listed available data quality assurance strategies and procedures to improve measurement accuracy, and identified other suitable sensors.

The research team evaluated the use of these sensors to collect accurate traffic volume data by class, vehicle speed, and axle weight. This evaluation considered sensor type, maintenance and calibration needs, and sensor service life to determine the following:

- Achievable weight measurement accuracy
- Equipment maintenance and calibration needs
- Data quality assurance activities necessary to maintain system accuracy
- Procedures to provide sustainable, long-term system reliability

The project team also reviewed previously published WIM best-practices reports and extracted relevant information from them. These findings are presented in Chapter 2 of this report.

State WIM Practices Survey

The project team surveyed successful WIM practices of selected federal and state highway agencies that use similar WIM system technologies under environmental conditions similar to those observed in Arizona. The survey was sent electronically to the WIM program managers or traffic data office managers in New Mexico, California, Florida, Mississippi, Georgia, Louisiana, Texas, Alabama, North Carolina, Virginia, Maryland, and Pennsylvania. Most of the states provided responses to the survey. In addition, the research team obtained inputs from industry experts representing the Transportation Research Board (TRB), North American Travel Monitoring Exhibition and Conference (NATMEC), and International Society for Weigh-In-Motion (ISWIM).

Based on the survey responses, the project team identified several agencies with experiences representing best practices relevant to ADOT's WIM program. The team then conducted an in-depth analysis of these states' practices, including their use of manuals, specifications, reports, and test beds related to the WIM program or WIM data quality. Based on this analysis, the research team defined practices beneficial to ADOT's WIM program. Details on the survey questionnaire's content and the survey results are provided in Chapter 3 of this report.

In addition, the project team reviewed and documented WIM processes developed and utilized by the Federal Highway Administration's (FHWA's) Specific Pavement Studies (SPS) Traffic Data Collection Pooled Fund Study TPF-5(004). This program is known for producing research-quality WIM data for a set of WIM sites located throughout the United States, including two sites in Arizona and six sites in states with at least some climatic conditions similar to Arizona's (Texas, New Mexico, Florida, and Louisiana).

Guidebook Development and Recommendations

Using findings from the literature search and the best practices survey, the research team developed a prototype guidebook for weigh-in-motion installation, calibration, maintenance, and data quality assurance. The guidebook includes procedures and recommendations that would help ADOT ensure quality data collection using WIM systems with piezo-polymer and piezo-quartz sensors. The guidebook describes recommended processes for WIM installation, calibration, maintenance, and data quality assurance. This guidebook is presented as Chapter 4 of this report.

Through review of the best WIM practices, a number of supporting tools, reporting procedures, reference documentation, and operational manuals used by highway agencies in the administration and operation of their WIM programs were identified. The research team evaluated the benefits of different tools and supporting materials and developed recommendations for ADOT to implement similar materials. These recommendations are included in Chapter 5.

CHAPTER 2. LITERATURE REVIEW

The literature review synthesized conclusions from past studies related to successful and failed practices in WIM data quality assurance, especially about correcting the effects of temperature variations on traffic classification, speed, and axle weight data collection. The review focused primarily on the two types of WIM sensors of interest to ADOT:

- Piezo-polymer (piezoelectric polymer) sensors. These sensors are also commonly referred to by the manufacturer's name, including Roadtrax® sensors, and as the previously mentioned PVDF BL. The term piezo-polymer is used in this report for consistency, unless a cited reference has a specific reference to the sensor by name, such as PVDF BL.
- Piezo-quartz (piezoelectric quartz) sensors. These sensors are commonly referred to by the manufacturer's name—Kistler. The term piezo-quartz is used in this report for consistency. All references to piezo-quartz sensors in this review are for sensors manufactured by Kistler.

In addition, a third type of piezoelectric WIM sensor, piezo-ceramic sensor, was included in the review because of its similarity to the piezo-polymer sensor in performance characteristics and cost.

The effect of temperature on the accuracy of axle and truck weight measured by these sensors is of particular concern. Therefore, the review placed special emphasis on evaluating WIM performance under climatic conditions similar to those of regions within Arizona. Available strategies and successful practices aimed at reducing the effect of temperature on the accuracy of weight measurements were researched, reviewed, and documented. The following list outlines the chapter contents:

1. Review of WIM systems with piezo-polymer and piezo-ceramic sensors
    - States' experience
    - Achievable weight measurement accuracy
    - The effect of temperature on WIM measurements
    - Temperature error compensation as an integral part of quality assurance for WIM with BL sensors
    - Maintenance and calibration needs
    - Summary of advantages and limitations
2. Review of WIM systems with piezo-quartz sensors
    - States' experience
    - Achievable weight measurement accuracy
    - Maintenance and calibration needs
    - Summary of advantages and limitations
3. Alternative WIM sensor options
4. Procedures to provide sustainable long-term WIM system reliability (installation, calibration and maintenance)
5. Data quality assurance activities necessary to maintain WIM system accuracy

6. Strategies to manage WIM installation costs and long-term costs
7. Conclusions from the literature review

This chapter ends with a summary of advantages and limitations of piezo-polymer and piezo-quartz sensors, strategies for improving measurement accuracy through data quality assurance and procedures, and recommendations for sensor use.

REVIEW OF WIM SYSTEMS WITH PIEZO-POLYMER SENSORS

States' Experience with Piezo-Polymer WIM Sensors

Long-Term Pavement Performance Program WIM Sites in Multiple States

A member of FHWA's Long-Term Pavement Performance (LTPP) program management team described the evolution of LTPP WIM data over the years from unusable data to research-quality data (Walker and Cebon 2011). LTPP defines research-quality data as data compliant with the performance requirements, shown in Table 1, for Type I WIM sensors in the American Society for Testing and Materials (ASTM) International's Active Standard E1318-09, *Standard Specification for Highway Weigh-in-Motion Systems with User Requirements and Test Methods* (ASTM 2009).

In 2001, the LTPP program ran pilot WIM performance evaluations of state-installed and maintained WIM sites in Arizona, Florida, Maryland, Michigan, and Texas. None of the LTPP pilot sites with piezo-ceramic or piezo-polymer sensors were found capable of consistently providing data that met ASTM E1318-09 performance requirements for Type I WIM sensors (Walker and Cebon 2011). As a result of this pilot, the WIM technologies recommended and used by a later LTPP WIM pooled-fund study included bending-plate, load cell, and piezo-quartz sensors, all of which meet the specifications for a Type I WIM system (Walker and Cebon 2011).

Table 1. ASTM Active Standard E1318-09 Type I WIM Systems Requirements

Data Item	Tolerance for 95% Compliance
Wheel Load	±25%
Axle Load	±20%
Axle-Group Load	±15%
Gross Vehicle Weight	±10%

Florida WIM Sites

In Florida, a side-by-side comparison of the performance of piezo-ceramic and bending-plate sensors showed that the piezo-ceramic did not perform as well as the bending plate (Walker and Cebon 2011). This resulted in the Florida Department of Transportation's (DOT) decision to move from piezo-ceramic sensors to quartz sensors. Figures 1 and 2 show histograms of gross vehicle weight (GVW) in thousands of pounds (kilopounds, or kips) for Class 9 trucks—a 3-axle tractor pulling a 2-axle semitrailer—for the Florida SPS WIM site before (2001) and after (2005) the sensor change. Both figures show monthly totals throughout the year. The data in 2001 were collected with ceramic-cable sensors similar in performance to piezo-polymer sensors, and the data in 2005 were collected with quartz sensors, installed and calibrated according to the LTPP pooled-fund study's protocols. Both graphs show two peaks in the histograms. The peak at a weight of approximately 30,000 lb corresponds to unloaded vehicles, and the peak at approximately 80,000 lb corresponds to loaded vehicles.

It is important to note a significant improvement in the consistency of monthly GVW distributions in Figure 2 compared to Figure 1. The WIM system that generated the data in Figure 1 was installed before standards were adopted, and the data are typical of data reported by piezo-ceramic and piezo-polymer sensors. The data in Figure 2 are typical of those collected with quartz sensors at the LTPP SPS WIM sites. Table 2 compares the accuracy of the WIM validation tests in 2001 and 2005 (Walker and Cebon 2011).

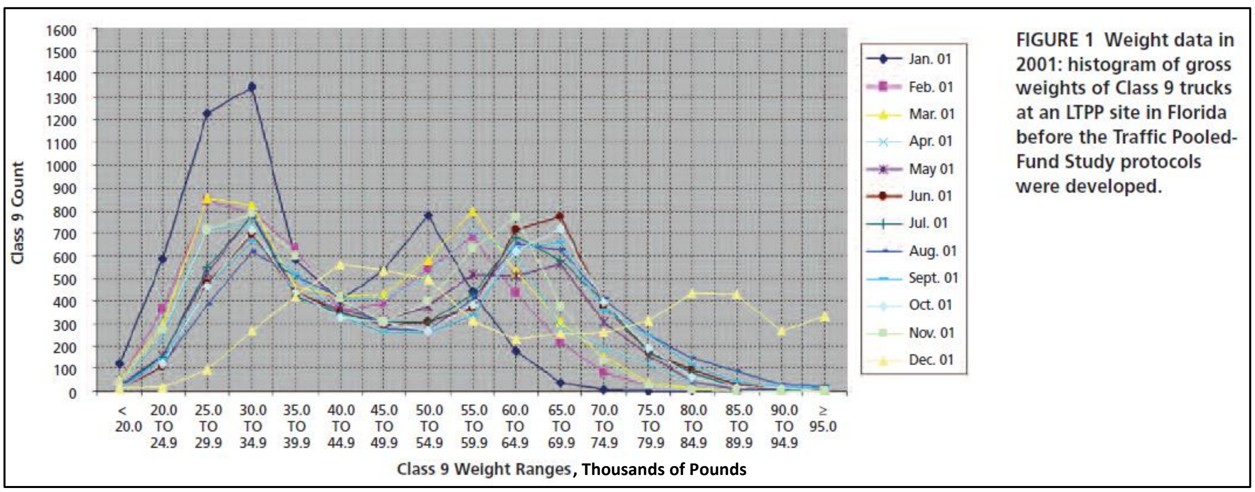

Figure 1. Weight Data in 2001: Histogram of Gross Weights of Class 9 Trucks as Measured with Piezo-Ceramic Sensors

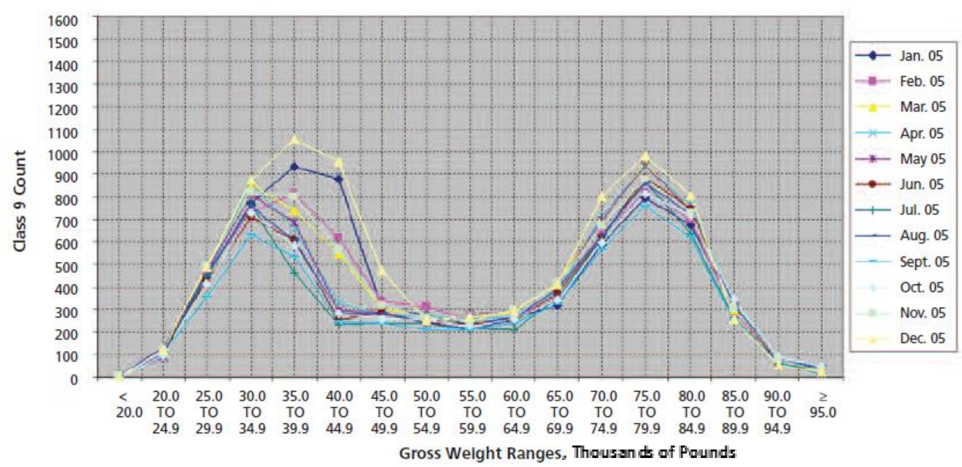

FIGURE 2 Weight data in 2005: histogram of gross weights of Class 9 trucks at an LTPP site in Florida using Traffic Pooled-Fund Study equipment and protocols.

Figure 2. Weight Data in 2005: Histogram of Gross Weights of Class 9 Trucks as Measured with Piezo-Quartz Sensors

Table 2. LTPP Data Comparison

Parameter	Accuracy Guideline	2001 Piezo-Ceramic Data	2005 Piezo-Quartz Data
Gross weight	10%	–18% to +30%	0.2% ± 8.2%
Tandem axles	15%	–26% to +41%	0.0% ± 10.2%
Single axle	20%	–31% to +38%	1.2% ± 10.0%

Arizona WIM Sites

Research conducted in 2011 by ARA’s team addressed the collection, preparation, and use of traffic data required for pavement design by ADOT, focusing on data required as inputs for the AASHTOWare *Mechanistic-Empirical Pavement Design Guide* (MEPDG) design procedures (Darter et al. 2011). At the time of the research, ADOT was performing an internal study to determine standard equipment for collecting WIM data. ADOT investigated several combinations of WIM controllers and in-road sensors:

- TDC Systems Limited controller with PVDF BL sensors
- Cardinal Q-WIM controller with Kistler quartz sensors
- Peek ADR controller with PVDF BL sensors
- ECM Hestia controller with Kistler quartz sensors

ADOT’s Multimodal Planning Division (MPD) is also monitoring the performance of its LTPP SPS WIM site equipment, which includes the International Road Dynamics (IRD) iSINC controller and bending-plate (iSINC/BP) technology. To date, ADOT has given strong consideration to the TDC Systems controller with piezo-polymer PVDF BL (TDC/BL) sensor configuration. As part of the 2011 research study (Darter et al.

2011), the TDC/BL system was compared with a nearby LTPP SPS WIM site. Since the LTPP SPS WIM site has been regularly calibrated by FHWA under the pooled-fund study and data analyses are performed regularly, the data are considered to be of research quality and provide a valuable source for comparison.

A breakdown of the reported GVW for Class 9 trucks by each equipment type is shown in Table 3. Compared to LTPP (iSINC/BP) values, the TDC/BL sensors under-predicted axle weights by up to 17 percent and GVW by 15 percent. This high bias is unacceptable for MEPDG pavement design and does not meet law enforcement needs. For MEPDG, bias over 5 percent for axle group weight measurements may lead to significant difference in pavement thickness prediction (Selezneva et al. 2013, 2016), while for law enforcement, the total GVW error (including both precision and bias components) should be less than 5 percent in the European Union or less than 6 percent in the United States (European Cooperation in Science and Technology 1998; ASTM 2009).

Table 3. Comparison of Axle Weight Measurements by TDC/BL and iSINC/BP Sites in Arizona

Equipment	GVW (kips)	Front Axle (kips)	Tandem 1 (kips)	Tandem 2 (kips)	Unloaded Peak GVW Value (kips)	Loaded Peak GVW Value (kips)
LTPP (iSINC/BP)	61.5	11.2	25.6	24.6	56.0	81.0
MPD (TDC/BL)	52.2	10.0	21.2	21.2	48.0	73.0
% Difference[1]	-15.1%	-10.7%	-17.2%	-13.8%	-14.3%	-9.9%

[1] Of the MPD value relative to the LTPP value

The weights displayed by the TDC/BL system did not vary directly with temperature, as ADOT had expected (Darter et al. 2011). This apparent stability could mean that the temperature correction of the TDC controller is superior to that of other piezoelectric WIM controllers, or that the ambient temperatures during data collection did not change significantly. It would be beneficial to ADOT to conduct further analysis to determine whether TDC/BL equipment can consistently compensate for the effects of temperature on measurement errors over a wide range of both seasonal and hourly temperatures, since other researchers have previously reported and quantified these effects (Gajda et al. 2012), as described later in this chapter.

Achievable Weight Measurement Accuracy

The piezo-polymer BL sensor manufacturer currently claims that its Class II WIM sensors have a uniformity of ±20 percent and are typically used only for classification purposes, and that its Class I sensors have a uniformity of ±7 percent and are typically used for WIM applications. However, over time the uniformity of the sensors typically degrades (Szary and Maher 2009).

Several studies evaluated the field performance over time of WIM systems using piezo-polymer sensors. As described in the following paragraphs, all of these studies report low accuracy of piezo-polymer sensors.

To test the various protocols and guidelines for the LTPP SPS Traffic Data Collection Project, FHWA conducted five pilot studies in the summer and fall of 2001. Two of the pilot project sites involved systems using piezo-polymer sensors (FHWA 2014). The first project, a WIM site evaluation study, was conducted at a site called SPS-5 on US 15 near Frederick, Maryland, on June 12 and 13, 2001. This site contained a pair of PVDF BL sensors without direct temperature compensation and a pair of inductance loops installed in asphalt. The system was calibrated on June 12 with three runs in each direction of a Class 9 truck loaded to 78,100 pounds. The results, shown in Table 4 (FHWA 2002), indicate that this system failed to meet ASTM E1318-09 tolerances for all weight measurements (single and tandem axles and GVW).

Table 4. Overall Maryland SPS-5 Site Results (Source: FHWA 2002)

Characteristic	**ASTM E1318-09 Tolerance for Type I WIM**	**Computed 95% Confidence Interval**	**Pass/Fail**
Axle weights: Steering axles	±20%	2.2% ± 21.1%	FAIL
Axle weights: Tandem axles	±15%	-4.2% ± 22.8%	FAIL
Gross vehicle weights	±10%	-3.25% ± 18.90%	FAIL
Vehicle speed	±1 mph [2 km/hr]	±2 mph	FAIL
Axle spacing length	±0.5 ft [150 mm]	+0.35 ft	PASS

The second pilot project was conducted on November 7 and the morning of November 8, 2001, at a site on US 319 south of Tallahassee, Florida. The traffic monitoring equipment included inductance loops and piezo-polymer sensors installed within an asphalt concrete (AC) pavement. The computed values of 95 percent confidence limits of each statistic for the total population on the scales are recorded in Table 5 (FHWA 2002). This system also failed to meet ASTM E1318-09 tolerances for all weight measurements (single and tandem axles and GVW).

Table 5. Overall Florida Piezo-Polymer WIM Site Results (Source: FHWA 2002)

Characteristic	ASTM E1318-09 Tolerance for Type I WIM	Northbound: Computed 95% Confidence Interval	Northbound: Pass/Fail	Southbound: Computed 95% Confidence Interval	Southbound: Pass/Fail
Axle weights: Steering	±20 %	-11.0% ± 24.0%	FAIL	6.30% ± 17.0%	FAIL
Axle weights: Tandem	±15 %	-2.96% ± 26.9%	FAIL	-4.11% ± 17.0%	FAIL
GVW	±10 %	-3.61% ± 25.0%	FAIL	-2.34% ± 11.3%	FAIL
Axle spacing: Between groups	±0.5 ft	0.16 ft ± 0.36 ft	FAIL	0.16 ft ± 0.34 ft	PASS
Axle spacing: Within groups	±0.5 ft	-0.12 ft ± 0.10 ft	PASS	-0.12 ft ± 0.10 ft	PASS

In September 2007, three types of WIM piezoelectric sensors (ceramic, polymer, and quartz) were installed and evaluated at the University of Waterloo's Centre for Pavement and Transportation Technology (CPATT) test site in Waterloo, Ontario, Canada. After installation and calibration of the systems, comparisons of static weights with the measured weights were made for each type of sensor with different test runs, speeds, temperatures, and types of vehicles. A monthly data analysis showed that the quartz sensor has the best estimation accuracy for all test records with different GVW classes of vehicles. The evaluation verified that the quartz sensor technology has the best weight measurement accuracy, non-sensitivity to temperature change, and overall best performance among these three sensor types (Jiang et al. 2009).

Based on the literature search findings, weight errors of 30 percent can be expected for sites with piezo-polymer sensors in the absence of reliable temperature compensation algorithms adaptable to rapid temperature changes (Gajda et al. 2012). When properly installed and calibrated, a piezoelectric WIM system could be expected to provide GVW within 15 percent of the actual vehicle weight for 95 percent of trucks measured (Yannis and Antoniou 2005).

The Effect of Temperature on WIM Measurements

The review of several studies indicated that the accuracy of axle weight measurements by both piezo-ceramic and piezo-polymer sensors is highly sensitive to changes in temperature. This is due to the positive relationship between the capacitive properties of the sensors and temperature, as supported by the findings of a long-term research study conducted by Janusz Gajda and his team from 2010 to 2012. Their work determined that the piezo-polymer sensors showed an increase in signal amplitude with increased pavement temperature. These increases resulted in an increase in weights, with weight measurement errors ranging between ±30 percent. At the same time, no research was found that provided any hypotheses or conclusions that the speed, classification, or axle spacing measurement accuracies are affected by the temperature. This result may be explained by differences in how these data are collected compared to how axle weight data are collected. Speed, classification, and axle spacing measurements are based on presence (binary yes/no signal output), while weight measurements are based on relative changes in the signal amplitude (Gajda et al. 2012).

A 2004 National Cooperative Highway Research Program (NCHRP) study identified the key issues that highway agencies must consider in selecting equipment for collecting truck volumes and weight data needed for analysis and design of pavement structures (Hallenbeck and Weinblatt 2004). The study concluded that temperature-sensitive WIM sensors are not good choices for WIM sites where field temperatures change rapidly. The authors stated that although such sensors are used with temperature compensation algorithms, the algorithms often rely on some type of auto-calibration technique that requires collection of a sample of axle or vehicle weights, which takes time. Therefore, these adjustments cannot be made fast enough to maintain scale accuracy in areas with rapid temperature changes, such as those experienced in mountain passes and in the Southwestern deserts (both day/night and seasonal changes apply). This conclusion is directly related to the climatic conditions observed in Arizona.

The same NCHRP study also concluded that, because the strength of asphalt pavements also changes as environmental conditions change, WIM sensor technologies such as the piezo-polymer that rely on direct structural support from the pavement itself will perform less consistently in these pavements than at locations where the pavement's strength does not change (e.g., thicker and stiffer asphalt and concrete sections).

A study by Andrew Nichols and his team in 2004 developed a quality control program for the Indiana DOT to improve the accuracy of data produced from a WIM system with piezo-polymer sensors. Nichol's study collected evidence that extreme temperatures and precipitation cause increases in error rates and system calibration drift. He concluded that an auto-calibration feature is not robust enough to account for this (Nichols and Bullock 2004).

A 2011 field investigation of environmental impacts on piezo-polymer concluded that temperature and transverse location of axle load over the sensors are the two most significant factors (comparing to weight range and speed) affecting piezo-polymer and piezo-ceramic sensors, specifically in warmer months (Vaziri 2011). The interaction effects of the temperature and transverse location of axle load over the sensors are also strongly significant for piezo-polymer and piezo-ceramic sensors.

Based on this review, it was concluded that no current field-tested and implemented procedures permit accurate axle weight measurement using piezo-polymer sensors under field conditions susceptible to rapid temperature changes, as typically observed in Arizona. Piezo-polymer sensors, however, could perform well under controlled temperature conditions or field conditions where temperatures stay consistent throughout the measurement period.

It is also clear from the literature that use of temperature compensation based on auto calibration is not suitable for Arizona WIM sites in areas that are subjected to rapid temperature changes, are susceptible to high seasonal temperatures, and have roads with low truck volume. Therefore, piezo-polymer sensors likely would not provide consistently accurate axle weight data under Arizona climatic conditions, though they would provide accurate speed, classification, and axle spacing measurements.

Temperature Error Compensation as an Integral Part of Quality Assurance for WIM with BL Sensors

Based on the literature review, WIM systems utilizing the piezo-polymer sensor must account for the effect of temperature on the roadway and on the sensor itself. Systems available today account for this effect through using either an auto-calibration feature, which is used for high truck volume sites, or a temperature compensation routine. However, both of these techniques present challenges and have limitations. Of specific relevance to Arizona, Hallenbeck and Weinblatt found that technologies that use these techniques to account for temperature sensitivity are ineffective in environments subjected to quick temperature changes (Hallenbeck and Weinblatt 2004). Nonetheless, a brief review of these techniques is provided in the following paragraphs.

Auto-Calibration

In roadways with high-volume truck traffic, the WIM system's auto-calibration feature can be used to compensate for the effects of temperature change on measured truck weights by periodically comparing the average front axle weight from the free-flowing traffic with a stored estimated weight of steering axles on Class 9 trucks. A deviation from this estimate is calculated after a pre-determined number (e.g., 100) of Class 9 trucks passes over the WIM scale, and an auto-calibration factor is adjusted accordingly to compensate for this error (Burnos 2008). This approach has two flaws. The first is that temperatures observed during the sampling may vary and may not represent the temperatures at the time the auto-calibration factor is adjusted. The second is the absence of a direct correlation between the steering-axle weight error and the error for heavy axle groups and, therefore, GVW. Consequently, an effective WIM system using the piezo-polymer sensor must provide compensation for these flaws. That is, the auto-calibration feature must itself be calibrated. Some WIM controllers, such as the IRD controller, provide a separate "Dynamic Compensation" factor for this purpose. However they would still require a consistent input of loads of known magnitude (as in the case of steering axle loads), which is not practically achievable based on uncontrolled truck stream characteristics. The Peek ADR does not have this feature and, thus, can be auto-calibrated to only one type of axle load.

Tests performed by LTPP showed that auto-calibration functions were not always successful in maintaining calibration of environmentally sensitive sensors when environmental conditions were changing rapidly. In addition, auto-calibration functions cannot be expected to calibrate a scale accurately if key auto-calibration values have not been independently confirmed at that site (Hallenbeck and Weinblatt 2004).

Enhanced Auto-Calibration Using a Temperature Sensor

Nichols and his team proposed an enhanced auto-calibration function using additional temperature input from a temperature sensor that is installed on the paved shoulder adjacent to the sensors. The temperature is used with the Class 9 GVW to sort the measured steering axle weights into bins. When a Class 9 steering-axle weight is obtained, it is logged into a bin based on the temperature and the GVW. At the end of each day, the measured steering-axle weights in each bin are averaged and compared to a target steering-axle weight. If these values differ by a certain percentage, the weight calibration factors are adjusted to minimize the difference. Depending on the temperature bin size, there are many auto-calibration factors, considering that these bins exist for each lane at the WIM site (Nichols and Bullock 2004). According to a conversation with Dr. Nichols in January 2015, no manufacturers have implemented this feature to date.

Temperature Compensation

It was recommended by Piotr Burnos at the fifth International Conference on Weigh-In-Motion in 2008 that in order to maximize the effectiveness of the temperature compensation, the temperature compensation factors must be determined by site, using seasonal calibrations to obtain multiple compensation points. Burnos proved a positive relationship between the number of compensation points distributed evenly along the temperature range and the accuracy of the WIM system. Burnos developed a temperature correction feature utilizing a pre-set, multiplicative compensation factor that is assigned to a particular range of temperatures (Burnos 2008).

The challenge to using Burnos' approach in Arizona is that it requires several hours of nearly constant temperature to conduct calibration runs using test trucks to establish a baseline compensation factor for that temperature point (or a narrow temperature range). This calibration would need to be conducted seasonally for the first year to collect sample data at different temperature points, and then free-flow traffic data would need to be analyzed to fill the gaps and create a full temperature compensation curve for the range of temperatures typically observed at the site through the year. This approach also assumes that seasonal changes observed in the field are far greater than day/night temperature changes.

Equipment Maintenance and Calibration Needs

No matter how much money is budgeted and spent for the initial purchase and installation of a WIM site, all WIM equipment requires continual care and attention. Without ongoing attention to equipment performance and data collection site conditions, equipment performance will degrade over time. It is poor practice to simply place equipment and hope that an auto-calibration function will soon bring the system into calibration (Hallenbeck and Weinblatt 2004).

ASTM Standard E1318-09 provides standard methods for calibrating WIM systems using test vehicles of known static weights and dimensions. According to the standard, WIM calibrations require two test trucks of known heavy weights and dimensions making multiple runs over the WIM system sensors at prescribed speeds in each lane. The user then analyses WIM-measured weights against known static weights and adjusts the WIM system performance parameters to compensate for measurement error.

The calibration process is similar for all types of WIM sensors; however, less precise sensors such as piezo-polymer sensors may require more truck runs to compute a reliable error estimate that can be used to calculate new equipment compensation factors. Imprecise sensors may also require more frequent calibrations to account for seasonal changes in temperature. In addition, implementation of special calibration measures may be needed for piezo-polymer sensor sites having rapid day/night temperature fluctuations.

Advantages

Based on a review of several studies involving use of the piezo-polymer sensor for WIM, the following advantages were identified:

- Because of their low installation and maintenance cost, piezoelectric sensors have been widely used in various WIM applications.
- WIM controllers that are equipped to interface with piezo-polymer sensors are widely available through many vendors and, in many instances, provide several cost-competitive price options (Hallenbeck and Weinblatt 2004).
- Piezo-polymer sensors easily conform to the shape of the roadway due to their flexibility (Fernando et al. 2009).
- When properly installed and calibrated, a piezoelectric WIM system should be expected to provide GVW within 15 percent of the actual vehicle weight for 95 percent of trucks measured (Yannis and Antoniou 2005).

Limitations

Previous studies identified a number of limitations to the use of piezo-polymer sensors for WIM. Most of the limitations stem from the high sensitivity of the sensors to changes in temperature, both daily and seasonal, and a need for strong structural support of the pavement underneath the sensor. Hallenbeck and Weinblatt (2004) essentially summarized conclusions from other published research (e.g., Middleton et al. 1999 and McCall and Vodrazka 1997). No recent reports or studies were identified that provide information contrary to that summarized by Hallenbeck and Weinblatt (2004):

- Due to calibration drift related to the effects of temperature, WIM systems using the BL sensor require frequent calibration, which is expensive.
- BL sensors are susceptible to lightning.
- Meticulous installation is required. The sensors must be installed strictly according to the manufacturer's instructions to achieve any degree of accuracy.
- Sensor accuracy is affected by the structural response of a roadway.
- Low cost and ease of installation often result in placement in slightly rutted pavements, resulting in loss of accuracy.

REVIEW OF WIM SYSTEMS WITH PIEZO-QUARTZ SENSORS

States' Experience with Quartz WIM Sensors

The Connecticut DOT (ConnDOT) was the first in the United States to install piezo-quartz sensors for WIM in 1999 (Fernando et al. 2009). Since then, this sensor has gained strong support from the industry (Hallenbeck and Weinblatt 2004). According to Kistler's website, IRD and Peek offer WIM systems that directly process the signals from the Kistler quartz sensor. Kistler also provides a charge amplifier unit for use with WIM controllers not equipped to handle the piezo-quartz sensor output signal.

Research by the Texas Transportation Institute (TTI) at the University of Texas at Austin in 2005 included a survey of several states to determine their experience with the piezo-quartz WIM sensors and full-scale field tests. The research team obtained the following findings from Illinois, Maine, Michigan, Minnesota, Montana, and Ohio (Middleton et al. 2005):

- The Illinois DOT has installed piezo-quartz sensors since 1999 in its Pre-Pass system as a sorter to determine the need for static weighing, believing that their average life was about two years. Illinois DOT calibrates the piezo-quartz sensors about three to four times per year, typically based on complaints from Pre-Pass personnel. Illinois DOT plans to replace all failed sensors with new piezo-quartz sensors. Piezo-quartz sensors installed by Illinois DOT in concrete seem to last longer and perform better than those installed in asphalt.
- The Maine DOT equipped 13 WIM stations with a total of 132 piezo-quartz sensors. It calibrated all sites once a year and checked sites weekly for data discrepancies. It has found the piezo-quartz sensors to be "extremely accurate." It has calibrated sensors to within a 2 percent error compared to test vehicle GVW and plans to continue using piezo-quartz sensors, even though their failure rate is of significant concern. The accuracy of the sensors is the overriding factor causing the Maine DOT to continue installing and using them.
- The Minnesota DOT (MnDOT) had no problems with piezo-quartz sensors, but their installation required complete attention to detail. According to MnDOT, the sensors have a good bond with the existing pavement and seem to be very durable when properly installed according to the manufacturer's detailed instructions.
- The Florida DOT (FDOT) replaced all its previous piezoelectric WIM sites in asphalt with piezo-quartz sensors (Phillips piezo-ceramic sensors were used previously: personal communication from FDOT's WIM manager, Rick Reel). FDOT found that the installation cost for piezo-quartz sensors is about the same as for bending plates, but hopes that the maintenance costs will be less. FDOT is considering regrinding the pavement due to increased rutting, but it finds that the piezo-quartz sensors are continuing to provide good data.

Many states have started replacing traditional piezo-polymer or piezo-ceramic sensors with the newer piezo-quartz sensors because of their reported greater accuracy and their low maintenance needs (Middleton et al. 1999, Hallenbeck and Weinblatt 2004). Proper installation on pavements that provide adequate support appears to be a key factor in getting good sensor performance and service life.

LTPP SPS WIM Sites in Multiple States

FHWA initiated its 2001 Pooled-Fund Study TPF-5(004) to standardize WIM data collection at select LTPP test sites. The objective of this study was to improve the quality and increase the quantity of monitored traffic data (volumes, classifications, and weights). Of different WIM technologies considered and tested, only bending-plate, load cell, and quartz piezoelectric sensors were found to consistently collect research-quality data. The *LTPP Field Operations Guide for SPS WIM Sites, 2012 update* (FHWA 2012 [LTPP]) addresses the pavement smoothness, equipment calibration checks, and equipment model specifications for the LTPP WIM systems. The average life of piezo-quartz sensors installed at LTPP pooled-fund sites is two to eight years.

According to Walker et al. (2012), all LTPP SPS WIM sites with piezo-quartz sensors perform within ASTM E1318-09 performance requirements for Type I WIM systems. All of these sites also meet the overall tolerance limits specified in the *LTPP Field Operations Guide for SPS WIM Sites* (FHWA 2012 [LTPP]) for research-quality WIM data. The LTPP SPS WIM sites using piezo-quartz sensors installed in asphalt pavement were more precise than those sites using piezo-quartz sensors installed in portland cement concrete (PCC) pavements.

Achievable Weight Measurement Accuracy

While more expensive per sensor than the piezo-polymer or piezo-ceramic sensors, the piezo-quartz sensors have the distinct advantage of being insensitive to temperature changes and therefore generally more accurate than the other two types of piezo sensors (Hallenbeck and Weinblatt 2004).

According to Walker et al. (2012), analysis of the LTPP SPS pooled-fund sites found that piezo-quartz, bending-plate, and load cell technologies produced values well within the ASTM E1318-09 specification for Type I WIM systems (ASTM 2009), as shown in Table 6.

Table 6. Average Weight Measurement Error Due to Equipment Precision Observed at LTPP SPS Sites with Different WIM Sensors

Measurement Type	Average errors due to equipment precision observed during post-validation		
	Piezo-quartz	Bending plate	Load cell
Steering Axle	7.9%	6.5%	5.8%
Tandem Axle	6.5%	4.7%	4.8%
GVW	5.0%	3.4%	3.3%

The Effect of Temperature on WIM Measurements

Unlike other piezo-polymer WIM sensors, piezo-quartz sensors are not sensitive to temperature because of the different properties of the material used for this sensor type. A 2009 study conducted by Emmanuel G. Fernando for the Texas DOT found that the errors in weight measurements showed no significant correlation with pavement temperature (Fernando et al. 2009). The study also concluded that the variability of WIM measurements due to the variation of asphalt concrete stiffness with pavement temperature does not appear to be an issue for the piezo-quartz sensor (Fernando et al. 2009). The errors for the WIM system utilizing the piezo-quartz sensor (as percentages of the reference GVW) are all within the 10 percent GVW tolerance specified in ASTM E1318-09 for Type I WIM systems.

During the LTPP validations at SPS WIM pooled-fund study sites, efforts were made to test the equipment over the highest range of temperatures possible (Walker et al. 2012). Temperature did not appear to have a significant effect on the mean error or variability in error for the majority of the sites, with the exception of the New Mexico SPS-1 and SPS-5 sites equipped with piezo-quartz sensors. The researchers suspected that the warmer climates observed in New Mexico may have caused the lower pavement stiffness that led to changes in sensor response, but they could not confirm their suspicion since no other LTPP sites using piezo-quartz sensors installed in the same type of environment are still part of the program. The New Mexico SPS-1 and SPS-5 WIM validation reports and the reports from all of the LTPP SPS WIM validations can be viewed at the LTPP Research website (Selezneva et al. 2016).

Kistler advertises that its sensors are not sensitive to temperature, and all studies of piezo-quartz sensor performance cited in this chapter have supported this claim. However, piezo-quartz sensor performance may be affected by changes in supporting structure underneath the sensor, i.e., changes in pavement stiffness with temperature. Two LTPP SPS WIM New Mexico sites with extreme temperature ranges yielded some evidence of possible temperature sensitivity of the WIM system with piezo-quartz sensors, most likely due to changes in pavement support under the sensors.

Figure 3 shows a distinctive relationship between GVW and temperature at the New Mexico SPS-5 LTPP WIM site. As temperature rises over the 50° F temperature range during a single day, the estimated GVW of the calibration truck decreases. It could be hypothesized that as pavement becomes softer, the sensors experience less compression, resulting in lower electrical reading. However, the limited information does not provide enough facts to establish the exact cause of temperature sensitivity observed at that site.

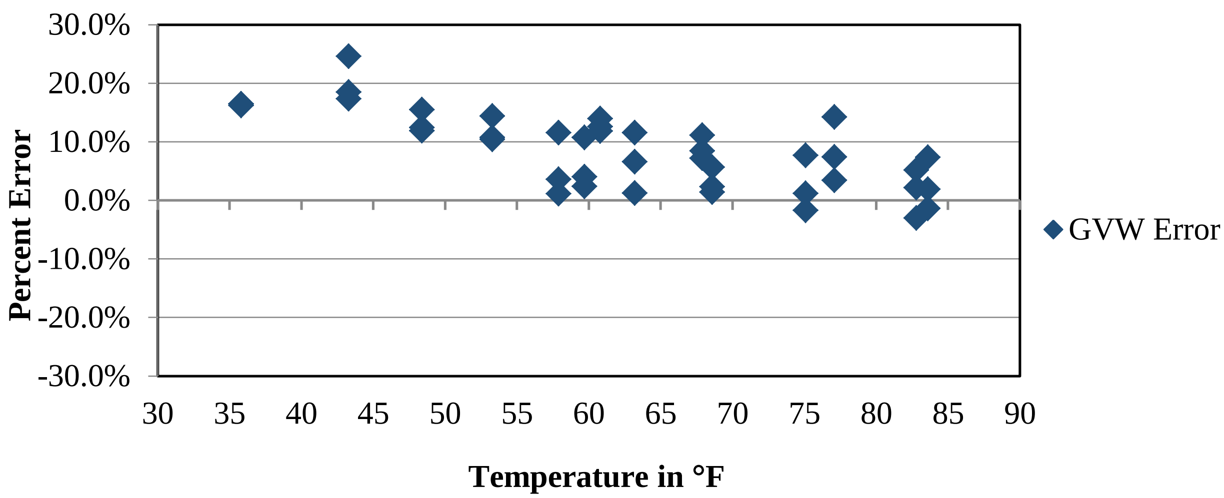

Figure 3. GVW Estimation Error by Temperature at the New Mexico SPS-5 LTPP WIM Site (Selezneva et al. 2016)

Equipment Maintenance and Calibration Needs

Equipment maintenance and calibration needs for WIM sites with piezo-quartz sensors follow the same general guidelines as those outlined for piezo-polymer sensors. However, piezo-quartz sensors need less frequent calibration and do not need temperature-related calibration when installed in stiff pavements. Based on an analysis of the calibration drift for LTPP SPS WIM sites with piezo-quartz sensors, Walker et al. (2012) concluded that these WIM systems should be calibrated at least every 18 months.

Advantages

According to the results of several studies reviewed by Hallenbeck and Weinblatt (2004), piezo-quartz sensor advantages include the following:

- They are not temperature-sensitive.
- They are easier and faster to install than bending plates or load cells.
- They allow WIM systems to require less frequent calibration than systems with piezo-polymer sensors.
- They may be more cost-effective (long term), if they prove to be long-lived.

Walker et al. (2012) demonstrated that all LTPP SPS WIM sites with piezo-quartz sensors consistently met ASTM E1318-09 requirements for Type I WIM systems. These systems could maintain this performance level if calibrated at least every 18 months as noted above.

Additionally, as mentioned earlier, an evaluation of three types of WIM piezoelectric sensors (ceramic, polymer, and quartz) verified that the piezoelectric quartz sensor technology has the best weight measurement accuracy, non-sensitivity to temperature change, and overall best performance among these three sensors (Jiang et al. 2009).

Limitations

Hallenbeck and Weinblatt (2004) summarize some disadvantages related to using the piezo-quartz sensor for WIM, including:

- Installation is much more expensive for a WIM system using the piezo-quartz sensor than for a WIM system using the piezo-polymer sensor.
- The quartz sensor's accuracy is highly dependent on proper installation, including the requirement for the top of the sensor to be completely flush with the pavement surface.
- These sensors must be re-sanded to account for pavement rutting.
- Sensor longevity is inconsistent. Although the sensors have been redesigned to address this issue, their life span can vary from two to eight years.

Hallenbeck and Weinblatt's 2004 conclusions are further confirmed by the WIM System Field Calibration and Validation Summary Reports for the WIM sites included in the FHWA LTPP Pooled-Fund Study, posted on the LTPP Research website (Selezneva et al. 2016). The piezo-quartz sensors' life expectancy has increased, but some of the sensors became non-functional after approximately two years, while others are still functional in 2015 after their installation in 2007.

ALTERNATIVE WIM SENSOR OPTIONS OFFERING COMPARABLE COST AND ACCURACY

Several WIM sensor alternatives to the piezo-polymer and piezo-quartz sensors are available but, with the exception of piezo-ceramic sensors, none are offered at a comparable cost of procurement and installation (though bending-plate systems have competitive *life cycle* costs due to their reduced calibration and maintenance needs and longer service lives). The 2009 Fernando study concluded that most DOTs use bending plates, load cells, piezo-polymer, piezo-ceramic, and piezo-quartz sensors at WIM installations. The study's summary includes (Fernando et al. 2009):

- The bending-plate sensor is highly accurate and very dependable. However, it comes with high installation and maintenance costs.
- The load cell sensor is even more accurate than the bending-plate sensor but is proportionately more expensive to install and maintain.
- The bending-plate and load cell sensors may only be installed in concrete pavements.
- The piezo-ceramic sensor is competitive with the piezo-polymer sensor in cost, but is more susceptible to temperature changes.

WIM systems that use strain gauges on single-span bridge structures (also called Bridge WIM systems) present another alternative. From a cost standpoint, such bridge WIM systems are competitive with bending-plate and piezo-quartz systems. Unfortunately, various other factors degrade the signal from the strain gauges and limit the accuracy of data (Hallenbeck and Weinblatt 2004). Bridge WIM may become a viable option for ADOT in the future once the accuracy of the technology has proven to be comparable with more traditional WIM systems.

Fiber-optic WIM sensors detect the presence of a load by measuring the decrease in optical transmission caused by constriction of the fibers when vehicles pass over them. The potential advantages of fiber-optic sensors are their relative insensitivity to road temperature and low cost. Although several studies have been performed on different fiber-optic sensors, no sensor systems are known to have been fully developed and placed into field operational use (Hallenbeck and Weinblatt 2004).

The 2009 Fernando study was aimed at finding less costly but equally viable alternatives for WIM installations. However, its review of WIM practices did not identify any new and innovative low-cost WIM sensors that could be recommended for practical use in a state WIM network at that time. The results reported at that time on fiber-optic and microwave sensors were, at best, inconclusive in the opinion of the researchers (Fernando et al. 2009).

Intercomp, Inc. (intercompcompany.com) has recently developed a high-speed strip scale that provides in-ground WIM capabilities featuring low-cost strain gauge load cell technology for increased accuracy, repeatability, and fast response times. Intercomp claims that its scales exceed the requirements of ASTM E1318-09 for Type I, Type II, and Type III (ASTM 2009, Papagiannakis et al. 2008) for high-volume data collection and screening for direct enforcement. The manufacturer's limited testing at two sites in

Minnesota provides initial evidence that this technology is capable of collecting accurate axle weight information.

A study conducted by Patrick Szary and his team for the New Jersey DOT in 1999 tested, under large loads, a piezoelectric ceramic/polymer composite sensor made with an active piezoelectric ceramic element embedded in a flexible, non-active epoxy polymer (Szary et al. 1999). Further research completed by Szary and Ali Maher in 2009 finished the development of a lower-temperature-dependent WIM sensor; they concluded that, after seven months, the sensor assemblies were still functioning, but stress patterns and other trends similar to those of conventional piezoelectric sensors had developed and the output voltages had diminished by 66 to 83 percent. Thus, for all intents and purposes, the sensor assemblies were considered failed (Szary and Maher 2009).

The general conclusion from the review of alternative WIM technologies is that no reliable, low-cost, accurate WIM system with proven long-term field performance is currently available on the market. Another important conclusion is that better-quality data will cost more for installation, maintenance, and data QA-QC (Hallenbeck and Weinblatt 2004).

PROCEDURES TO PROVIDE SUSTAINABLE, LONG-TERM WIM SYSTEM RELIABILITY

Research conducted by Bill McCall for the Center for Transportation Research and Education at Iowa State University in cooperation with four states in 1997 resulted in a *States' Successful Practices Weigh-in-Motion Handbook* (McCall and Vodrazka 1997). Although this reference is somewhat dated, the handbook lays out several key components for the longevity of a WIM system that remain critical today, including:

- Site selection
- Site location
- Road geometry
- Pavement smoothness
- Maintenance
- Calibration
- Installation

These elements, in combination with the quality assurance program discussed later in this chapter, represent necessary elements for sustainable, long-term WIM system reliability.

Site Selection

Selecting an adequate site for the WIM installation is very important to ensure desired accuracy of WIM data. To meet these requirements, the geometric design, pavement condition, and general characteristics of a potential site should be considered. ASTM E1318-09 for WIM systems sets forth requirements for WIM site selection.

Site Location

To minimize installation cost and provide favorable conditions for site maintenance and operation, the following conditions should be considered:

- Availability of access to power and telephone
- Adequate location for controller cabinet
- Adequate drainage
- Traffic conditions
- Easy and safe site access for maintenance and calibration

Road Geometry

The geometric design of a roadway should provide favorable conditions for accurate estimation of static loads from dynamic load measurements. ASTM E1318-09 for WIM systems sets guidelines for horizontal curvature, longitudinal gradient, cross (lateral) slope, and the width of the paved roadway lane (McCall and Vodrazka 1997).

Pavement Smoothness

The roadway pavement condition is important in the reduction of vehicle bounce. Vehicle bounce increases with road roughness and leads to greater variations in the vertical load imposed by a moving axle (McCall and Vodrazka 1997).

The *Pavement Smoothness Specifications for LTPP WIM Locations* developed by Steven Karamihas and his team aimed to minimize axle motion effects and vehicle body bounce. The specifications are used for WIM verification, annual checks, and acceptance of new WIM sites (Karamihas et al. 2004).

The guideline set forth in ASTM E1318-09 states that, for 46 meters (150 feet) before and after the sensor, the roadway surface "shall be maintained in a condition such that a 150 millimeter (6 inch) diameter circular plate, 3 millimeters (0.125 inches) thick, cannot be passed beneath a 6 meter (20 ft) long straightedge." The standard also states that a foundation must be provided and maintained to accommodate the sensors.

Maintenance

A systematic preventive and corrective maintenance program should be established for the site to help ensure that the expected "site design life" is attained (McCall and Vodrazka 1997). Preventive maintenance ensures that the site will function properly by periodically inspecting the system and roadway. Corrective maintenance repairs or replaces any malfunctioning equipment or roadway deterioration.

For the LTPP SPS Pooled-Fund WIM sites, two contractors perform the system validation and maintenance activities to ensure that the systems are calibrated, maintained, and operated correctly to generate the highest quality of data at each site. The first contractor is responsible for ongoing maintenance for each of the sites, performing semi-annual preventive and corrective maintenance as required (Walker and Cebon 2011). The second contractor's primary focus is to make sure that the WIM systems collecting traffic data at the SPS test sites are operating at peak performance by calibrating them when necessary and by validating them annually. Using this approach, the second contractor provides an independent and unbiased evaluation of the performance of the WIM system maintained by the first contractor. Further information about the LTPP SPS WIM Pooled-Fund study can be viewed at the LTPP Research website (Selezneva et al. 2016).

Calibration

Athanassios Papagiannakis, in a survey study his team conducted in 2007 (Papagiannakis et al. 2008), stated that WIM data quality can be ensured through routine WIM system calibration involving test trucks, traffic stream vehicles of known static weight, or simply WIM data quality control (QC). The team surveyed several state agencies on how they calibrate their most common WIM systems utilizing test trucks. The number of agencies utilizing test trucks for WIM calibration varies depending on their function:

- Twenty-two of the 34 agencies managing traffic data collection WIM systems use Class 9 semi-trailer test trucks for WIM calibration. Six of the 22 report that their most common WIM systems are Type I, while the rest report Type II.
- Six of the seven agencies managing traffic data and enforcement screening WIM systems use Class 9 semi-trailer test trucks for WIM calibration. Four of these six report that their most common WIM systems are Type I, while the remaining two report Type II.
- Two of the 11 agencies managing only enforcement WIM systems use Class 9 semi-trailer test trucks for WIM calibration. Their most common WIM system is Type I.

A number of procedures for calibrating WIM scales exist. Appendix F of the 2013 FHWA *Traffic Monitoring Guide* (FHWA 2013) provides a reasonably complete description of the current state of the art in WIM system calibration. In addition, ASTM E1318-09 and the FHWA's *LTPP Field Operations Guide for SPS WIM Sites* (ASTM 2009, FHWA 2012 [LTPP]) recommend the use of two test trucks of known weight but different vehicle characteristics (different classifications and/or suspension types) for performing WIM scale calibration to better represent the different weights and suspensions of trucks crossing a particular WIM site.

Installation

Proper installation of sensors is key to both WIM system performance and life span (Fernando et al. 2009). To ensure the quality of any given installation, it is good practice to have at least one agency representative and one vendor representative oversee the sensor installation process at permanent sites (McCall and Vodrazka 1997). This practice ensures that both the state's and the vendor's requirements are met, and that both parties are satisfied with the initial site conditions and the installation, which is particularly important when warranties are used to ensure system performance. For WIM performance warranties, site conditions must usually match ASTM E1318-09 specifications.

These site conditions should be verified by both parties when the site is first selected, well *prior* to the beginning of the installation process (Hallenbeck and Weinblatt 2004).

DATA QUALITY ASSURANCE ACTIVITIES NECESSARY TO MAINTAIN WIM SYSTEM ACCURACY

Data quality assurance is a critical component of any well-designed traffic monitoring program. The FHWA's *Traffic Monitoring Guide* (FHWA 2013) recommends that each agency improve the quality of reported traffic data by establishing quality assurance processes for traffic data collection and processing. Each highway agency should have formal, documented rules and procedures for their quality control efforts. Consequently, another key successful WIM practice component is for highway agencies to implement and use a quality assurance program that monitors data being collected and reported (Hallenbeck and Weinblatt 2004).

To ensure accuracy of WIM data collection, the data must be validated periodically in the field through validation/calibration activities and checked systematically in the office using a WIM user's QA program. A QA program adds confidence to the validity of the WIM data and alerts the data analyst to problems occurring at the WIM site. QA checks conducted regularly in the office will point out problems at the WIM site and help maintain the system throughout the site design life. The need for quality assurance prompted the development of several software programs that can be used to validate data in the office and point to problems occurring at the WIM site. Effective examples of these programs include the FHWA LTPP Traffic Analysis Software (LTAS), developed by FHWA Long-Term Pavement Performance program, and the FHWA Travel Monitoring Analysis System (TMAS), Version 2.0 software, developed by FHWA office of Highway Policy Information.

While the LTAS and TMAS software are available to states upon request, individual states also develop their own QA programs that better fit their specifications. These states work either independently or with a vendor to produce a QA process and reports. The advantages of a state's personalized QA process lie in the state's ability to meet its specific requirements.

The FHWA *WIM Data Analyst's Manual* by Richard Quinley provides recommended procedures for an agency's WIM office data analyst in performing validation and QC checks of WIM traffic data. The manual provides the following information (Quinley 2010):

- Basic WIM system information
- Guidance and recommendations on performing remote data validation and real-time monitoring of the WIM system
- Procedures for performing extensive analyses of individual vehicle records
- Procedures for monitoring a system's calibration over time
- Procedures to fine-tune a system's calibration

The North Carolina DOT (NCDOT) collects WIM data using procedures consistent with recommended industry practices to estimate static vehicle axle weights based on dynamic traffic measurements. A 2011 research study (Ramachandran et al. 2011) documents the NCDOT WIM QC procedures. Data errors and poor-quality data are captured regardless of the technology used. The NCDOT WIM QC process consists of a combination of automated and manually applied procedures in a user-friendly graphical user interface (GUI). A collection of auto-applied rules is used to identify invalid entries using checkmarks and flags displayed in the GUI for the fields under suspicion. The checked and flagged records are automatically excluded.

The QC process also consists of forms that flag the data displayed in the forms to alert the analyst to review certain data and manually exclude invalid data. In addition to these automated features, the QC process also uses plots and statistics to qualitatively assess the suitability of the data. Unusual patterns in the plots indicate that inconsistent data has been captured and may not be suitable. The process is applied sequentially, such that all QC steps for the vehicle weight data are completed prior to evaluating vehicle class data (Ramachandran et al. 2011).

Ramachandran provided several recommendations as part of his study, including:

- Develop effective equipment procurement procedures.
- Establish inspection procedures for newly installed equipment.
- Schedule periodic maintenance and calibration activities.
- Develop automated quality control procedures to review and detect corrupt data.

A report developed by Rafiqul Tarefder and James Brogan for presentation at the Transport Research Arena in 2014 identified appropriate measures to ensure that the New Mexico DOT collects, processes, analyzes, and reports high-quality traffic data in an optimal and cost-effective way. Brogan reported that New Mexico performs a number of checks on its WIM data, including the following (Tarefder and Brogan 2011):

- Consistency of the vehicle class, number of axles, number of axle spacings, GVW, weight of each axle, and the maximum wheelbase for each truck recorded
- Acceptable ranges of axle weights and axle spacings
- Calculated GVW and front steering axle weight frequency distributions for each vehicle class
- Peak values for unloaded and loaded Class 9 vehicles
- Class 9 front steering axle weight distribution

The *LTPP Traffic Data Collection and Processing Guide*, *Version 1.3*, developed for the FHWA in 2009, documented the processes and procedures used by LTPP to collect and store the traffic data used to estimate pavement loadings. Section 2 of this report covers data manipulation and validation/calibration of WIM equipment (Ostrom 2009).

The QA procedure developed by the California DOT (Caltrans) may be termed a “successful practice” due in part to the agency’s 10-plus years of WIM data experience. During those learning years, the state developed and used a QA procedure for validating data from the WIM systems it installed. Although its procedure bears several similarities to the LTPP procedure, it is distinctly different in many respects.

Therefore, it is a good example of an individual state's QA procedure formed separately from the LTPP program (McCall and Vodrazka 1997).

STRATEGIES TO MANAGE WIM INSTALLATION COSTS AND LONG-TERM COSTS

Each highway agency must determine its own tradeoffs among the cost of equipment and its installation, the cost of calibration, the expected life span of the WIM sensor, and the expected life span (and structural performance) of the pavement into which the equipment will be placed (Hallenbeck and Weinblatt 2004).

Good data collection is not necessarily achieved by purchasing the most expensive technology. What is necessary is to correctly budget the resources needed to buy reliable equipment, install that equipment properly, calibrate the equipment, and maintain and operate the equipment. The cost of performing these tasks will almost always be returned to the highway agency in improved reliability in the pavement design process (Hallenbeck and Weinblatt 2004).

Typically, the cost of the WIM controller is related to its capabilities, so its selection should be based on its ability to consistently deliver the collected data to the user (Darter et al. 2011).

A good practice for equipment installation includes choosing good equipment and sensor locations in the first place. For intrusive sensors, this means placing them into or onto pavement that is in good condition and likely to last well past the sensors' design life. Poor installation of any features can lead to early system failure and significant increases in both sensor downtime and maintenance and repair costs (Hallenbeck and Weinblatt 2004).

Calibration is a key part of the initial equipment setup. However, calibration alone will not compensate for a poorly installed piece of equipment. Poorly installed sensors often produce inconsistent signal outputs, making calibration either impossible or unstable over time, particularly as sensor performance declines. Poor installation also leads to early system failure and significant increases in both sensor downtime and maintenance costs. A key part of installation and calibration efforts is to ensure that installed sensors are producing consistent signals (Hallenbeck and Weinblatt 2004).

Preventive maintenance keeps equipment operating. Perhaps more importantly, preventive maintenance helps keep data quality problems to a minimum by reducing the number of spurious axle detections that occur during early phases of sensor and pavement failure. Proper and timely maintenance increases sensor life, improves data quality, and decreases overall system life-cycle costs (Hallenbeck and Weinblatt 2004).

Adoption of these practices or variations thereof is likely to improve the quality of the data collected and reduce the overall cost of the data collection effort (Hallenbeck and Weinblatt 2004).

As part of research conducted for the ADOT, and as a supplement to an MPD WIM selection study, a cost analysis was performed of the different types of WIM sensor technologies. The information (Table 7) is based on one lane of sensors only and does not include costs that are associated with installation or maintenance (Darter et al. 2011).

Table 7. Performance and Cost of WIM Equipment Sensors

Technology	Performance	In-Road Equipment
Piezoelectric	±10%	$3,500
Quartz	±5%	$14,500
Bending Plate	±3-5%	$21,000
Load Cell	±3%	$60,000

CONCLUSIONS FROM THE LITERATURE REVIEW

This literature search summarized the advantages, limitations, and data quality assurance strategies and procedures to improve measurement accuracy of WIM systems with piezo-quartz sensors and piezo-polymer sensors. Special emphasis was placed on evaluating WIM performance under climatic conditions similar to those in regions within Arizona. Consideration was given to previously published WIM best-practices reports identified during the literature search, and relevant information was extracted and presented.

Many studies were conducted to evaluate the accuracy of the piezo-polymer and piezo-quartz sensors. In each of these studies, it was determined that the piezo-quartz sensors performed much better than the piezo-polymer sensors due to their consistent reliability, reduced calibration requirements, and relative temperature insensitivity (assuming that strong and non-temperature-sensitive pavement is provided). Analysis of the LTPP Pooled-Fund Study WIM equipment validation results conducted in 2011 determined that the piezo-quartz sensors work well in both asphalt and concrete pavements. All literature findings support a conclusion that piezo-quartz WIM sensors should provide accurate axle and truck weight measurements in Arizona. However, to achieve sensor longevity, special attention should be given to proper installation and site location selection, including selection of pavement that provides sufficient structural support and is not susceptible to changes in stiffness due to changes in ambient temperature.

It was also concluded that using piezo-polymer sensors to consistently collect accurate axle and truck weight data in Arizona may be very challenging; the challenges are primarily due to a known issue of piezo-polymer sensor temperature sensitivity and the limitations of auto-calibration and temperature compensation technologies in environments subject to high seasonal temperatures and rapid day/night temperature changes. Nonetheless, piezo-polymer sensors should perform well in Arizona for vehicle classification, traffic volume, and speed studies, because these data are obtained using a different data-processing algorithm that is not related to weight data.

Several of the references that were reviewed stressed critical elements of a WIM system installation and maintenance program that must be considered. These elements, in combination with a quality assurance program, are vital to sustainable, long-term WIM system reliability:

- The WIM site should have access to power and telephone, an adequate location for a controller cabinet, adequate drainage, free-flowing traffic conditions, and easy and safe site access for maintenance and calibration.
- The roadway geometric design should provide favorable conditions for accurate estimation of static loads from dynamic load measurements, including horizontal curvature, the longitudinal gradient, the cross (lateral) slope, and the width of the paved roadway lane.
- The roadway should be smooth to reduce adverse vehicle dynamics that lead to greater variations in system accuracy.
- The agency should establish a systematic preventive and corrective maintenance program for the site to help ensure that the expected “site design life” is attained.
- The agency should perform routine WIM system calibration involving test trucks, preferably heavy Class 9 trucks.
- The agency should perform routine and systematic WIM data QC checks, including both field validations and routine office data checks, to ensure WIM data quality.
- The agency should know that proper installation of sensors is key to both WIM system performance and life span.

ADOT must determine its acceptable tradeoffs among the cost of equipment and its installation, the cost of calibration, the expected life span of the WIM sensor, and the application (i.e., data accuracy requirement) of the collected data. The key to purchasing WIM equipment is value. Higher-quality data comes at higher cost, and some tradeoffs, such as using a less-expensive sensor, are not acceptable when a data accuracy requirement cannot be met.

CHAPTER 3. SURVEY OF STATE WIM PRACTICES

SURVEY PURPOSE

The purpose of the survey was to review WIM practices implemented by selected state highway agencies that use WIM system technologies similar to the ones desired by ADOT—WIM systems with piezo-polymer and piezo-quartz sensors—and who operate in environmental conditions similar to Arizona's. The goal of the survey was to identify successful WIM practices applicable to the ADOT WIM program.

The survey was designed to seek input from similar highway agencies on their experience installing and maintaining WIM sites, providing quality weight data to their customers, and managing WIM programs. In addition, ADOT was interested in getting input from WIM experts who actively participate in professional forums such as the TRB Traffic Monitoring Committee and WIM Subcommittee, NATMEC, and ISWIM.

SURVEY PARTICIPANTS

Based on the research team's prior knowledge and on the response to the survey participation invitation announced during the January 2015 TRB Annual meeting, it was suggested that the following states have WIM experience that would be beneficial to thestudy: New Mexico, California, Florida, Mississippi, Georgia, Louisiana, Texas, Alabama, North Carolina, Virginia, and Pennsylvania. These states utilize or have utilized the same WIM technologies that ADOT is using or is planning to use, and most of these agencies have at least some regions within their boundaries with climatic conditions similar to regions in Arizona.

Several WIM professionals who are widely considered to be industry experts, who are well versed in WIM technology and applications, and who have been involved in TRB, NATMEC, and American Association of State Highway and Transportation Officials (AASHTO) standing committees were identified and invited to participate in the survey. The surveys were e-mailed to each state's WIM program managers or Traffic Data Office managers with a request to distribute the surveys internally to the appropriate staff for completion.

A list of agencies and industry professionals who participated in the survey is provided in Table 8.

Table 8. Survey Participants

Agency	Title
Connecticut DOT	Transportation Engineer, Vice-President – International Society for Weigh-in-Motion, Chair – TRB WIM Subcommittee on Weigh-in-Motion, Member – TRB Highway Traffic Monitoring Committee
Florida DOT	Administrator, Transportation Data
Georgia DOT	State Transportation Data Administrator
Louisiana DOTD	Director, Louisiana Transportation Research Center
New Mexico DOT	Chief, Data Management Bureau
Pennsylvania DOT	Manager, Transportation Planning Division
Texas DOT	Traffic Data Systems Engineer
Virginia DOT	Program Manager, Traffic Engineering Division
West Virginia DOT (Marshall University)	Professor of Engineering, Secretary of TRB Traffic Monitoring Committee, and member of WIM Subcommittee. West Virginia WIM consultant.
International Road Dynamics	Customer Service/ Sales Manager, guest of Traffic TRB Traffic ETG as WIM Expert.
US DOT, FHWA	Senior Transportation Specialist - Office of Highway Policy Information (OHPI), member of TRB Traffic Monitoring Committee, Secretary of TRB WIM Subcommittee, former ODOT WIM Program Manager.
US DOT, FHWA	Highway Research Engineer - Turner-Fairbank Highway Research Center, Office of Infrastructure Research and Development – Long Term Pavement Performance (LTPP) Team, Manager – LTPP SPS WIM TPF 5(004), Executive Secretary – International Society for Weigh-in-Motion

Once survey design and content was approved by ADOT, the survey questionnaire was distributed electronically to 12 relevant states and four WIM professionals to obtain federal government, state agency, academia, and WIM vendor perspectives. Their responses are summarized in the following sections.

WIM SYSTEM TYPES USED BY AGENCIES

Currently Used Systems

Each of the respondents was asked to identify the type of WIM systems he or she currently uses. The information requested included the number of WIM systems by WIM controller and sensor type, ASTM E1318-09 WIM type, pavement type, roadway classification, and type of temperature compensation used. The responses to this question were received from the nine state agency programs and the FHWA WIM program, as summarized in Table 9.

Table 9. Agency WIM Equipment

Agency	Number of WIM Systems	Controller	Sensor	ASTM Type(s)	Pavement Type(s)
Connecticut DOT	10	Telemetrics	Piezo-Polymer	II	Asphalt
	100	Raktel	Piezo-Polymer	I	Asphalt
Florida DOT	25	IRD-ISINC	Piezo-Quartz	I and III	Asphalt
	4	IRD-iSINC	Bending Plate	I and III	PCC
	3	PAT Traffic	Piezo-Quartz	I and III	Asphalt
	1	PAT Traffic	Bending Plate	I	PCC
Georgia DOT	6	Peek ADR	Piezo-Polymer	I and II	Asphalt
	9	Peek ADR	Piezo-Quartz	I	PCC
	1	IRD-iSINC	Piezo-Quartz and Piezo-Polymer	I	PCC
Louisiana DOTD	5	IRD TC540	Bending Plate	Unknown	PCC
New Mexico DOT	11	Peek ADR	Piezo-Quartz	Unknown	Asphalt
	2	IRD	Piezo-Quartz	Unknown	Asphalt
	3	IRD	Bending Plate	Unknown	PCC
Pennsylvania DOT	11	IRD-iSINC	Piezo-Quartz	I	Asphalt
	1	PAT Traffic	Piezo-Polymer	I	Asphalt
	1	PAT Traffic	Piezo-Quartz	I	Asphalt
Texas DOT	17	PAT Traffic	Piezo-Quartz	II	Asphalt
	15	PAT Traffic	Bending Plate	II	PCC
Virginia DOT	7	Peek ADR	Piezo-Quartz	I	Asphalt(3) and PCC(4)
	1	IRD-iSINC	Bending Plate	I	PCC
West Virginia DOT (Marshall University)	50	ECM	Piezo-Polymer	Unknown	Asphalt
FHWA LTPP	1	Mettler-Toledo	Load Cell	I	PCC
	11	IRD-iSINC	Bending Plate	I	PCC
	13	IRD-iSINC	Piezo-Quartz	I	PCC(2) and Asphalt(11)

The summary data in Table 9 may be expanded into Tables 10 through 18. The respondents used seven brands of controllers among their 308 installations (with IRD controllers occurring in three variations) in the quantities shown in Table 10.

Table 10. Controller Types and Quantities Represented in Survey

Controller	Installations
Raktel	100
IRD-iSINC	66
ECM	50
PAT Traffic	38
Peek ADR	33
Telemetrics	10
IRD	5
IRD TC540	5
Mettler-Toledo	1
Total	**308**

The respondents used four sensor technologies among their 308 installations (with one case in which two sensor technologies occurred at the same installation) in the quantities shown in Table 11.

Table 11. Sensor Technologies and Quantities Represented in Survey

Sensor	Installations
Piezo-Polymer	167
Piezo-Quartz	99
Bending Plate	40
Load Cell	1
Piezo-Quartz and Piezo-Polymer	1
Total	**308**

The respondents used all three ASTM sensor types among their 308 installations (though they sometimes reported the types in lots, e.g., Type I and III, or just did not know some types) in the quantities shown in Table 12.

The respondents installed sensors in two types of pavement in the quantities shown in Table 13.

Table 12. ASTM Sensor Types and Quantities Represented in Survey

ASTM Type(s)	Installations
I	157
Unknown	71
II	42
I and III	32
I and II	6
Total	**308**

Table 13. Pavement Types and Quantities Represented in Survey

Pavement Type	Installations
Asphalt	251
PCC	57
Total	**308**

The respondents used some controller brands with only one sensor technology and other controller brands with multiple sensor technologies among their 308 installations in the quantities shown in Table 14.

Table 14. Controller-Sensor Combinations Represented in Survey

Controller	Sensor	Installations
ECM	Piezo-Polymer	50
IRD	Bending Plate	3
IRD	Piezo-Quartz	2
IRD TC540	Bending Plate	5
IRD-iSINC	Bending Plate	16
IRD-ISINC	Piezo-Quartz	49
IRD-iSINC	Piezo-Quartz and Piezo-Polymer	1
Mettler-Toledo	Load Cell	1
PAT Traffic	Bending Plate	16
PAT Traffic	Piezo-Polymer	1
PAT Traffic	Piezo-Quartz	21
PEEK ADR	Piezo-Polymer	6
PEEK ADR	Piezo-Quartz	27
Raktel	Piezo-Polymer	100
Telemetrics	Piezo-Polymer	10
	Total	**308**

The participants were asked if they use temperature compensation methods for WIM sensor performance affected by temperature changes. This primarily concerns WIM systems with piezo-polymer WIM sensors. The responses from the survey participants regarding temperature compensation varied:

- Each of Connecticut's piezo-polymer WIM systems uses the WIM controller's auto-calibration feature to compensate for temperature fluctuations.
- Each of Georgia's Peek ADR WIM systems that is integrated with piezo-polymer sensors uses the WIM system's auto-calibration feature to compensate for temperature fluctuations. Georgia's nine WIM systems that use the Peek controller and piezo-quartz sensors do not use any temperature compensation. Georgia's remaining WIM system, which uses the IRD iSINC controller with piezo-quartz and piezo-polymer sensors, does not use any temperature compensation feature.
- For Louisiana, the type of temperature compensation, if used, is unknown.
- Each of Pennsylvania's and Texas's WIM systems uses a temperature probe to compensate for fluctuations in pavement temperature.
- Each of West Virginia's ECM piezo-polymer WIM systems uses the WIM system's auto-calibration feature to compensate for temperature fluctuations.
- None of the WIM systems managed by the FHWA LTPP program, Florida, New Mexico, or Virginia uses any type of temperature compensation. These systems do not use piezo-polymer WIM sensors.

Thus, the respondents used two temperature compensation approaches, or no compensation, with various controller-sensor combinations among their 308 installations in the quantities shown in Table 15.

Table 15. Temperature Compensation Methods Used by the Surveyed States for the Represented Controller-Sensor Combinations

Controller	Sensor	State(s)	Temperature Compensation (TC)	Installations
Raktel	Piezo-Polymer	CT	Auto	100
Telemetrics	Piezo-Polymer	CT	Auto	10
PEEK ADR	Piezo-Polymer	GA	Auto	6
ECM	Piezo-Polymer	WV	Auto	50
Mettler-Toledo	Load Cell	FHWA	No TC	1
IRD-iSINC	Piezo-Quartz	FHWA, FL	No TC	38
IRD-iSINC	Bending Plate	FHWA, FL, VA	No TC	16
PAT Traffic	Bending Plate	FL	No TC	1
PAT Traffic	Piezo-Quartz	FL	No TC	3
IRD-iSINC	Piezo-Quartz and Piezo-Polymer	GA	No TC	1
PEEK ADR	Piezo-Quartz	GA, NM, VA	No TC	27
IRD	Bending Plate	NM	No TC	3
IRD	Piezo-Quartz	NM	No TC	2
PAT Traffic	Piezo-Polymer	PA	Temperature probe	1
IRD-iSINC	Piezo-Quartz	PA	Temperature probe	11
PAT Traffic	Piezo-Quartz	PA, TX	Temperature probe	18
PAT Traffic	Bending Plate	TX	Temperature probe	15
IRD TC540	Bending Plate	LA	Unknown	5
			Total	**308**

The respondents generally used each of the four sensor technologies with only asphalt or only PCC pavement, except for the piezo-quartz sensor type, among their 308 installations in the quantities shown in Table 16.

Table 16. Sensor-Pavement Type Combinations Represented in Survey

Sensor	Pavement Type	Installations
Bending Plate	PCC	40
Piezo-Polymer	Asphalt	167
Load Cell	PCC	1
Piezo-Quartz	Asphalt	84
Piezo-Quartz	PCC	15
Piezo-Quartz and Piezo-Polymer	PCC	1
	Total	**308**

The respondents generally reported each of the sensor technologies variously as ASTM Type I or III (high weight measurement accuracy) and Type II (lower accuracy) in the quantities shown in Table 17.

Table 17. Sensor-ASTM Type Combinations Represented in Survey

Sensor	ASTM Type(s)	Installations
Bending Plate	I	13
Bending Plate	I and III	4
Bending Plate	II	15
Bending Plate	Unknown	8
Piezo-Polymer	I	101
Piezo-Polymer	II	10
Piezo-Polymer	I and II	6
Piezo-Polymer	Unknown	50
Load Cell	I	1
Piezo-Quartz	I	41
Piezo-Quartz	I and III	28
Piezo-Quartz	II	17
Piezo-Quartz	unknown	13
Piezo-Quartz and Piezo-Polymer	I	1
	Total	**308**

The respondents' installations were composed of 23 unique combinations of controller brands, sensor technologies, sensor ASTM types, and pavement types, though 10 particular combinations constituted almost 90 percent of the installations. These combinations are shown in Table 18.

Table 18. Installation Combinations Represented in Survey

Controller	Sensor	ASTM Type(s)	Pavement Type	Quantity	%	Cumulative %
Raktel	Piezo-Polymer	I	Asphalt	100	32%	32%
ECM	Piezo-Polymer	Unknown	Asphalt	50	16%	49%
IRD-ISINC	Piezo-Quartz	I and III	Asphalt	25	8%	57%
IRD-iSINC	Piezo-Quartz	I	Asphalt	22	7%	64%
PAT Traffic	Piezo-Quartz	II	Asphalt	17	6%	69%
PAT Traffic	Bending Plate	II	PCC	15	5%	74%
Peek ADR	Piezo-Quartz	I	PCC	13	4%	79%
IRD-iSINC	Bending Plate	I	PCC	12	4%	82%
Peek ADR	Piezo-Quartz	Unknown	Asphalt	11	4%	86%
Telemetrics	Piezo-Polymer	II	Asphalt	10	3%	89%
Peek ADR	Piezo-Polymer	I and II	Asphalt	6	2%	91%
IRD TC540	Bending Plate	Unknown	PCC	5	2%	93%
IRD-iSINC	Bending Plate	I and III	PCC	4	1%	94%
IRD	Bending Plate	Unknown	PCC	3	1%	95%
PAT Traffic	Piezo-Quartz	I and III	Asphalt	3	1%	96%
Peek ADR	Piezo-Quartz	I	Asphalt	3	1%	97%
IRD	Piezo-Quartz	Unknown	Asphalt	2	1%	98%
IRD-iSINC	Piezo-Quartz	I	PCC	2	1%	98%
IRD-iSINC	Piezo-Quartz and Piezo-Polymer	I	PCC	1	0.3%	99%
Mettler-Toledo	Load Cell	I	PCC	1	0.3%	99%
PAT Traffic	Bending Plate	I	PCC	1	0.3%	99%
PAT Traffic	Piezo-Polymer	I	Asphalt	1	0.3%	100%
PAT Traffic	Piezo-Quartz	I	Asphalt	1	0.3%	100%
			Totals	**308**	**100%**	**100%**

Future Plans for WIM System Change or Upgrade

The respondents were asked to describe any recent or planned future changes in WIM sensor or WIM system type and the rationale for the changes, if applicable to their WIM program. The responses are summarized below:

- Connecticut DOT is looking into a WIM sensor that may provide a longer life span, possibly bending plates or piezo-quartz. It is also looking into an improved system for automating its data collection efforts.
- It is expected that West Virginia will move away from using the piezo-polymer sensor in the future because of temperature impacts. West Virginia has just installed its first bending-plate system in several years as part of a special project.

- Florida DOT is in the process of replacing its PAT Traffic WIM controllers with IRD iSINC controllers since service parts are no longer available for the DAW-190 system. As a rule of thumb, FDOT puts only bending plates in concrete pavements and piezo-quartz sensors in asphalt. It does not use piezo-polymer sensors for collecting weight data any more, only for classification data because of low weight measurement accuracy.
- Pennsylvania DOT is upgrading its PAT Traffic DAW-190/Kistler WIM systems to IRD iSINC/Kistler since the former is no longer supported.
- Georgia DOT (GDOT) stated that, although its planning and research offices have requested that WIM data be collected, they have yet to consume the data. However, they do anticipate more use of the data in the future. GDOT pavement users asked for installation of ASTM E1318-09 Type I piezo-quartz systems to satisfy loading data accuracy needed for pavement design.
- New Mexico DOT is planning to add WIM stations to one interstate and two state routes.

Conclusions on WIM Systems Used by Agencies

Information collected from the survey leads to the following conclusions:

- The initial expectation of the project team was to see higher usage of piezo-polymer sensors by the selected agencies. The results of the survey, particularly as shown in Table 11, indicate that while those sensors were used in the past, the current trend is to replace them with more accurate and less temperature-sensitive piezo-quartz or bending-plate sensors. Piezo-polymer sensors are continuing to be used for vehicle classification.
- As shown in Table 15, all 167 piezo-polymer installations use temperature compensation; most of these are automatic except for one that uses a temperature probe. Ninety-two installations use no temperature compensation for a mix of load cell, piezo-quartz, and bending-plate sensors. Forty-five installations use a temperature probe for a mix of piezo-quartz and bending-plate sensors, plus one piezo-polymer sensor mentioned above. The temperature compensation at five installations, all in Louisiana, is unknown. No piezo-polymer installation was without temperature compensation, and no other sensor technology received automatic temperature compensation.
- The sites are installed in a combination of roadway types, with no particular relationship between type of WIM controller or WIM sensor type and roadway functional classification.

A clear trend was observed between pavement and sensor types, as shown in Table 16:

- All of the bending-plate and load cell systems were installed in concrete pavements.
- All of the piezo-polymer sensors were installed in asphalt pavements.
- The majority of the quartz sensors were in asphalt pavements, and some were in concrete pavements.

A relationship between the brand of controller and the type of WIM sensor appeared in only some cases. As shown in Table 14, the ECM, Raktel, and Telemetrics controllers were used with only piezo-polymer sensors, the IRD TC540 was used with only bending-plate sensors, and the Mettler-Toledo was used with only load cell sensors. The IRD, IRD-ISINC, PAT Traffic, and Peek ADR were used with multiple sensor types. It does appear from the results, particularly in Table 10, that the Raktel, IRD-ISINC, and ECM WIM controllers are the WIM controllers of choice among the respondents, accounting for fully 216 of the 308 installations.

Most of the WIM systems in each of the three pervasive sensor technologies (excluding the sole case of a load cell) were generally reported as a mix of ASTM Type I or III (high weight measurement accuracy) and Type II (lower accuracy), with the bending-plate type divided about equally and with the piezo-polymer and piezo-quartz types tending toward Type I, as shown in Table 17.

TYPES OF DATA COLLECTED BY WIM SYSTEMS

The respondents provided information about what types of data are being collected by WIM systems. Generally, each of the WIM systems reported provided the following data:

- Volume
- Speed
- Classification
- Axle Weight
- Gross Vehicle Weight (GVW)
- Per-Vehicle Records

Specific responses from the states included the following:

- Louisiana DOTD reported that the IRD TC 540 does not report GVW. However, it does report axle weights, which can be summed to provide overall weight.
- Florida DOT reported that it also collects temperature data from its WIM systems.
- Georgia DOT reported that, for the 16 WIM systems that it manages, one of the systems that uses the Peek controller and piezo-polymer sensors reports only per-vehicle records.
- New Mexico reported that, for each of its WIM systems, it collects volume, classification, and GVW data. It indicated that it does not collect speed, axle weight, or per-vehicle record data.
- Three of the 26 WIM systems managed by FHWA for the LTPP SPS Pooled-Fund also collect images for trucks (Class 4 and above). This information is used to verify a vehicle classification algorithm and for any other research studies that require information about truck body in addition to arrangement of axles. LTPP SPS WIM sites collect axle weight, GVW, speed, vehicle volume and classification, axle spacing, and per-vehicle record data.

WIM DATA CUSTOMERS

Table 19 shows respondents' WIM data customers and the type of WIM controller/sensor combination used to collect the data.

Table 19. Count of WIM Systems Used by DOTs to Collect Data for Customers, Sorted by Sensor Type

WIM Data Customer	Count of WIM Systems by Sensor Type		
	Piezo-Polymer Sensor	**Piezo-Quartz Sensor**	**Bending Plate Sensor**
Asset Management	Connecticut (110)	Florida (28) Texas (17)	Florida (5) Louisiana (5) Texas (15)
Design	Connecticut (110) Pennsylvania (1)	Florida (28) Pennsylvania (12) Texas (17) Virginia (7)	Florida (5) Louisiana (5) Texas (15) Virginia (1)
Environmental	Connecticut (110)	Florida (28)	Florida (5) Texas (15)
Planning	Connecticut (110) Pennsylvania (1) Georgia (6) West Virginia (50)	Florida (28) Georgia (10) New Mexico (13) Pennsylvania (12) Texas (17) Virginia (7)	Florida (5) Louisiana (5) New Mexico (3) Texas (15) Virginia (1)
Research	Connecticut (110) West Virginia (50)	Florida (28) Georgia (10) New Mexico (2) Texas (17) Virginia (7) FHWA-LTPP (15)	Florida (5) Louisiana (5) Texas (15) Virginia (1) FHWA-LTPP (13)
Safety	Connecticut (110)	Florida (28)	Florida (5) Louisiana (5) Texas (15)
Weight Enforcement	West Virginia (50)	Pennsylvania (5) Texas (17)	Texas (15)

As shown in the table above, the majority of the WIM data customers are researchers and planners, followed by Design, Environmental, Safety, and Asset Management data customers. Weight enforcement customers represent the smallest number of WIM data users. As shown also in Table 11, the most widely used WIM sensor types, as reported by the most respondents, are the piezo-polymer and piezo-quartz types, accounting for 256 of the 308 installations.

WIM PROGRAM MANAGEMENT

The respondents were asked to provide information about WIM program management and staff support of different WIM program activities.

Source of WIM Program Support Staff: In-House and Outsourced

The respondents provided information about staffing that supports their current WIM program. As shown in Table 20, of the 10 agencies with a WIM program that responded to this survey question (nine state programs and one FHWA program), only one has a WIM program that is supported solely by in-house staff (Louisiana). Two agencies (New Mexico and Connecticut) use a combination of in-house staff and on-site contract staff to support their WIM program. Nine of the agencies outsource their WIM program activities, in whole or in part, as shown in Tables 20 and 21.

Table 20. WIM Program Staffing

Staffing Option	Number of Agencies
In-house staff, full-time employees	1
In-house support and on-site contract staff	2
Part or all of WIM operation is outsourced	7

Table 21. Outsourced WIM Program Support Activities by Respondent – Equipment

Agency	Installation	Maintenance	Calibration	Field QA
Connecticut DOT	X			
Texas DOT	X	X		
Virginia DOT	X	X	X	X
Georgia DOT	X	X	X	X
Florida DOT	X	X	X	X
Pennsylvania DOT	X	X	X	
FHWA LTPP	X	X	X	X

WIM Program Support Staff and Qualification

The respondents were asked to provide information regarding dedicated staff that works exclusively with WIM equipment, using descriptors such as personnel qualification standards, titles and roles. Nine state agencies provided this information, as summarized below:

- Connecticut DOT indicated that it has four full-time positions dedicated to its WIM program—a Supervisor of Traffic Monitoring; a manager of the TMS and WIM; a person responsible for field data collection, inspection, and data processing; and a field technician.
- Florida DOT has one contractor staff on site full-time: a senior engineer who fills the role of WIM specialist and provides data QA-QC, WIM calibration QA-QC, and on-site inspections for sensor maintenance activities and installations. This person is also the point of contact for WIM hardware and software issues.
- Georgia DOT uses a subcontractor to install, maintain, calibrate, and conduct field QA of WIM sites as part of its contract to maintain all GDOT traffic counter and WIM sites. It does not have dedicated staff who work exclusively for the WIM program.
- Louisiana DOTD has two dedicated engineering technicians who devote most of their time to WIM and vehicle classification.
- The New Mexico DOT employs a traffic data reporting supervisor and two electronics technicians as its dedicated WIM program staff.
- Pennsylvania's WIM section consists of three dedicated WIM staff, including a WIM supervisor and two analysts. The WIM supervisor manages the two analysts, creates FHWA and LTPP submittals, creates data book publication from permanent data, and works with a contractor to schedule calibrations, maintenance, and repairs. The two analysts perform daily polling and analysis of WIM data.
- Texas has a traffic systems specialist who has thorough knowledge of WIM systems, including installation, maintenance, inspection, and calibration. The Texas DOT WIM staff also includes a traffic systems technician, who must have a commercial driver's license to drive the calibration truck. All training for WIM staff is performed on the job. WIM staff has a piezo-quartz installation certification.
- Virginia DOT contracts most of its WIM-related work, but it does have one dedicated WIM manager who works exclusively with the WIM program. This is an Engineer I position that has the primary responsibility of data processing, reporting, and data QA-QC. This staff member also works with other staff and the contractor on other aspects of the WIM program (site selection, inspections, maintenance, calibration, contract administration, etc.).
- The Marshall University West Virginia WIM consultant indicted that West Virginia has one person who is responsible for polling sites and reporting problems. They also have a person who compiles the data and submits reports. A third staff member, a field technician, performs basic troubleshooting at the sites.

WIM Installation Quality Assurance Staff

The survey participants were asked to identify personnel who perform quality assurance of their WIM system installations. In many cases, more than one option was selected. The results were tabulated and are provided in Table 22.

Table 22. WIM Installation Quality Assurance Staff

Identified Personnel	Number of Agencies
Resident Engineer	1
Manufacturer's Representative	3
District Engineer	1
State QA Personnel	5
WIM Technician	5
Contracted Personnel	3
Federal Staff	1

Of the 12 respondents, each indicated the use of a dedicated QA inspector for WIM equipment installations. The majority of respondents use state QA personnel or a WIM technician for this purpose.

WIM Calibration and Maintenance Support Staff

Survey participants were asked to describe their agencies' current staffing practice for maintaining and calibrating their WIM systems. Ten participants responded. The results were tabulated and are provided in Table 23.

Table 23. WIM Maintenance and Calibration Staff

Response Option	Number of Agencies	Agency Name
In-house personnel calibrate and maintain our WIM systems	1	Texas
In-house staff maintain our equipment but we outsource calibration	1	West Virginia
In-house personnel calibrate our systems, but we outsource maintenance	2	Louisiana, Connecticut
We outsource all calibration and maintenance of WIM systems	6	Florida, Georgia, New Mexico, Virginia, FHWA LTPP, Pennsylvania[1]

[1] Even though Pennsylvania outsources all calibration and maintenance for its WIM systems, it uses PennDOT staff to make minor repairs.

The 10 respondents all indicated that contracted or in-house staff fulfill this function. As shown in the table, the majority of the respondents indicated that WIM maintenance and calibrations are outsourced. The initial calibration is typically performed by manufacturer representatives when the systems are installed. Follow-up calibrations are performed by contractor staff in all states except Texas, which uses an agency field technician to perform the calibrations. For Pennsylvania, although all of its calibrations are performed by contractor staff, an agency staff member is required to be on site. For equipment maintenance, most responding states use contracted staff, except West Virginia and Texas. Pennsylvania, New Mexico, and Louisiana use agency staff to make minor repairs.

WIM Calibration Support Staff

Survey participants were asked to indicate how many qualified WIM calibration staff their agency has. The responses from the nine participants are summarized in Table 24. As shown in the table, less than half of the agencies have qualified WIM calibration staff.

Table 24. Qualified WIM Calibration Staff

Number of Staff Members	Number of Agencies
0	5
1-2	4
2-5	0

Survey participants were asked to indicate how many WIM calibration staff they require on site for a WIM calibration. The results for the nine respondents are provided in Table 25. As shown in the table, six of the nine agencies require at least one WIM calibration staff on site. Pennsylvania indicated that it requires a manufacturer's representative and one PennDOT staff member from its WIM program to be on site during calibrations.

Table 25. On-Site WIM Calibration Staff

Number of Staff Members	Number of Agencies
0	3
1	4
2	2

WIM Maintenance Support Staff

The survey participants were asked to indicate how many dedicated WIM maintenance staff they currently have. Only eight state agencies provided responses. As summarized in Table 26, about half of those state agencies do not have a dedicated WIM maintenance staff. Four of the states have at least one.

Table 26. WIM Maintenance Staff

Number of Staff Members	Number of Agencies
0	4
1-2	3
2-5	1

WIM Program Data Support Staff

Regarding each agency's staffing approach to WIM data processing and reporting, the following responses were received:

- The Texas and Florida DOTs and the FHWA LTPP WIM program outsource all of their WIM Data support activities, including data processing, reporting, and data QA-QC.
- Louisiana, Pennsylvania, Virginia, and West Virginia perform all data activities using in-house staff.
- Connecticut and Georgia indicated that their data activities are performed by a combination of in-house staff and on-site contracted staff.

Conclusions about WIM Program Staffing

According to the results, most of the surveyed agencies use a combination of in-house and outsourced staff (either on-site or off-site contractors). Three of the states (Florida, Georgia, and Virginia) rely primarily on contractor staff to manage major components of their WIM program but employ at least one dedicated staff member to manage the program.

It appears that most of the agencies employ a program manager who is not necessarily dedicated entirely to WIM or who may be a WIM Specialist/Engineer with some management responsibilities. Most of the agencies also employ at least one data analyst and at least one field technician.

WIM SITE QUALIFICATION AND CONSTRUCTION PRACTICES

WIM Site Qualification Factors

Once the desired WIM site locations are identified by the WIM data users, these locations are evaluated by the WIM experts to see whether site conditions are conducive for the collection of accurate WIM data. The respondents were asked to rank several site selection criteria by indicating whether they felt they were very important, moderately important, or unimportant for qualifying potential WIM site locations. Table 27 summarizes the results.

Table 27. Site Qualification Criteria Ranking

Criteria	Very Important	Moderately Important	Unimportant
Pavement smoothness	9	1	0
Roadway geometrics	9	1	0
Traffic conditions (free-flow, intersections, traffic signalization, etc.)	10	0	0
Proximity to AC power service	0	4	6
Proximity to landline telephone	0	4	6
Cellular service coverage	6	4	0
Proximity to test truck turnarounds	1	8	1
Pavement condition other than smoothness	10	0	0
Easy and safe access for technicians	10	0	0
Upgrade of existing traffic monitoring site	5	1	4
Roadway gradient	7	3	0

According to the results shown in the table, the criteria most important to the respondents are traffic conditions, pavement condition (other than smoothness), and easy and safe access for technicians. For most respondents, pavement smoothness, roadway geometrics, and grade were also very important. Most respondents do not consider proximity to landline telephone or utility power service important when selecting their WIM site locations. This is most likely due to the increasing use of solar power and the use of cellular service for communicating with the site, when accessible.

Documentation Used to Support WIM Site Selection and Qualification

The respondents were asked to indicate whether they use established written procedures, specifications, standard drawings, special provisions, department-furnished materials lists, etc., for qualifying WIM site locations and their constructability. Table 28 summarizes the results.

Table 28. Site Selection Documentation

Response Option	Number of Agencies
ASTM E1318-09	3
Contract specifications	5
Agency document	1

As shown in the table, the majority of respondents use contract specifications to ensure that the potential WIM sites are selected properly and that the WIM systems are installed properly. A few use the WIM site qualification criteria provided in the ASTM E1318-09 specification.

In addition, Connecticut uses site drawings that are shared during installation. Georgia's contracts provide generalized specifications and may include some specifications by reference. The FHWA LTPP Program developed the *LTPP Field Operations Guide for SPS WIM Sites* (FHWA 2012 [LTPP]) to qualify potential WIM sites using ASTM and inputs from WIM experts from the TRB LTPP Traffic Expert Task Group. Virginia DOT has provided specific WIM site qualification specifications in its contract solicitations.

Additional efforts used by state agencies to qualify potential WIM sites include Louisiana's WIM program field survey, which uses 48-hour routine sensors, and Texas Construction Division's pavement profiling to determine whether the roadway meets specifications.

WIM EQUIPMENT INSTALLATION PRACTICES

Documentation Used to Support WIM Site Installation

The respondents were asked to indicate whether they use established written procedures, specifications, standard drawings, special provisions, department-furnished materials lists, etc. for their WIM equipment installations. As shown in Table 29, all of the state agencies indicated that they use contract specifications to ensure the proper installation of their WIM systems. Some state agencies use additional supporting documentation, such as manufacturer guides, federal specifications or standards, or a contractor's proprietary installation guides.

Table 29. WIM Installation Documentation

Response	Number of Agencies
Contract specifications	9
Agency document	1
ASTM E1318-09	1
Manufacturer's Installation Manual	1
Sensor Installation Manual	1
Contractor's proprietary guidelines	1
Traffic Monitoring Guide	1

WIM EQUIPMENT MAINTENANCE PRACTICES

WIM Maintenance Documentation and Procedures

The survey participants were asked about standards, procedures, and protocols used by their staff or contractor to maintain their WIM systems. As shown in Table 30, the majority of agencies that responded use user guides and/or contract specifications for maintaining their WIM systems. Georgia DOT indicated that it also uses the ASTM E1318-09 standard. Virginia DOT uses specifications provided in its contract solicitations, and its WIM maintenance contractor uses a proprietary procedures manual.

Table 30. WIM Maintenance Documentation

Response Option	Number of Agencies
Manufacturer's User Guide	4
Contract	4
Agency document	1
Traffic Monitoring Guide	1
Other	2

Preventive and Corrective Maintenance Frequency and Response Time

The survey participants were asked how often they perform preventive maintenance on their WIM systems. The tabulated results for the nine respondents are provided in Table 31.

Table 31. WIM Preventive Maintenance Frequency

Response	Number of Agencies
Annually	5
Semi-annually	2
Every 18 months	0
Other	2

As shown in the table, the majority of agencies perform annual maintenance on their WIM systems. As additional comments, the following responses were provided:

- Connecticut DOT indicated that it conducts WIM maintenance as technicians travel to the sites.
- Georgia DOT indicated that the schedule for WIM maintenance is unknown, since maintenance is performed by its WIM maintenance contractor.

Survey participants were asked to assess the adequacy of their WIM maintenance activities. The results for the nine respondents are summarized in Table 32.

Table 32. WIM System Maintenance Assessment

Response	Number of Agencies
We would like to perform maintenance more frequently, but do not have the staff	3
We perform adequate maintenance of our WIM systems	5
We would like to perform maintenance more frequently, but do not have the funding	1

As shown in the table, half of the respondents indicated that they perform adequate maintenance of their WIM systems—two perform maintenance semi-annually, and three perform maintenance annually. Three agencies indicated that they lack the staff to perform adequate maintenance, and one indicated that it does not have adequate funding to support WIM maintenance activities.

The survey participants were asked to indicate how long it takes for their maintenance staff or contractor to respond to and fix the problem from the time that a malfunction has occurred. The tabulated results for the nine respondents are provided in Table 33.

Table 33. WIM Repair Response Time

Response	Number of Agencies
< 48 hours	0
2 to 4 days	2
4 to 6 days	0
> 1 week	1
Other	6

For the respondents who selected “Other,” the following additional comments were provided:

- Florida indicated that most repairs take two to four days. Since its maintenance staff is relegated to a 40-hour work week, a problem that shows up in the middle of the week might take up to six days to repair if its staff already has a full week of work scheduled.
- Pennsylvania and Texas indicated that minor issues can sometimes be resolved within a day using agency staff, while other issues can take more than a year to resolve if they are a result of poor road conditions that require road resurfacing before the site can be repaired.
- Texas indicated that the replacement of bending-plate sensors can take anywhere from two weeks to six months.
- Some states (Florida, Pennsylvania, Virginia, and FHWA LTPP) use contract documents to control response times. Virginia indicated that its contractor has up to 10 days to respond to a normal service call, and the contract provides options for quicker turnaround (24 to 48 hours) when necessary.

WIM EQUIPMENT CALIBRATION PRACTICES

Documentation and Procedures for WIM Calibration

Survey participants were asked if they use established, written WIM calibration standards, procedures, and protocols to conduct their WIM calibration. The results for the 10 respondents are provided in Table 34. As shown in the table, a majority of the agencies use ASTM E1318-09 specifications, followed by their contract specifications and the manufacturer's User Guide.

Table 34. WIM Calibration Documentation

Response Option	Number of Agencies
Manufacturer's User Guide	5
Contract	6
ASTM E1318-09	7
Agency Document	1
Other	2

In addition, Florida DOT indicated that it has developed and now uses its own calibration procedures for new and existing WIM sites. The LTPP calibration contractor indicated that it uses contract specifications, ASTM E1318-09, and the *LTPP Field Operations Guide for SPS WIM Sites* for WIM site calibrations (ASTM 2009, FHWA 2012 [LTPP]).

WIM Calibration Frequency and Effort

The survey participants were asked to assess the adequacy of their agency's calibration activities. Table 35 provides a summary of responses.

Table 35. WIM Calibration Frequency and Effort Assessment

Response	Number of Agencies	Agency Names
We would like to perform calibrations more frequently, but do not have the staff	3	New Mexico, Texas, Connecticut
We perform adequate calibrations of our WIM systems	4	Pennsylvania, Virginia, FHWA-LTPP, Florida
We would like to perform calibrations more frequently, but do not have the funding	0	
Other	1	Georgia

As shown in the table, half of the respondents indicated that they perform adequate calibrations of the WIM systems. Of the three agencies that indicated that they would like to perform calibrations more often, each of them cited lack of adequate staff as their limitation. Georgia indicated that its contractor performs all calibrations. Georgia did not indicate whether or not it felt that the effort or frequency of its calibrations was adequate.

Calibration of Piezo-Polymer WIM Systems

Frequency of WIM Systems Calibration

The survey participants were asked to indicate how often they perform calibration on their piezo-polymer WIM systems. Of the four responding agencies that own WIM systems using piezo-polymer sensors, the following responses were obtained:

- As needed (Connecticut)
- Annually (Pennsylvania)
- Only after the initial installation (West Virginia)
- Only uses WIM system's auto-calibration feature (Georgia)

Calibration Trucks

In response to the question about how many calibration trucks the agencies use to calibrate their piezo-polymer WIM systems, two responses were provided:

- Only Pennsylvania indicated that it uses a calibration truck to calibrate its piezo-polymer WIM systems. It also indicated that it uses one Class 9 truck loaded to approximately 75,000 pounds. Pennsylvania requires 10 passes of the calibration truck to verify the accuracy of the WIM system. For Pennsylvania, the achievable, acceptable mean error for its piezo-polymer WIM Systems is ±10 percent of GVW, both after calibration and during routine data checks.
- Connecticut responded that it calibrates its piezo-polymer WIM systems using trucks from the traffic stream and does not use a calibration truck.

Acceptable Weight Measurement Accuracy for Piezo-Polymer Sensors

Three state agencies that currently use piezo-polymer WIM systems provided the acceptable GVW mean error and range in error. These are the target values used by each agency. The FHWA Office of Highway Policy also provided input based on its past experience working with state DOTs. Table 36 provides a summary of the responses.

Table 36. Acceptable GVW Mean Error and Range in Error by Agency – Piezo-Polymer

Agency	GVW Mean Error		GVW Range in Error	
	After Calibration	During Routine Checks	After Calibration	During Routine Checks
Connecticut	2 to 5%	2 to 5%	2 to 5%	2 to 5%
Georgia	2 to 5%	2 to 5%	2 to 5%	5 to 10%
FHWA-Highway Policy	10 to 20%	5 to 10%	5 to 10%	5 to 10%
Pennsylvania	5 to 10%	5 to 10%	5 to 10%	5 to 10%

The table shows that FHWA, experienced in working with multiple state DOTs, indicated much higher acceptable GVW mean errors and somewhat higher acceptable GVW error ranges than the three surveyed state DOTs that provided GVW error ranges for piezo-polymer sensors (though the respondents did not specify whether these accuracies are being routinely achieved or are merely desired). The FHWA figures also reflect the research team's experience in working with piezo-polymer WIM data submitted by the states to the FHWA LTPP and FHWA Vehicle Travel Information System (VTRIS) databases. Accordingly, the relatively low error figures from the three respondents may be considered optimistic, leading to a conclusion that their heavy tandem-axle truck weight piezo-polymer measurements, which are not auto-calibrated like steering-axle measurements, are likely inaccurate overall.

Calibration of Piezo-Quartz WIM Systems

Frequency of Piezo-Quartz WIM Systems Calibration

The survey participants were asked to indicate how often they perform calibration on their piezo-quartz WIM systems. From the seven responding agencies that own WIM systems that use quartz sensors, the following responses were obtained:

- Annually (Florida, Virginia, Texas, Pennsylvania)
- Annually, but schedules are determined by the WIM maintenance contractors (New Mexico and Georgia)
- 18 months apart or less, as required to test for seasonal variations (FHWA LTPP WIM program)

Calibration Trucks

In response to the question about how many calibration trucks they use to calibrate their piezo-quartz WIM systems, the agencies provided the following responses:

- Six of the seven state agencies (Florida, Georgia, New Mexico, Pennsylvania, Texas, Virginia) indicated that they use one truck to calibrate. They each use a Class 9 truck loaded to approximately 90 percent of the truck's legal operating limit of 80,000 pounds.

- For the FHWA LTPP SPS WIM program, two calibration trucks are used, weighing approximately 78,000 pounds and 65,000 pounds.

Each of the seven respondents that own WIM systems that use the piezo-quartz systems was asked to indicate the minimum number of test truck passes that he or she requires to verify the accuracy of the quartz WIM system calibration. The responses are summarized below.

- 40 truck runs, i.e., 20 for each of two test trucks (LTPP SPS WIM Program)
- 10 runs (Florida, New Mexico, Pennsylvania, Virginia)
- Six runs (Georgia)
- Four runs (Texas)

It is worthwhile to note that the small sample size (i.e., the small number of calibration test truck runs) used by most of the surveyed agencies, while cost-effective, does not provide enough data for achieving meaningful statistical confidence in the calibration results. Also, samples of fewer than 10 passes do not provide enough observations to test against the ASTM E1318-09 95th percent compliance criteria. Applying a criterion that 95 of 100 observations should be within tolerance limits would require 9.5 out of 10 observations. Since 9.5 observations are not meaningful, the criterion is 10 out of 10 observations or 19 out of 20 observations.

Acceptable Weight Measurement Accuracy – Piezo-Quartz

The seven survey participants that own WIM systems that use the piezo-quartz sensor were asked to provide the achievable, acceptable mean error (i.e., measurement bias) and the range of error (i.e., measurement precision) for their quartz WIM Systems expected after calibration and during routine data checks. Table 37 provides a summary of the responses.

Table 37. Acceptable GVW Mean Error and Range in Error by Agency – Piezo-Quartz

Agency	GVW Mean Error		GVW Range in Error	
	After Calibration	During Routine Checks	After Calibration	During Routine Checks
Florida	<2%	2 to 5%	2 to 5%	5 to 10%
FHWA-LTPP	<2%	2 to 5%	5 to 10%	5 to 10%
FHWA-Highway Policy	5 to 10%	5 to 10%	5 to 10%	5 to 10%
Georgia	<2%	2 to 5%	<2%	<2%
New Mexico	5 to 10%	5 to 10%	5 to 10%	5 to 10%
Pennsylvania	5 to 10%	5 to 10%	5 to 10%	5 to 10%
Texas	2 to 5%	2 to 5%	2 to 5%	2 to 5%

Three of the respondents expect their GVW mean error to be less than 2 percent after the system is calibrated and 2 to 5 percent during routine checks, while the other three respondents expect 5 to 10 percent errors. The majority of respondents indicated that an acceptable range for GVW error for their piezo-quartz WIM systems after calibration and during routine checks is between 5 and 10 percent. The survey did not specify whether these accuracy levels are being achieved routinely or are the desired levels.

WIM DATA ACCURACY AND QUALITY ASSURANCE (WIM DATA QA-QC PROGRAM)

WIM Accuracy Requirements for Different Customers

The survey respondents were asked to use a table with multiple-choice accuracy level options to specify the WIM weight data accuracy requirements for each of their WIM data customers. The results, compiled for each type of customer (e.g., users of weight enforcement or planning data), are presented in Tables 38 through 44.

Table 38. WIM Measurement Bias and Error Tolerance Table – Weight Enforcement

Agency	Acceptable WIM Measurement Bias (%)			Acceptable WIM Error Tolerance (± % error for selected confidence level)		
	GVW	Single Axle	Axle group	GVW	Single Axle	Axle group
FHWA-Highway Policy	<2%	<2%	<2%	<2%	<2%	<2%
Florida	2 to 5%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%

Table 39. WIM Measurement Bias and Error Tolerance Table – Planning

Agency	Acceptable WIM Measurement Bias (%)			Acceptable WIM Error Tolerance (± % error for selected confidence level)		
	GVW	Single Axle	Axle group	GVW	Single Axle	Axle group
Connecticut	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%
FHWA-Highway Policy	5 to 10%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%
Florida	2 to 5%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%
Georgia	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
New Mexico	<2%			5 to 10%		
Pennsylvania	5 to 10%	Unknown	Unknown	Unknown	Unknown	Unknown
Texas	2 to 5%	10 to 20%	5 to 10%			
Virginia				5 to 10%	10 to 20%	10 to 20%

Table 40. WIM Measurement Bias and Error Tolerance Table – Research

Agency	Acceptable WIM Measurement Bias (%)			Acceptable WIM Error Tolerance (± % error for selected confidence level)		
	GVW	Single Axle	Axle group	GVW	Single Axle	Axle group
Connecticut	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%
FHWA-Highway Policy	10 to 20%	10 to 20%	10 to 20%	10 to 20%	10 to 20%	10 to 20%
FHWA-LTPP	<2%	2 to 5%	2 to 5%	5 to 10%	10 to 20%	10 to 20%
Florida	2 to 5%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%
Georgia	<2%	<2%	<2%	Unknown	Unknown	Unknown
Texas	5 to 10%	10 to 20%	2 to 5%			
Virginia				5 to 10%	10 to 20%	10 to 20%

Table 41. WIM Measurement Bias and Error Tolerance Table – Environmental

Agency	Acceptable WIM Measurement Bias (%)			Acceptable WIM Error Tolerance (± % error for selected confidence level)		
	GVW	Single Axle	Axle group	GVW	Single Axle	Axle group
Connecticut	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%
FHWA-Highway Policy	10 to 20%	20 to 30%	20 to 30%	10 to 20%	20 to 30%	20 to 30%
Florida	2 to 5%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%

Table 42. WIM Measurement Bias and Error Tolerance Table – Safety

Agency	Acceptable WIM Measurement Bias (%)			Acceptable WIM Error Tolerance (± % error for selected confidence level)		
	GVW	Single Axle	Axle group	GVW	Single Axle	Axle group
Connecticut	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%
FHWA-Highway Policy	5 to 10%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%
Florida	2 to 5%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%

Table 43. WIM Measurement Bias and Error Tolerance Table – Design

Agency	Acceptable WIM Measurement Bias (%)			Acceptable WIM Error Tolerance (± % error for selected confidence level)		
	GVW	Single Axle	Axle group	GVW	Single Axle	Axle group
Connecticut	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%
FHWA-Highway Policy	10 to 20%	20 to 30%	20 to 30%	10 to 20%	20 to 30%	20 to 30%
Florida	2 to 5%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%

Table 44. WIM Measurement Bias and Error Tolerance Table – Asset Management

Agency	Acceptable WIM Measurement Bias (%)			Acceptable WIM Error Tolerance (± % error for selected confidence level)		
	GVW	Single Axle	Axle group	GVW	Single Axle	Axle group
Connecticut	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%	2 to 5%
FHWA-Highway Policy	10 to 20%	20 to 30%	20 to 30%	10 to 20%	20 to 30%	20 to 30%
Florida	2 to 5%	5 to 10%	5 to 10%	5 to 10%	10 to 20%	10 to 20%

Based on the results obtained from this survey, accuracy levels varied significantly by WIM data customer and by agency. In general, the most accurate WIM data were required by the weight enforcement customers (<2 percent to 5 percent GVW measurement error and tolerance), while less accurate WIM data were identified as acceptable for environmental and asset management customers (2 to 30 percent GVW measurement error and tolerance).

WIM Data QA-QC Checks

The survey participants were asked to select from a list of each of the WIM data QA-QC checks that they perform. They were asked to select all data checks applicable or add checks performed that were not on the list. The tabulated results from the eight respondents that indicated that they perform QA-QC checks on their WIM data are provided in Table 45.

Table 45. WIM Data QA-QC Checks Performed

Response	Number of Agencies
Data file size	4
Class 9 hourly or daily volume check	6
Class 9 loaded/unloaded peak loads	2
Average Class 9 front axle	3
Average truck GVW	3
Site identification, lane, direction, date, time, and location description checks	5
Seasonal shift in axle load spectra for Class 9 trucks	1
Other	2

As demonstrated by the eight different kinds of responses, not all the agencies use the same QC checks. In addition, several agencies have provided their agency-specific checks. A review of the agency-supplied checks indicates that all of them have some type of weight accuracy check. Use of regular weight accuracy checks is very important because, without these checks, changes in WIM system performance characteristics may go undetected, and inaccurate data will be collected and supplied to the users.

The following are summaries of the additional data checks implemented by several agencies.

Florida DOT Checks

Florida indicated that it performs each of the checks listed in Table 45. In addition, they perform the following checks:

- Right- and left-wheel weight comparison on front axle data
- Front axle wheel weight distributions by hour
- Polling errors
- Volume, class, and speed errors based on site-specific traffic volume, class, and speed averages
- Invalid weight counts

Pennsylvania DOT Checks

Pennsylvania performs the following checks on a daily basis:

- Total daily volume by direction and lane
- Total hourly volume
- Hourly volume by class
- Each axle weight – left and right
- Overweight vehicles

Virginia DOT Checks

Virginia, in addition to performing some of the checks from Table 45, evaluates the number of error vehicles per day and evaluates Class 9 front axle weights against a minimum weight standard to determine off-scale detections.

FHWA LTPP WIM Program Checks

For the FHWA LTPP WIM program, the contractor performs each of the checks listed in Table 45, in addition to the following checks:

- Confirmation of zero counts per hour per lane
- Confirmation of no greater than 2,500 counts per hour, per lane
- Percent-error vehicles, status-clear vehicles, and good-weight vehicles
- Percent of Class 9 vehicle warnings issued per day
- Average GVW of Class 9 vehicles per day

FHWA TMAS Checks

The FHWA Traffic Monitoring Analysis System (TMAS) performs QA-QC of traffic data received from the state agencies. Of the checks listed above, the TMAS system only performs checks on Class 9 loaded/unloaded peak loads. However, the TMAS performs the following checks:

- Minimum/maximum axle weight
- Minimum/maximum axle spacing
- Tandem axle spacing against historical data
- Class 9 steering axle weight average against historical data
- Total wheel base based on vehicle class

The complete list of TMAS QC checks is available in the 2013 edition of the *Traffic Monitoring Guide* (FHWA 2013).

Georgia DOT Checks

Georgia DOT stated that it uses customized software with built-in default values for WIM data QA-QC checks, but did not provide the specific checks that it performs.

WIM Data QA-QC Procedures and Tools

Each survey participant was asked to provide information regarding established WIM data QA-QC procedures. The following information was provided:

- New Mexico uses Chaparral Systems Corporation's TRADAS traffic data analysis software to perform QA-QC functions.

- Florida DOT uses software that it developed in house, called Traffic Polling and Analysis System (TPAS), to conduct QA-QC checks on its WIM data. It also uses manufacturer's software to process its WIM data. It uses the WIM Data Analyst's Manual for guidance and a stand-alone spreadsheet for WIM data analysis.
- Pennsylvania uses an in-house tool to evaluate its WIM data on a daily basis. Data is flagged if it exceeds set parameters. Pennsylvania indicated that the tools that it developed in house are new and that it is still fine-tuning flags and parameters to weed out bad data.
- Texas DOT uses the Statewide Traffic Analysis and Reporting System (STARS II), which is hosted by Midwest Software Solutions (MS2).
- The FHWA LTPP WIM Program WIM services contractor uses the contract specifications to determine whether the data meet the program standards for data quality. Many of the QC checks are implemented in a software package used by the LTPP WIM vendor and in LTPP LTAS and traffic data analysis software.
- The FHWA Office of Highway Policy Information (OHPI) uses the TMAS System, which it developed, and the 2013 edition of the *Traffic Monitoring Guide* (FHWA 2013).
- Georgia DOT uses the default QA-QC checks that are built into the Transmetric America software.

WIM DATA SHARING BETWEEN STATE TRANSPORTATION AND WEIGHT ENFORCEMENT AGENCIES

The nine survey participants representing state highway agencies were asked if they have established procedures for WIM data sharing between state transportation and weight enforcement agencies. Only four of nine agencies—Connecticut, Pennsylvania, Texas, and Virginia DOTs—indicated that they have established procedures.

Following are participants' responses to the question about what type of document provides procedures for sharing data with weight enforcement agencies:

- Connecticut has its own procedures for aiding truck enforcement at truck stops.
- Pennsylvania uses its WIM Report Guide.
- Virginia uses an informal agreement between the Department of Motor Vehicles (enforcement agency) and the Department of Transportation (data collection agency).
- Texas did not provide the type of procedures used.

The state agency survey participants were asked to provide their assessment of the relationship between their state's transportation and weight enforcement agencies. The tabulated results are provided in Table 46. Of the seven respondents to this question, all indicated that there is some degree of cooperation between their agency and the state's weight enforcement agency, mostly on an as-needed basis.

Table 46. Assessment of Relationship with Weight Enforcement Agency

Response	Number of Agencies	Agency Names
There is no cooperation between agencies	0	
There is minimal cooperation between agencies	1	Florida
There is cooperation as-needed	5	Connecticut, Louisiana, Pennsylvania, Texas, West Virginia
There is full cooperation	1	Virginia
Data is integrated and shared by both agencies/offices	0	

The survey participants were asked to describe the roles of the two agencies and the extent of data sharing. The following responses were received:

- WIM program sponsorship: Six of the seven respondents (Connecticut, Florida, Louisiana, Pennsylvania, Texas, and West Virginia) indicated that their WIM programs are sponsored by the state department of transportation. Virginia indicated that each agency owns and operates its own WIM equipment and data.
- WIM data ownership: Connecticut responded that the data are not owned by anyone, but are shared through the Freedom of Information Act and published on its website. Each of the other respondents indicated that the agency that sponsors the WIM program owns the data that are collected.
- Data sharing practices:
    - Connecticut indicated that the data are shared on its website. It also provides data as requested, either verbally or by e-mail.
    - Florida provides its data upon request, but indicated that its weight enforcement agency uses its own WIM systems as sorter scales in its weigh stations and very rarely requests additional data.
    - Pennsylvania provides reports to the Pennsylvania State Police.
    - Texas indicated that weight data is provided to weight enforcement agencies for sorting at some weigh stations.
    - In Virginia, the Department of Motor Vehicles (DMV) provides WIM data from its equipment to the DOT on a monthly basis. The DOT allows the DMV field crews to connect remotely to DOT WIM equipment to screen for overweight trucks to pull over for inspection and static weighing.
    - The Marshall University West Virginia WIM consultant indicated that the sharing of weight data in West Virginia occurs at weigh stations that use the Pre-Pass system.

- User-friendly interface to WIM sites: The survey participants were asked if they have a real-time, user-friendly data interface to WIM sites that can be used by enforcement staff and that signals overweight vehicles to pull over.
  - Texas stated that Virtual WIM is not possible due to a prohibition against Texas DOT's engaging in law enforcement activities.
  - Virginia indicated that its WIM equipment has a feature that outputs vehicle monitor data to a serial port. The feature is turned on and used in conjunction with matched radio modems to allow enforcement staff to see real-time weight data using only a generic terminal program running on a laptop as long as they are in range.

RECOMMENDATIONS OBTAINED FROM THE SURVEY FOR WIM SYSTEM TYPE AND SYSTEM COMPONENTS

The survey participants were asked which WIM sensors/controllers or WIM system types they would recommend and for what applications/customers. Several states and industry experts provided the following equipment recommendations:

- Florida DOT recommended the IRD iSINC and quartz sensor WIM system combination for asphalt pavement installations mainly because of its ease and quickness of installation. FDOT stated that the disadvantage of using the piezo-quartz sensor is its unknown longevity. For concrete pavement installations, it recommends the IRD iSINC WIM controller with the bending-plate sensor due to sensor longevity and accuracy. However, FDOT feels that the bending-plate sensor should be installed only in concrete pavements, thus constituting a drawback. Both the quartz sensor and the bending-plate sensor, when controlled by the IRD iSINC controller, provide ASTM Type I and III level accuracy.
- Texas DOT also recommended the IRD iSINC WIM controller with either piezo-quartz or bending-plate sensors. It did not distinguish which sensor should be used for which type of pavement, but recommended both for highway design applications. Texas indicated that it expects GVW mean errors of 5 percent or less for WIM systems using the quartz sensors, and 2 percent or less for systems using the bending-plate sensor. It stated that the quartz sensor is the easier to install of the two sensors, but the bending plate provides better accuracy. The drawbacks of using the bending plate, according to Texas DOT, are higher maintenance costs and the greater deterioration of the roadway.
- Virginia DOT recommended the Peek ADR WIM controller combined with the piezo-quartz sensor for asphalt installations. It indicated that the main disadvantages of using the quartz sensor are its limited life span and high cost. It also recommended the WIM system using the IRD iSINC controller and bending-plate sensor for accuracy and longevity, but cautions that the system comes with a high cost and must be installed in concrete.
- The FHWA LTPP SPS WIM program manager shared that the program, prior to installing its WIM systems, conducted research to identify which WIM sensors were capable of providing research-quality WIM data. For the purpose of this study, research-quality data was defined to be at least 210 days of data in a year of known calibration meeting LTPP's precision requirements (i.e., ASTM E1318-09 requirements for Type I WIM systems) for steering and tandem axles, GVW,

speed, and axle spacing. The program found that the load cell, piezo-quartz, and bending-plate WIM sensor technologies could meet its research needs. Its research was not intended to determine which WIM controller should be used, but the FHWA—with input from the TRB Expert Task Group on LTPP Traffic Data Collection and Analysis—ultimately chose the IRD iSINC controller for the program's new WIM site installations. In addition, there were a few WIM systems already installed by the state agency that met the program's requirements. These systems utilize Mettler-Toledo's WIM controller and load cells and the IRD 1068 WIM controller combined with the piezo-quartz sensor. Because the systems were providing data for a research project, a high level of accuracy was paramount in the program's decision to use these systems. None of the piezo-ceramic or piezo-polymer WIM systems used in the pilot were able to meet the ASTM E1318-09 accuracy requirement for Type I WIM systems needed to collect research-quality data.

- FHWA's Senior Transportation Specialist in OHPI's Traffic Monitoring and Surveys Division did not make any recommendations for the type of controller but identified load cell technology for weight enforcement applications due to its high level of accuracy, and the bending plate or piezo-quartz for Virtual WIM and planning because they are reliable and are less costly to install and maintain than the load cell. The specialist also suggested that the piezo-quartz sensor may exhibit a higher dynamic error than the bending-plate or load cell technologies.

WIM TECHNOLOGY TESTING USING TEST BEDS/FACILITIES

Each survey participant was asked whether the agency built a test bed/facility for WIM equipment testing and/or research. Only the Florida and Connecticut DOTs and the IRD WIM vendor responded that they had. All three respondents wrote that their test facilities were built for their own purposes and that no other state agency had utilized their facilities.

The Florida test facility was used to test various WIM controllers, including IRD and Peek, and the piezo-quartz sensor. FDOT stated that it had just finished the installation of the test site and had not drawn any conclusions that it could report.

IRD constructed a test facility to test the integration of its WIM controller with various types of sensors, including piezo-polymer, piezo-quartz, bending-plate, and single load cell. Through its tests, it has concluded that each sensor has its own strengths and weaknesses regarding cost, accuracy, and longevity.

Connecticut DOT performed extensive testing on the piezo-quartz sensor when it was first developed.

SUPPORTING DOCUMENTATION

Each respondent was asked to indicate which documentation he or she could provide to ADOT during an interview or upon request. The results are summarized in Table 47. The table shows that one or more respondents can supply each document that provides information relevant to development of ADOT's *WIM Installation, Calibration, Maintenance, and Data Quality Assurance Guidebook* (Chapter 4 of this report).

Table 47. WIM Program Documentation Available for ADOT Program Development

Reference Materials	FHWA-OPI	FHWA-LTPP	FDOT	NMDOT	LADOT	TXDOT	VDOT	PennDOT	GDOT	ConnDOT	Total
WIM equipment manufacturer's guides				x		x					2
WIM site selection guidelines	x	x			x	x					4
WIM installation manual	x						x				2
WIM equipment maintenance manuals and/or reporting forms			x				x	x		x	4
WIM equipment calibration manuals and/or reporting forms		x	x			x	x	x	x	x	7
WIM equipment calibration spreadsheet tools, etc.	x	x	x				x			x	5
WIM equipment inspection and QA-QC procedures, manuals, protocols, etc.	x	x	x				x			x	5
WIM data QA-QC procedures, manuals, protocols, etc.	x		x			x		x	x	x	6
WIM data processing and reporting procedures, manuals, protocols, etc.	x	x	x			x		x		x	6
WIM equipment contract performance specifications	x	x						x		x	4

CONCLUSIONS BASED ON SURVEY RESPONSES

The following elements, listed in sequential order, for the development of a successful WIM program were identified through the survey of selected highway agencies and industry experts:

1. WIM Site Location Selection and Assessment
    a. The selection of a WIM site location that is conducive to accurate weight measurements is of utmost importance. If the desired location is provided by the WIM data user, the WIM data provider must make an assessment as to whether the site conditions of the selected location are favorable for collection of accurate WIM data. If site conditions would negatively affect WIM data quality, an alternative site location must be selected in collaboration between the WIM data user and data provider.
    b. The primary objective of selecting the location of the WIM sensor installation along the identified desired road segment is to minimize weight errors due to site characteristics that may directly affect the quality of WIM data collected. According to the responses

provided by the survey participants who manage successful WIM programs, the most important aspects to consider when evaluating a candidate WIM site, in order of importance to the respondents, are:

    i. Traffic conditions (free-flow, no nearby intersections or traffic signals)
    ii. Pavement condition (other than smoothness)
    iii. Safe access for technicians
    iv. Pavement smoothness
    v. Roadway geometrics
    vi. Roadway gradient

c. Several reference resources have been developed by FHWA and state DOTs (e.g., North Carolina, Montana, and Oklahoma) to provide guidance when selecting WIM site locations, including:
    i. *ASTM E1318-09* (ASTM 2009)
    ii. LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
    iii. WIM Data Analyst's Manual (Quinley 2010)
    iv. Smoothness Criteria for WIM Scale Approaches (Karamihas and Gillespie 2002)
    v. Distress Identification Manual for the Long-Term Pavement Performance Program (Miller and Bellinger 2003)
d. Many state agencies (Georgia, Florida, New Mexico, Virginia) stipulate acceptable WIM site selection criteria in their contract specifications to further ensure correct selection of WIM site location by the WIM installer along the road segment.

2. WIM Installation
    a. The most critical element for WIM site installations is ensuring that the in-road sensors are installed in accordance with the manufacturer's specifications. This not only includes the proper placement (spacing, layout, depth, etc.) but also includes the proper mixing and application of the chemicals and binding agents that are used to install the sensors.
    b. All personnel involved in the installation should be qualified and certified.
    c. An independent quality assurance inspector or other agent acting on behalf of the agency should be on site to observe the installation. The QA inspector would verify that procedures compliant with contract and manufacturer specifications are performed. He or she may also be tasked with taking measurements to verify critical dimensions and photographing and videotaping all WIM site installation activities. The QA inspector would also observe final testing and calibration of the WIM system.
    d. Once the WIM system is properly installed, an initial calibration of the equipment should be performed by a qualified WIM technician according to manufacturer's specifications and requirements/guidelines set forth in ASTM E1318-09.
    e. Several references have been developed by manufacturers, WIM vendors, and FHWA that could be used by ADOT to ensure that its WIM systems are installed properly and the initial testing is performed correctly. These resources include:
        i. International Road Dynamics' (IRD) instructions for the use of AS-475 Grout
        ii. Kistler Instrument's installation instructions for Lineas sensors
        iii. LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])

iv. "LTPP WIM System Installation and Calibration Audit" from *LTPP Field Operations Guide for SPS WIM Sites* (FHWA 2012)
v. ASTM E2561-07a – Standard Practice for Installation of Inductive Loop Detectors (ASTM 2007)
vi. ASTM E2759-10, Standard Practice for Highway Traffic Monitoring Truth-in-Data (ASTM 2010)
vii. ASTM E1318-09 - Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM 2009)

3. WIM System Calibration
   a. Once the WIM system has been installed and initially calibrated by the installer or manufacturer, it is imperative to routinely monitor WIM system performance (using remote data access from the office) and to systematically calibrate the WIM system to ensure that the data remain usable.
   b. The next calibration should include two tractor semi-trailer trucks (FHWA Class 9 truck) of differing weights (90 percent and 80 percent of allowable capacity) conducting test truck runs at the widest possible ranges of speeds and temperatures observed at the site. A sufficient number of pre-calibration runs should be performed to quantify WIM measurement bias (i.e., mean measurement error percent): at least 10 test runs per truck, per lane. After initial pre-calibration test truck runs, the system should be calibrated to minimize bias, and then the same number of post-calibration test truck runs should be performed to validate the system and quantify measurement data accuracy (expressed as mean percent error ±2 standard deviations of the percent error).
   c. For the subsequent routine calibrations, one truck that is representative of the weights and types of trucks at the site may be used unless the initial calibration determined that a second truck of different weight must be used. A reduced number of runs may be performed to "validate" the current calibration settings or to determine the bias that must be compensated using the system calibration factors. After compensation factors have been adjusted, the same number of runs must then be used to verify that the calibration had the intended effect on the system measurement's bias and that the biases for all weight, spacing, and length measurements are as close to zero as possible.
   d. A sample of data covering two weeks immediately after each successful calibration (four weeks for low truck volume sites with fewer than 100 Class 9 trucks per day) should be downloaded and used to develop site benchmark values that can be used to validate data that are downloaded in the future. Benchmark values should include an average weight of front axle and GVW for Class 9 trucks and the location of loaded and unloaded peaks in load distribution of front axle, tandem axles, and GVW for Class 9 trucks (for example, range of values corresponding to tandem axle loaded peak: 30-34 kips).
   e. The WIM systems with piezo-quartz sensors should be calibrated every 12 to 18 months.
   f. If the data drifts more than 5 percent from the benchmark values for Class 9 GVW, the system should also be calibrated out of normal cycle.

g. If systems with piezo-polymer sensors are used for collection of axle weight data, these systems should be calibrated seasonally or have other means for consistent compensation of temperature effects on weigh measurements.
h. For climatic condition observed in Arizona (i.e., high time-of-data and seasonal temperature differentials), piezo-polymer systems are recommended for vehicle classification and not for weight data collection, unless low-precision WIM data (±30 percent error in weight measurements) is acceptable for customer applications.
i. For systems that are using temperature compensation, the temperature compensation function should remain on. However, if the system uses an auto-calibration routine using temperature or free-flow traffic truck weights, the function should be turned off during calibration.
j. Some of the reference sources available for WIM system calibration include:
    i. WIM Vendor Maintenance Guides
    ii. LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
    iii. ASTM E1318-09 — Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM 2009)

4. Maintenance
    a. To maximize the life of the WIM system, a comprehensive maintenance program must be put into practice. It is important to perform routine preventive maintenance every six to 12 months and to develop a schedule and event procedure for timely repairs of system failures.
    b. The maintenance function is frequently outsourced. Most WIM vendors provide maintenance schedules and procedures for maintaining and repairing their WIM systems. Many maintenance guides contain a list of required spare service parts, tools, and equipment necessary to properly maintain the vendors' WIM systems.
    c. The FHWA published the *WIM Field Inspectors' Troubleshooting Guide* in 2009 to assist WIM technicians in adequately maintaining WIM systems and provide guidance on how to properly identify and repair system faults (Quinley 2009).
    d. During each preventive maintenance visit, all in-road sensors should be checked for proper electronic values. The entire WIM system should be visually inspected, including the pull boxes, in-road sensors, telephone and power service equipment, and the roadway leading up to and into the WIM scale area. All deficiencies should be recorded and reported.
    e. It is also important to maintain an accurate record of all maintenance performed at each WIM site; important records include maintenance logs, maintenance reports, and photographs that are kept in the cabinet for easy reference by field technicians.

5. Data Quality Assurance
    a. WIM data quality assurance includes both field measurement data checks and office data analysis. Field data checks are used to support field validation and calibration of WIM systems, and off-site office checks are used to remotely monitor and evaluate WIM system performance over time and to identify changes in WIM data parameters that may signal WIM system malfunction or calibration drift.

b. Field data QC is performed as part of WIM validation or calibration activities. It involves comparing weights reported by the WIM system with known static weights. Test trucks representing the most frequently observed heavy vehicles at the site (typically Class 9 trucks) are used for these checks. Using a sample of test truck runs, errors between known static and WIM weight measurements are computed and used to determine the mean error and the statistical confidence interval (that represents the range of errors for the 95 percent confidence level). The mean error and confidence interval values are combined (mean error ±2 standard deviations of error), and the resulting range is compared with the tolerance levels specified in ASTM E1318-09 to check whether the WIM system is producing inaccurate weight measurements.

c. The following checks of polled WIM data were identified through the survey and recommended as part of routine WIM data checks done in the office:
    i. Polling errors: number of error vehicles, status-clear vehicles, and good-weight vehicles per day
    ii. Data file size
    iii. Site identification, lane, direction, date, time, and location description checks
    iv. Volume, class, and speed errors based on site-specific traffic volume, class, and speed averages
    v. Invalid weight counts
    vi. Class 9 hourly or daily volume checks
    vii. Class 9 loaded/unloaded peak loads
    viii. Class 9 front axle weights against a minimum weight
    ix. Average Class 9 front axle weights against historical data
    x. Right- and left-wheel weight comparison on front-axle data for Class 9 vehicles
    xi. Average Class 9 GVW against historical data
    xii. Percentage of overweight vehicles against historical data
    xiii. Minimum/maximum axle weight for Class 9 vehicles
    xiv. Minimum/maximum axle spacing for Class 9 vehicles
    xv. Tandem axle spacing of Class 9 vehicles against historical data
    xvi. Total wheelbase based on vehicle class

6. WIM Program Support Staff

a. Whether or not the work is performed in-house or is contracted, and whether or not the tasks performed are specific to WIM, it is very important to have at least the following personnel, either dedicated to the WIM program or shared with other agency programs:
    i. WIM Program Manager. Duties: supervise in-house or contracted personnel, including data analysts and field technicians; submit reports; schedule installations; perform calibrations, maintenance, and repairs; manage contracts for outsourced WIM operations; take responsibility for overall WIM equipment and data QA-QC; and be the primary point of contact with WIM data customers.
    ii. Field technician. Duties: Maintain, calibrate, and repair WIM systems. May provide on-site QA of WIM installations and repairs.

    iii. Data analyst. Duties: Download, process, and QA-QC data and compile it for reporting; be an alternative point of contact for WIM data customers.
    iv. WIM QA inspector/WIM Specialist. Duties: Technically oversee and manage WIM system installation, maintenance, and calibration.

b. Most agencies share staff resources, including program supervisors and managers, data analysts, and technicians, with other sections within the traffic monitoring division.
c. Among those state agencies that outsource all or part of their WIM programs, the most frequently outsourced function is installation, which is typically performed by qualified contractors or WIM vendors. Maintenance and calibration functions, when performed by staff outside the agency, are typically performed by qualified traffic monitoring system installation and maintenance companies or by the WIM vendors themselves. Most data functions are carried out by in-house staff. Only two agencies (Florida and FHWA LTPP) indicated that they outsource their data processing and QA-QC functions.

CHAPTER 4. GUIDEBOOK FOR WEIGH-IN-MOTION INSTALLATION, CALIBRATION, MAINTENANCE, AND DATA QUALITY ASSURANCE

OVERVIEW

This sample guidebook (Guide) is designed to aid in implementing and managing ADOT WIM operations. It was developed by compiling the best available practices of other state and federal highway agencies for WIM installation, calibration, maintenance, and data quality assurance. Note that the forms and reports mentioned in this chapter are concepts only; the user agency will need to design their own versions. Appendices B through F show examples of reports and forms from other state departments of transportation.

Guide Organization

The Guide includes the following sections:

Section 1 – WIM Site Location Selection and Assessment. This section includes requirements for site location to minimize weight measurement errors due to site characteristics.

Section 2 – WIM System Installation. This section includes a description of QA inspection of WIM installation and acceptance testing requirements.

Section 3 – WIM System Calibration. This section describes recommended calibration and validation activities.

Section 4 – WIM Equipment Maintenance. This section includes recommended scheduling, testing, and documentation.

Section 5 – WIM Data Quality Assurance and Analysis. This section includes recommended QC checks to support field validation and system calibration, as well as off-site checks to monitor and evaluate WIM performance.

Section 6 – WIM Program Support Staff. This section describes personnel needed to operate and maintain the WIM systems, including titles, qualifications, and duty descriptions.

Navigating the Guide

Sections 1 through 5 follow a similar structure and format and contain the following information:

- Purpose
- Personnel Requirements
- Reference Documentation
- Tools and Equipment
- Recommended Supporting Forms and Documentation
- Procedure

Procedures described in the Guide may include subheadings called “Actions” and “Criteria.” The “Actions” subheading identifies lists of actionable items described in the procedure. These lists are identified by arrow bullets, as shown in the following example.

Actions:

- ➢ This is an example of a bulleted list entry used to identify actionable items.

“Criteria” or “Criterion” subheadings are used to identify evaluation criteria used in some procedures. To make these criteria easily visible and identifiable, the words “Criteria” or “Criterion” are shown in bold italic font, and the text describing the criteria is shown in italic font, as shown in the following example.

Criteria: *This is an example of a text feature used to identify evaluation criteria supporting different procedures described in the Guide.*

SECTION 1 – WIM SITE LOCATION SELECTION AND ASSESSMENT

Purpose

Selecting the appropriate site for the WIM installation is critical to obtaining accurate measurements. Certain site characteristics may result in faulty measurements that cannot be corrected through equipment calibration or maintenance. Therefore, it is a good practice to stipulate acceptable WIM site selection criteria in WIM installation contract specifications. These criteria can be used to further ensure correct selection of WIM site locations by WIM installers along the roadway segments identified by the WIM data users.

The primary objective of selecting the most suitable location for a WIM sensor installation within a desired road segment is to minimize weight errors due to site characteristics. According to industry standards and best practices, the following list represents the most important aspects to consider when evaluating a candidate WIM site:

- Roadway Geometrics – horizontal curvature, grade, cross slope, lane width, and markings
- Traffic Conditions – stop-and-go traffic, lane-changing, passing, signalization, and intersections
- Pavement Condition – structure and smoothness, pavement-truck interaction
- Site Location – proximity to power and communications, safety, cabinet location, test truck turnarounds, drainage, and existing equipment

Preferred configurations for each of these aspects are discussed in greater detail in this Guide.

Personnel Requirements

WIM site selection should be performed by an engineer or WIM technician who has a clear understanding of the effect of vehicle-pavement interaction on the accuracy of WIM measurements, and who is familiar with the requirements for site selection from the American Society for Testing and

Materials (ASTM) *Standard Specification for Highway Weigh-In-Motion Systems with User Requirements and Test Methods* E1318-09. (This standard specification is referenced as ASTM E1318-09 throughout the Guide.) This person will take site measurements to verify critical dimensions and then complete a site evaluation form. It may be necessary to engage two or more individuals to perform all tasks.

Reference Documentation

Several reference resources have been developed by highway agencies, with the assistance of industry experts, to guide the selection of WIM sites, including:

- ASTM E1318-09–Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM 2009)
- LTPP Manual for Profile Measurements and Processing (Perera et al. 2008)
- LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
- WIM Data Analyst's Manual (Quinley 2010)
- Smoothness Criteria for WIM Scale Approaches (Karamihas and Gillespie 2002)
- Distress Identification Manual for the Long-Term Pavement Performance Program (Miller and Bellinger 2003)
- States' Successful Practices Weigh-in-Motion Handbook (McCall and Vodrazka 1997)
- Traffic Detector Handbook: Third Edition – Volume I (Klein et al. 2006)
- WIM Field Inspectors' Troubleshooting Guide (Quinley 2009)

Tools and Equipment

The following tools and equipment are required for the site evaluation:

- Clipboard
- Digital camera
- 10-ft level
- Tape measure
- Multimeter
- 20-ft straightedge
- 6-inch diameter x ⅛-inch height aluminum disc
- Hand tool set – screwdrivers, nut driver set, pry bar, etc.

Recommended Supporting Forms and Documentation

ADOT should provide the appropriate forms and templates to personnel tasked with selecting or evaluating the proposed WIM site locations. The entered data will be used to determine whether the proposed sites are suitable for WIM system installation and accurate weighing in motion. The recommended templates and forms include:

- WIM site evaluation form – An evaluation form should be used to record all information from the preliminary investigations and on-site evaluation. The form should include the criteria listed in the following "Procedure" section, and it should include sufficient space for noting supporting qualifying or quantifying information for each criterion.
- Pavement distress survey forms and map – These forms are represented in Appendix A of the *Distress Identification Manual for the Long-Term Pavement Performance Program* (Miller and Bellinger 2003). See pages 100-105 of the manual for examples, including a distress map and survey summary forms.
- WIM site selection roadway plan – This plan should be used to record all physical features of the proposed WIM site installation location, including the geometric information, roadway structures and assets, drainage, ramps, intersections, and signalization. During the on-site evaluation, the plan should be updated with the recommended WIM system component layout, including all applicable measurements. This plan will be the basis for the new WIM site design.

Procedure

Before initiating the WIM site selection process, ADOT's Multimodal Planning Division (MPD) identifies the highway segment for the desired WIM data collection on the basis of its WIM data user inputs. This segment is then evaluated to determine whether the site conditions are conducive to accurate weighing in motion.

The WIM site selection process consists of two parts, referenced as Part 1.1 and 1.2 in this Guide. Part 1.1 is a preliminary site selection based on data, reports, and documentation that identifies potential WIM locations along the highway segment. Part 1.2 involves field verification of the conditions at potential WIM site locations and final selection of the desired site for WIM system installation.

Part 1.1 Conduct Preliminary WIM Site Selection

Preliminary WIM site selection is accomplished in the office, typically using all available supporting documentation and data. The entire roadway segment selected by the user as a desirable WIM site location must be evaluated to ensure it meets the ASTM E1318-09 requirements for horizontal alignment and for structure.

The goal of preliminary site selection is to identify a roadway section(s), no less than 0.5 miles long, acceptable for WIM installation. The potential location(s) will be confirmed later with an on-site visit.

Step 1.1.1 – Determine Horizontal Curvature. Construction plans typically contain information about the horizontal curvature of a proposed roadway segment.

Criterion: *The horizontal curvature of the roadway lane for 200 ft prior to and 100 ft beyond the WIM sensors shall have a radius not less than 5,700 ft measured along the centerline of the roadway (*ASTM E1318-09).

Actions:

- ➢ Review the available construction plans to determine the horizontal curvature of a proposed roadway segment.
- ➢ Record the horizontal curvature of the proposed WIM site roadway on a site evaluation form.

Step 1.1.2 – Determine Pavement Structure. Adequate pavement structure and surface smoothness is needed to accommodate the WIM-system sensors throughout their service life. Field tests have shown that WIM sensor installations in smooth portland cement concrete (PCC) pavement have greater longevity than installations in flexible pavements. Also, PCC pavement retains smoothness characteristics longer than flexible pavement since it is not as susceptible to damage, such as rutting caused by heavy truck loading. Evaluation of the expected pavement structure longevity should be based on current conditions and planned maintenance activities.

Criteria:

- The pavement structure and surface smoothness must be properly maintained (i.e., smooth and free of medium- and high-severity distresses) to accommodate the WIM sensors throughout their service lives.
- The ideal roadway segment will have been constructed within the past year, or the proposed WIM site will be part of a new roadway construction or rehabilitation project.
- A 300-ft-long continuously reinforced concrete pavement or a jointed concrete pavement with transverse joints spaced 16 ft or less apart is preferred for WIM installations (ASTM E1318-09).
- Piezo-quartz and piezo-polymer sensors can be installed in rigid pavements or relatively stiff flexible pavements with adequate pavement thickness. The thickness of the asphalt layer where the devices are installed in flexible pavements should exceed 4 inches.

Actions:

- ➢ Review the available information about the roadway's pavement structure and pavement surface condition.
- ➢ If the available information about pavement condition leads to the conclusion that the pavement condition within the selected roadway segment is not suitable for a WIM installation, consult the pavement engineer to determine whether mill-and-fill or grinding the pavement to reduce roughness is economically feasible given the pavement type, life cycle, and thickness.
- ➢ Record the results of the pavement structure evaluation on a WIM site evaluation form, indicating the roadway's type of pavement, thickness, pavement surface condition, build year, and next scheduled rehabilitation.

Step 1.1.3 – Locate Truck Turnarounds. WIM calibration test trucks should have a reasonable turnaround time to return to the WIM test site after each calibration run. Up to 40 test truck runs may be needed for calibration on the day of testing.

Criterion: *The turnaround location along the roadway exits should be located so that a test truck can safely turn around and come back to the WIM test site in 20 minutes or less.*

Actions:

- Use tools such as Google Earth or Google Maps to find optimal locations where test trucks can safely turn around to return to the WIM testing site within a reasonable time.
- Record the proposed test truck turnaround locations on a WIM site evaluation form.

Step 1.1.4 – Conduct Pavement Smoothness Analysis Using Available Pavement Profile Data. The goal of the pavement smoothness analysis is to determine whether a 300-ft section is available within the selected roadway segment that satisfies the ASTM E1318-09 pavement profile and smoothness criteria for WIM sensor installation. The preliminary pavement smoothness analysis may be accomplished in the office using profile data collected with a high-speed profiler (described in the *LTPP Manual for Profile Measurements and Processing* [Perera et al. 2008]) and the WIM Smoothness Index software, which can be obtained by contacting LTPP customer support at ltppinfo@dot.gov. The smoothness indices produced by the software provide an indication of whether or not the pavement roughness may affect the operation of the WIM equipment.

Criteria:

- The candidate roadway section(s) must meet the ASTM E1318-09 smoothness requirements. The surface of the pavement 200 ft before and 100 ft after the WIM-system sensors shall be smooth before sensor installation (ASTM E1318-09).
- The recommended thresholds for the WIM smoothness index on site pavement are provided in Table 48. If any of the values are over the upper threshold for any of the runs, the site does not meet acceptable smoothness criteria for WIM system installation. An alternative section of pavement must be found (FHWA 2012 [LTPP]).

Table 48. Recommended WIM Smoothness Index Thresholds

Index	Upper Threshold (m/km)
Long-Range Index (LRI)	2.1
Short-Range Index (SRI)	2.1
Peak LRI	2.1
Peak SRI	2.9

Actions:

- Request the International Roughness Index (IRI) data for the roadway segment that contains the proposed WIM site location from the pavement engineering office.
- Process the IRI data files using the WIM Smoothness Index software.
- Record the smoothness index values for the proposed WIM system pavement section on a site evaluation form.
- Compare the WIM smoothness index values with the threshold values provided in Table 48. If all values are less than the lower threshold, it is unlikely that pavement conditions will significantly influence sensor output. Values between the threshold values may or may not influence the accuracy of the sensor output. Values above the upper threshold would lead to sensor output that would preclude achieving high-quality loading data.
- Record findings and conclusions from pavement smoothness evaluation on a WIM site evaluation form.

Step 1.1.5 – Determine Optimal WIM Site Location (Optional). Conduct this step if IRI data is available. This step requires using the Optimal WIM Locator (OWL) module of the ProVAL software (available free of charge from http://www.roadprofile.com). This software uses an algorithm from the AASHTO MP 14-12 – *Standard Specification for Smoothness of Pavement in Weigh-in-Motion (WIM) Systems* to analyze pavement profiles collected at candidate WIM sites (AASHTO 2012). The AASHTO MP 14-12 criteria are applied to screen WIM sites for excessive truck dynamic loading that results in an excessive WIM measurement error. The report generated by the OWL includes a WIM index plot with a horizontal line at the lower threshold and another at the upper threshold, a companion plot below the WIM index plot, and a table to list start and stop locations for acceptable WIM locations.

Criterion: *The WIM index values for qualified WIM sites should be between 84.44 and 171.09 inches/mile for Type I WIM systems and between 117.89 and 237.73 inches/mile for Type II WIM systems.*

Actions:

- Obtain the available IRI data for the selected road segment from ADOT MPD.
- Import the IRI data files from the high-speed profile analysis into the OWL module of the ProVAL software.
- Use the visual outputs from the OWL module to identify acceptable locations for the WIM sensor installation.
- Record the optimal WIM sensor installation locations on a WIM site selection roadway plan. This information will provide guidance for the pavement condition survey that will be conducted as part of Step 1.2.3 of the On-Site WIM Location Qualification.

Part 1.2 Perform On-Site WIM Evaluation

After one or more acceptable WIM sensor locations have been identified through the off-site data assessment performed in Part 1.1, the proposed WIM scale locations must be confirmed through an on-site visit by a trained WIM specialist using this Guide and the ASTM E1318-09 criteria.

During the on-site WIM evaluation, assess roadway geometrics using the following steps.

Step 1.2.1 – Evaluate Longitudinal Alignment (Roadway Grade). To avoid adverse driver behaviors (e.g., braking and accelerating), the longitudinal roadway inclinations and/or declinations must meet the criteria in the ASTM E1318-09 specification.

Criterion: *The longitudinal gradient of the road surface 200 ft before and 100 ft after the WIM sensors shall not exceed 2 percent (ASTM E1318-09).*

Actions:

- Use a 10-ft digital level placed parallel to the roadway centerline at 50-ft intervals along the 300-ft WIM scale approach/departure road segment to measure the longitudinal gradient.
- Record the percent longitudinal grade for each measurement on a WIM site evaluation form.

Step 1.2.2 – Evaluate Lateral Alignment (Transverse Slope of Roadway or Cross Slope). To avoid adverse driver behaviors (e.g., veering and lane wandering), and to ensure balanced truck loads, make sure that the proposed WIM site location meets the ASTM E1318-09 specifications for lateral slope (i.e., cross slope).

Criterion: *The cross slope (lateral slope) of the road surface 200 ft before and 100 ft after the WIM sensors shall not exceed 3 percent (ASTM E1318-09).*

Actions:

- Use a 10-ft digital level placed perpendicular to the roadway centerline to measure the cross-slope of the roadway every 50 ft within the 300-ft WIM scale approach/departure road segment.
- Record the cross-slope measurement (the percent lateral grade for each measurement) for each location on a site evaluation form.

Step 1.2.3 – Evaluate Lane Width and Markings. To install the WIM sensors properly, the travel lanes for the proposed WIM site must be wide enough to ensure proper layout of the weighing sensors and sufficient spacing between the inductive loops.

Criterion: *The optimal lane width for WIM sensor installations is between 12 and 14 ft, with a minimum of 10 ft. The lanes must be clearly marked with lane lines 4 to 6 inches in width throughout the WIM section. There should be a shoulder of at least 3 ft throughout the WIM scale section to accommodate wide loads (ASTM E1318-09).*

Actions:

- Measure and record the lane and shoulder widths and note the measurements on a WIM site evaluation form.
- Measure and record the width of the pavement markings, observe the condition (i.e., deterioration) of the markings, and note the information on a site evaluation form.

Step 1.2.4 – Evaluate Traffic Conditions. The characteristics of the passing traffic should be recorded over the course of the observation period, tabulated, and reported on a WIM site evaluation form. It is important to evaluate the traffic conditions when the highest volume of traffic is anticipated, especially during the rush hour.

Criteria: *The WIM systems should be in an area of free traffic flow with good sight distances (McCall and Vedrazka 1997), including:*

- No stop-and-go traffic
- Minimal lane changing
- Minimal passing
- No intersections within 1 mile of the proposed WIM site location
- For two-lane roadways, a "no-passing" zone within the 1,000-ft WIM scale road segment is recommended.

Actions:

- Find a safe observation point from which to observe traffic conditions at the site for an extended period of time (2 to 4 hours).
- Measure and record the distances to all intersections and signalization within the roadway segment on the WIM site selection roadway plan.
- Measure and record distances to nearby permanent roadway assets (e.g., bridges, road signs, drainage culverts, or sound walls) on the WIM site selection roadway plan.
- Record any presence and frequency of stop-and-go traffic, lane-changing, and vehicle passing.

Step 1.2.5 – Inspect Pavement Condition. Pavement distresses (cracking, faulting, rutting, potholes, etc.) within the WIM scale section should be avoided, as they will interfere with the proper installation of the WIM system sensors and will adversely affect the accuracy of the WIM system (by inducing truck bounce or other non-uniform movement).

Criterion: *The pavement 200 ft before and 100 ft after the WIM-system sensors is free of distresses.*

Actions:

- Use safety equipment, including a hard hat and safety vest, during pavement inspection.
- Use a designated spotter to watch traffic and warn the inspector of any oncoming vehicles.
- Conduct the evaluation from the shoulder if a lane closure is not practical.
- Visually inspect the pavement condition and note any pavement surface distresses and their locations. Photograph the distresses.
- Record pavement distress on the Pavement Distress Survey Map and attach to the WIM site selection roadway plan.

Step 1.2.6 – Analyze Pavement Surface Smoothness. The goal of the pavement smoothness analysis is to determine whether a 300-ft section for WIM sensor installation is available within the selected roadway segment that satisfies ASTM E1318-09 pavement profile and smoothness criteria. The pavement smoothness analysis may be accomplished by any one of the following three methods:

1. Using available profile data for the selected roadway segment (see Step 1.1.5)
2. Combining on-site profile data collection using a high-speed profiler (as described in the *LTPP Manual for Profile Measurements and Profiling*, Perera et al. 2008), followed by in-house data analysis (see Step 1.1.5). (The preferred equipment for collecting longitudinal profile data is an inertial profiler meeting the Class 1 standards specified in ASTM Standard E950-98 (FHWA 2012 [LTPP]).)
3. On-site data collecting using a 20-ft-long straightedge, as described in ASTM E1318-09.

Criterion: *If the straightedge method is used, apply the following criterion: for a distance of 200 ft before and 100 ft after the sensor, the roadway surface shall be maintained in a condition such that a 6-inch-diameter circular plate 0.125 inches thick cannot be passed beneath a 20-ft-long straightedge (ASTM E1318-09).*

Actions:

- If a high-speed profiler is available, analyze the profile data according to Section 1.1.5.
- If the straightedge method is preferred and lane closures are possible, perform the pavement smoothness testing in accordance with Section 6.1.5.1 of ASTM E1318-09, following the procedure of using the 20-ft-long straightedge and the 6-inch-diameter, ⅛-inch-high (0.125 inches) aluminum disc.
- Record findings on a site evaluation form.

Step 1.2.7 – Evaluate Pavement-Truck Interaction. Any visible truck bounce may affect the performance of the WIM scales. Specific roadway locations that demonstrate consistent adverse truck dynamics should be investigated closely to determine the cause, including dips or bumps in the roadway. Also, a verification that trucks track down the center of the lane must be performed.

Criterion: *Adverse truck dynamics, such as bouncing, swinging, or rocking, should be minimal.*

Actions:

- ➢ Observe trucks as they approach, traverse, and leave the proposed sensor area.
- ➢ Identify and record any adverse vertical or horizontal truck dynamics (vertical bounce or lateral swinging, rocking) on a site evaluation form.
- ➢ Describe all distresses that may cause adverse truck dynamics on a site evaluation form.

Step 1.2.8 – Evaluate Site Location for Safety, Communication Services, and Convenience. When evaluating the exact location for the cabinet, consider such elements as technician safety, equipment protection, accessibility to power and communication services, drainage, and proximity to test truck turnaround locations.

<u>Proximity of Power and Communication Services</u>

The selection of power and communication may be performed as part of the preliminary site selection described in Part 1.1 or may be determined on site after an evaluation of what is available at or near the site.

Criteria:

- The site should have access to an alternating current (AC) power source and telephone utilities. Solar power and cellular phones can be used if preferred, or if utilities are not available.
- Selection of the power source and phone service at a site depends on the amount of truck data to be collected.
- For high-data volume sites, a wired phone service is more cost effective than cellular (wireless) service (McCall and Vodrazka 1997).

Actions:

- ➢ Identify on site and record the available options and locations of power and communication service lines on a site evaluation form.
- ➢ Provide recommendations for power and communication services on a site evaluation form.

WIM Controller Cabinet Location and Service Technician Access

The WIM controller cabinet enclosure houses the WIM controller, communication and power devices, and interconnecting devices such as cabling and terminal strips. The cabinet should be NEMA 3R rated. The selected location should accommodate placement of the cabinet and satisfy the following criteria.

Criteria:

- The cabinet needs to be in a protected area, preferably behind a guardrail, so it cannot be hit by a vehicle leaving the roadway.
- The cabinet should have a clear line of sight to the sensors and an unobstructed view of passing traffic (McCall and Vodrazka 1997). The Manual on Uniform Traffic Control Devices (FHWA 2012 [Manual]) provides clear zone dimensions for roadways based on traffic speed.
- The WIM site must have a large, flat area for technicians to park service vehicles outside the clear zone, also known as the recovery area.

Actions:

- ➢ Evaluate whether the cabinet location satisfies the above criteria and provides a safe location for service technicians to stand without turning their backs to oncoming traffic.
- ➢ Record the proposed locations of the cabinet and pull boxes on the WIM site selection roadway plan. Indicate safe parking areas for service vehicles outside the clear zone, and do not require the technician to cross the roadway to access the cabinet.

Drainage

To ensure the equipment and sensor lead-ins are protected from flooding and subsequent water damage, it is important to select a site adjacent to the roadway with adequate drainage or on a level higher than the pavement surface. Drainage for the pull boxes is also important, so the pull boxes must not be installed in a gully or ditch.

Criterion: *The site adjacent to the roadway must have good drainage or be on a level higher than the pavement surface to ensure adequate drainage. Pull boxes must not be installed in a gully or ditch.*

Actions:

- ➢ Identify cabinet and pull box locations that satisfy the above criterion.
- ➢ Mark the optimal locations for the cabinet and pull boxes on the WIM site selection roadway plan.
- ➢ Record existing drainage features on a site evaluation form. Provide their locations as they relate to the proposed cabinet and pull box locations.

Existing Equipment for Possible Upgrade

If an existing traffic monitoring site is being considered for a possible upgrade to a WIM site, the existing equipment should be evaluated.

Criterion: *The existing equipment is structurally sound, is in good physical and operational condition, and will continue to operate for as long as the newly installed equipment operates.*

Actions:

- ➢ Inspect all existing equipment and evaluate whether each item is structurally sound, is in good physical and operational condition, and will continue to operate as long as the newly installed equipment does.
- ➢ If existing loop sensors will be incorporated into the upgrade, perform electrical checks to determine whether the sensors demonstrate electronic values that are within tolerance (see Section 4 – Preventive Maintenance).
- ➢ Record all test readings on a site maintenance and inspection form (see Section 4—WIM Equipment Maintenance).
- ➢ Provide information about the condition of the existing equipment on a site evaluation form.

Test Truck Turnarounds

The amount of time technicians and test trucks spend on site is one of the greatest contributors to WIM calibration cost. That time may be greatly reduced if the test truck turnarounds are reasonably close to the WIM site to provide the quickest, safest truck route possible. (See Step 1.1.3, "Locate Truck Turnarounds.")

Criteria:

- The WIM system should be installed no closer than 1 mile and no farther than 5 miles from the nearest turnaround.
- A turnaround time under 20 minutes is preferred.

Actions:

- ➢ Drive to the proposed turnaround locations identified in Step 1.1.3 to verify that they are suitable for a safe and repeated turnaround of semi-tractor trailer trucks.
- ➢ In rural areas, request private landowners' permission to use their land for a truck turnaround, if necessary.
- ➢ Record the GPS coordinates of acceptable truck turnaround locations on a site evaluation form.

Step 1.2.9 – Record findings and conclusions from the WIM site evaluation on a site evaluation form. The WIM site evaluation form must show that the candidate location meets all ASTM E1318-09 requirements for the following:

- Roadway Geometrics
    - Acceptable horizontal curvature
    - Acceptable roadway grade
    - Acceptable roadway cross slope
    - Sufficient lane width
    - Clear pavement markings
- Traffic Conditions
    - No stop-and-go traffic
    - Minimal lane changing
    - Minimal vehicle passing
    - Even traffic flow/speed
    - No signalization
    - No intersections within 1 mile (based on truck turnaround requirements)
- Pavement Condition
    - Sufficient pavement structure
    - Adequate pavement smoothness
    - Minimal pavement-truck interaction
- Site Location
    - Safe technician accessibility
    - Sufficient drainage
    - Accessible power and communication services

Actions:

- ➢ Evaluate all available information for each candidate WIM site to determine whether all aspects of the proposed location are suitable for installation and maintenance of a WIM system.
- ➢ Identify candidate WIM site location(s) that meet all the above requirements.
- ➢ If none of the sites meet all the requirements, identify what requirements were not met and consult with a traffic or pavement engineer or WIM expert, as applicable, to determine whether the site could still be feasible with some exceptions to the requirements.
- ➢ Document findings on the WIM site evaluation form.
- ➢ The WIM site evaluation form, with identified WIM site locations and recommendations, must be reviewed and approved by the WIM program manager, district engineer, chief pavement engineer, and WIM data users.

SECTION 2 – WIM SYSTEM INSTALLATION

Purpose

Proper installation of the WIM equipment is one of the most critical elements of collecting high-quality WIM data. WIM sensors improperly installed in even the smoothest pavement will most assuredly provide unusable WIM data. This section includes a scope of recommended WIM installation quality assurance activities based on widely used industry practices and describes recommended WIM system installation quality assurance checks that will ensure the WIM system meets accuracy requirements and design life expectations.

ASTM E1318-09 requires that the WIM equipment be installed and maintained in accordance with the recommendations of the WIM system vendors. In addition, the following installation requirements must be followed, regardless of which type of WIM) system or sensor is being installed (FHWA 2012 [LTPP]):

- The installation must be done in good weather. Avoid wet, freezing, or hot conditions (over 90^{o} F), which may be detrimental to equipment or personnel.
- The equipment cabinet must protect the system electronics from extreme temperatures, dust, humidity, insects, and rodents.
- The equipment must be protected from power surges and lightning.
- The equipment must be installed so that routine maintenance does not disrupt data collection.

Personnel Requirements

Typically, the WIM vendor performs the complete WIM system installation. The WIM installation should be supervised by a certified WIM installer. Most WIM vendors also provide on-site installation supervision or training and certification for agency or contractor personnel. The installation supervisor should direct the installation crew in a manner that ensures the WIM system is installed properly, within the time allotted, and without incurring additional costs or budget overruns.

In addition, an independent quality assurance inspector or other agent acting on the behalf of ADOT should be on site to observe the installation. The QA inspector must be experienced with WIM installation and calibration protocols and procedures. The QA inspector should verify that procedures being performed comply with the contract and manufacturer specifications. The QA inspector is also tasked with taking measurements to verify critical dimensions and photographing and videotaping all or some of the WIM site installation activities. The QA inspector observes final testing and calibration of the WIM system and reports results to the ADOT WIM program manager.

Reference Documentation

Several references have been developed by manufacturers, WIM vendors, and FHWA to help ensure that WIM systems are installed properly and that the critical elements of installation and initial testing are performed correctly. The available resources include:

- WIM Manufacturers' Installation Manuals
- Section 7, WIM System Installation and Calibration Audit, of the *LTPP Field Operations Guide for SPS WIM Sites* (FHWA 2012 [LTPP])
- International Road Dynamics' (IRD) instructions for the use of AS-475 Grout
- Kistler Instrument's installation instructions for Lineas sensors
- ASTM E2561-07a – Standard Practice for Installation of Inductive Loop Detectors (ASTM 2007)
- ASTM E2759-10 – Standard Practice for Highway Traffic Monitoring Truth-in-Data (ASTM 2010)
- ASTM E1318-09 - Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM 2009)
- FHWA LTPP Sample Installation and Calibration Report for California SPS-2 (Appendix C)
- FHWA LTPP WIM Model Specifications-Draft (Appendix C)
- VDOT Continuous Count Station Installation Contract Requirements (Appendix C)
- States' Successful Practices Weigh-in-Motion Handbook (McCall and Vodrazka 1997)

Tools and Equipment

A list of the tools, equipment, and materials needed by the WIM installers to properly perform the WIM installation are provided in the WIM vendor's installation manual.

The tools and equipment that will be needed by the QA inspector to properly perform the WIM installation inspection include:

- Cellular phone
- Safety and comfort accessories
- Steel measuring tape (50 ft)
- Thin measuring ruler (6 inch)
- Clipboard, paper, and pencil
- Digital camera
- Handheld GPS receiver
- AA Batteries

Recommended Supporting Forms and Documentation

WIM Installation Audit Checklist Form

A WIM installation audit checklist form should be used by the Installation QA inspector to record information about the WIM installation. The form should provide documented confirmation that the WIM equipment was installed in accordance with the roadway construction plans, manufacturer instructions, and state and local road and bridge standards. A sample WIM installation audit checklist form used by the FHWA LTPP WIM program and the *VDOT Continuous Count Station Installation QA Checklist* are provided in Appendix C.

The WIM installation audit checklist form should include a checklist to ensure that all necessary items are on hand: tools, materials, a site selection roadway plan, roadway construction plans, and manufacturer's installation guides.

This form also provides a means to verify compliance with the installation requirements and to record the following information:

- Verification of utility locations
- Equipment inspection
- All layout information, including distance measurements between lane sensors
- Excavation process details and checks
- Loop wire installation details and checks
- WIM sensor installation details and checks
- Final sensor testing results, including electronic measurements
- Operational verification
- Calibration results
- Photograph logs and maps

WIM System Installation Acceptance Report

A WIM installation acceptance report should briefly summarize the results of the installation and subsequent calibration of the WIM system, including any conditions of acceptance, if applicable. The installation acceptance report should be prepared by the QA inspector as soon as possible after the successful completion of the WIM installation and initial calibration. The report must be submitted to the WIM program manager and serve as evidence of WIM installation acceptance by ADOT. An example of such a report is the LTPP Traffic Sheet 29 – Audit Summary provided under Section 10 – Forms, page 89 of the *LTPP Field Operations Guide for SPS WIM Sites* (FHWA 2012 [LTPP]).

Non-Compliance Report

In addition, a non-compliance report (NCR) should be used by the QA inspector to document any refusals by the installation contractor to comply with the directions given by the QA inspector to resolve deficiencies. The NCR shall be signed by the installation supervisor and immediately forwarded to

ADOT’s WIM program manager. Any NCRs shall also be submitted as a supplement to the WIM installation acceptance report. A sample WIM installation audit checklist form used by the FHWA LTPP WIM program and the *VDOT Continuous Count Station Installation QA Checklist* are provided in Appendix C.

Additional Documentation

Additionally, the installation contractor must have all pertinent information on hand during the entire WIM system installation, including:

- Approved WIM site selection roadway plan and roadway construction plans
- Approved utility locations
- Approved lane closure permits
- Approved traffic control plans
- Manufacturer’s installation guides
- Contract specifications and standards

WIM System Installation QA Procedure

Installation Quality Assurance Checks

The installation QA checks provided below are based on a compilation of successful industry practices currently being used by vendors and state and federal highway agencies. These checks highlight critical elements of the WIM installation process:

- Installation start date and the time to complete installation work should be established, and any press release information provided to ADOT, in advance of field work.
- A vendor representative should be on site to ensure vendor requirements are met.
- A state representative, experienced with WIM installation, should be on site to ensure ADOT’s requirements are met.
- The QA inspector should confirm that the WIM installation supervisor has all up-to-date and pertinent information, permits, and documentation on hand before work begins.
- The QA inspector and the WIM installation supervisor should review and be familiar with all contract, state, local, and manufacturer installation standards and specifications for specific guidance and installation instructions prior to the start of any construction work.
- Pre-construction meetings should be held before any lane closures.
- All necessary equipment or materials, including WIM system components, should be on site before construction work begins.
- The WIM site selection roadway plan and complete roadway construction plans should be available on site to ensure proper placement of equipment.
- All installations should be performed in accordance with the WIM manufacturer’s specifications and any additional ADOT requirements.

- Due to warranty liabilities, the installation must be carried out by those who have successfully completed a vendor training course and hold a valid vendor certificate authorizing them to install the sensors.
- ADOT's QA inspector should document and photograph all stages of WIM site installation using a WIM installation audit checklist form, as described in the next section.
- ADOT's QA inspector should review the WIM installation audit checklist form with the installation supervisor and make sure that all "punch list" deficiencies are addressed prior to installation completion.
- An accurate set of as-built plans should be developed after installation for future construction and maintenance work.

The following procedures are not meant to supersede any established manufacturer installation specifications. Action items listed below are related to the work performed by the QA inspector.

Part 2.1 Pre-Construction Work

Pre-Construction Meeting. A pre-construction meeting of all personnel involved in the WIM system installation should be held prior to the start of construction. Topics to be discussed should include safety, lane closure time limits, contingency plans, and a detailed discussion of the work to be performed.

Actions:

- ➢ Review all requirements related to the work to be performed at the meeting.

Protection of Utilities. Before the installation of any support equipment such as cabinets, conduit, pull boxes, or electrical service or telephone devices, the QA inspector and the installation supervisor must examine all existing utility markings and verify that the location of existing utilities within the work area has been performed within the past two weeks.

Actions:

- ➢ Examine all existing utility markings within the work area.
- ➢ Verify that the location of existing utilities has been performed within the past two weeks.

Equipment Inspection. Prior to installation, all equipment should be inspected and checked for proper operation by the QA inspector and the WIM installation supervisor.

Actions:

- Inspect and verify that the equipment is new and undamaged.
- Verify that the electrical equipment is UL listed (i.e., has been tested and certified by UL LLC).

Part 2.2 WIM System Installation

Layout and Cutting. To ensure that the WIM sensors and loops are placed properly in the travel lane as shown on the WIM site selection roadway plan and in the manufacturer's installation guide, the QA inspector must perform the following checks.

Actions:

- Compare roadway chalk markings with the installation documents to verify the following:
  - Square lines and markings are correct and match the roadway construction plans to within ¼ inch.
  - The upstream loop leading edge is the proper distance from the downstream loop leading edge.
- Observe to ensure the following:
  - The WIM sensor array layout is squared in each lane. Verify that the sensor array layout is perpendicular to the lane edge marking, which is typically the painted fog line. This could be accomplished using the 3-4-5 method:
    - Mark the pavement with chalk where the painted loop homerun intersects the edge of the lane marking, which is typically the painted fog line.
    - Measure 3 ft along the lane from the first mark and make a second mark with chalk.
    - Measure 4 ft along the loop homerun from the first mark and make a third mark with chalk.
    - Ensure that the diagonal measurement between the second and third chalk markings is 5 ft, which indicates that the painted loop homerun layout line is perpendicular to the edge of the roadway.
  - All other layout lines are measured from the painted loop homerun line to ensure that all sensors in the lane are square.
  - All saw cuts are neat and straight.
  - Saw cuts are at the proper depth, as determined for the type of sensor and pavement, as shown in Table 49. To accomplish this, measure loop slots every two feet and at corners, and measure WIM sensor channels at both ends and in the middle of each perimeter cut.
- During the saw-cutting process, ensure that the saw cuts have been rinsed and dried with water and high-pressure air, and that all residue and moisture is removed for proper epoxy adhesion.
- If any of the above specifications are not met, inform the installation supervisor of the deficiency and ensure that the deficiency is corrected.
- Photograph the entire site layout in-lane, with all markings visible.

Table 49. Recommended Sensor Channel and Homerun Slot Depths

Sensor Type	Piezo-Polymer		Piezo-Quartz		Loop	
Pavement Type	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**
Sensor channel depth	2”	2”	2”	2”	4”	2”
Homerun depth	4”	2”	2”	2”	4”	2”

Excavation and Conduit. The QA inspector must ensure that all conduit used for the WIM installation is buried at the proper depth and that the conduit type and dimension match the WIM site selection roadway plan. The QA inspector must also ensure that the installation crew does not remove any more pavement material than is necessary and that any pavement that is damaged during the installation process is repaired properly. The QA inspector must perform the following checks.

Actions:

- For the excavation and installation of conduit, observe and record on a WIM installation audit checklist form, capturing photographs as necessary, to confirm the following:
  - Only material necessary for the installation is removed
  - Excessive pavement damage is repaired with like material or epoxy
  - All conduit used within the travel lane is galvanized rigid steel (GRS) conduit; sometimes termed rigid metal conduit (RMC)
  - Polyvinyl chloride (PVC) conduit is used only in the travel lane to run loop wires into the sensor recess or over pavement joints
  - Conduit openings are sealed with duct seal
  - Drain conduits in the sensor recess are lower than the electrical conduit openings
  - Exit holes are drilled for the correct size of PVC conduit
  - Proper size of PVC conduit is used between the pull box and the cabinet base
- If any of the above specifications are not met, inform the installation supervisor of the deficiency and ensure that the deficiency is acceptably resolved.

Pole/Cabinet. The QA inspector shall inspect the pole and cabinet equipment to verify that it meets contract specifications.

Actions:

- Inspect the cabinet attributes to ensure they meet contract specifications, which may include:
  - Hinged door with lock and two sets of keys
  - Louvered vent with standard filter
  - Air exhaust through roof overhang with temperature-activated forced-air fan system
  - Switched light
  - Ground fault circuit interrupter (GFCI) duplex outlet and a circuit breaker for AC input
  - Surge suppression

- Ensure that these cabinet placement criteria are met:
  - Is not subject to rain runoff, or standing or moving water
  - Will not be hit by a moving vehicle and is preferably behind a guard rail
  - Is accessible with a clear line of sight to the sensors
  - Is serviceable without technician endangerment
- Record on a WIM installation audit checklist form that each of the items above is acceptable.
- If any of the above specifications are not met, inform the installation supervisor of the deficiency and ensure that the deficiency is acceptably resolved. Do not allow the installation contractor to use unapproved cabinet equipment without approval from ADOT.

Solar Panels. The QA inspector must ensure that the proper solar panels and mounting equipment are installed.

Actions:

- During the installation of the solar panels, verify the following:
  - The panels are facing in the proper direction (8° west of magnetic south).
  - The panels are installed at the proper angle (latitude +15°).
  - All hardware is installed using anti-seize compound.
  - All vegetation that may block the solar panels' sun exposure has been removed.
- Record on a WIM installation audit checklist form that each of the items above is acceptable.
- If any of the above specifications are not met, inform the installation supervisor of the deficiency and ensure that the deficiency is acceptably resolved. Do not allow the installation contractor to use unapproved solar panels or mounting hardware without approval from ADOT.

Pull Boxes. The QA inspector must ensure that properly sized and rated pull boxes are installed at the locations shown on the WIM site selection roadway plan and away from water collection areas.

Actions:

- Verify the following:
  - The lid is flush with adjacent grade or surfaces.
  - Adequate drainage was installed.
  - A grounding rod is installed, if required from the WIM vendor.
- Record on a WIM installation audit checklist form that each of the items above is acceptable.
- If any of the above specifications are not met, inform the installation supervisor of the deficiency and ensure that the deficiency is acceptably resolved. Do not allow the installation contractor to use unapproved pull boxes without approval from ADOT.

Sensor Installation. The most critical element for WIM site installations is ensuring that the in-road sensors are installed in accordance with the manufacturer's specifications. This not only includes the proper placement (spacing, layout, depth, etc.) but also includes the proper mixing and application of the chemicals and binding agents used to install the sensors.

Actions:

- Ensure that the in-road sensors are installed in accordance with the manufacturer's specifications, including the following:
  - Loop home run cuts are 3/8" wide.
  - Loop wires are installed without the use of sharp implements and then secured with backer rod.
  - Loop wires are in the bottom of the slot, wrapped around the loop four times.
  - Loop wires run to the pull box without any splicing and are twisted around each other at least once every 4 inches.
  - Each loop wire pair is clearly labeled before being pulled through the conduit.
  - Loop wires are completely covered with sealant and flush with the pavement, with no voids or dips.
- Videotape the sensor installation to provide visual evidence in case the sensors do not work properly after installation.
- Record on a WIM installation audit checklist form that each of the items above is acceptable.
- If any of the above specifications are not met, inform the installation supervisor of the deficiency and ensure that the deficiency is acceptably resolved. Do not allow the installation contractor to install the WIM sensors incorrectly.

<u>Piezo-Quartz Sensor Installation</u>

The QA inspector should be experienced with the piezo-quartz installation process. Perform the following checks to ensure proper installation of the piezo-quartz WIM sensor.

Actions:

- During the installation of the piezo-quartz WIM sensors, the QA inspector should verify the following:
  - Axle sensor channels are cut 2 inches deep and 3 inches wide.
  - Quartz sensor insulation resistance is pre-checked prior to installation.
  - Only vendor-specified installation grout is used.
  - WIM sensors are installed in accordance with manufacturer specifications.
  - Quartz sensors are ground exactly flush with pavement.
  - All voids in the pavement around the sensors are filled in with epoxy and/or caulk. All high spots in the epoxy are ground flush.
  - All sensor lead-in wires exit the pavement through conduit and all the way to the pull box.
- Record on the WIM installation audit checklist form whether each of the items listed above is in conformance with its condition.

- If any item is not in conformance, the work must be stopped until the non-conformance is addressed with the installation supervisor and properly resolved.

Piezo-Polymer Sensor Installation

The QA inspector should be experienced with the piezo-polymer installation process. Perform the following checks to ensure proper installation of the piezo- polymer WIM sensor.

Actions:

- During the installation of the piezo-polymer WIM sensors, the QA inspector should verify the following:
  - Sensors are not dented or bent.
  - Sensors are pre-tested for proper capacitance and resistance using a multimeter.
  - Sensors are placed in accordance with the WIM site selection roadway plan.
  - Sensor channels are cut ¾ inches wide and no greater than 2 inches deep.
  - Concrete removal from the slots is done with care to ensure proper slot width and depth.
  - Slots are cleaned and dried before sensor placement.
  - Installation brackets are properly attached to the sensor, 6 inches apart.
  - Channel is filled halfway with epoxy, the sensor is then placed carefully into the epoxy to avoid air pockets, and then the rest of the sensor channel is filled.
  - Weights are placed onto the installation brackets to prevent sensor float.
  - Once the epoxy is cured, the brackets are removed and the sensor is ground to within 1/16" of the pavement surface.
  - The sensor is post-tested to ensure proper capacitance and resistance readings.
  - The sensor output signal is tested for proper voltage output.
- Record on the WIM installation audit checklist form that each of the items above is acceptable.
- If any item is not in conformance, the work must be stopped until the non-conformance is addressed with the installation supervisor and properly resolved, including replacement of the sensor, if necessary.

Cabling. During the installation of the sensor cabling from the side of the pavement, through pull boxes, and into the cabinet, the QA inspector must ensure that the cables are pulled carefully to avoid damage to the external protection.

Actions:

- Ensure that the following take place during the cable installation:
  - The cables are pulled carefully to avoid damage to the external protection.
  - All cabling is labeled clearly in each pull box and in the cabinet.
  - Service loops of at least five extra feet of wire are left in each pull box and cabinet for repairs.

- Splices are industrial-quality, watertight, hermetically sealed, and made with bifurcated terminals to prevent shorting.
- Splices, if used, are used in the pull box closest to the sensor.
- Each sensor is tested before final terminations are made.

- Record on the WIM installation audit checklist form that each of the items above is acceptable.
- If any of the above specifications are not met, inform the installation supervisor of the deficiency immediately to ensure that the WIM sensor cables are not damaged during installation. Do not allow the installation contractor to pull on cables that appear to be stuck or difficult to pull. Damaged lead-in cables may require an expensive replacement.

Cabinet Equipment. Once the technician has installed the equipment, wired up the sensors to the terminal strip, and set up the WIM system in accordance with the manufacturer's specifications, the QA inspector must ensure that the system is properly collecting, storing, and transmitting data to the host computer.

Actions:

- See *Operational Testing and Verification* section under Part 4.1 of Section 4 of this Guide for instructions for verifying the proper operation of the WIM system.
- Conduct operational testing to ensure the system is properly collecting, storing, and transmitting data to the host computer.
- Record on the WIM installation audit checklist form that each of the items above is acceptable.
- If any item is not acceptable, the work must be stopped until the unacceptable item is properly addressed with the installation supervisor and properly resolved, including replacement of the WIM controller, in part or whole, if necessary.

Part 2.3 Initial WIM System Calibration

Since the WIM vendor is typically obligated to perform the initial calibration of the system under the installation contract, it is recommended that ADOT consider the Acceptance Test criteria in Section 6.4 of the ASTM E1381-09 specification when developing standard contract language. It is also recommended that the calibration procedure described in Section 3 of this Guide be written into all ADOT WIM system contract specifications.

It is extremely important that the specifications for the initial calibration be followed closely to ensure the WIM system is providing high-quality data from which a proper comparison data set (CDS) can be developed and used for future calibrations.

Part 2.4 WIM Site Acceptance

Once all of the installation and initial calibration procedures have been completed, the QA inspector reviews the QA checks provided on the WIM installation audit checklist form with the installation supervisor to address any remaining “punch list” deficiencies that may still need to be addressed. Once all deficiencies have been addressed, the QA inspector reports the completion of WIM site installation to ADOT. The ADOT WIM program manager will then accept the WIM site installation and verification as complete.

Part 2.5 WIM System Installation Report

After the WIM system installation has been completed, including calibration and acceptance testing, a WIM system installation report should be developed by the QA inspector, detailing all facets of the WIM system installation.

Actions:

- Prepare WIM system installation report using the following outline:
  1. Cover Sheet – site ID, location, dates of installation and report, name of installer, name of QA inspector or person who prepared the report
  2. Executive Summary – general site information, dates of installation, installation acceptance status, any outstanding issues
  3. Description of Installed WIM Equipment – make, model, layout, sensors
  4. General Site Information – truck distribution, truck speeds, heavy truck types, road geometry and condition
  5. Acceptance Testing – electronic, operational
  6. Initial WIM System Calibration Summary
  7. Supporting Documentation:
     a. QA installation checklist – checklist, non-compliance reports, acceptance report
     b. WIM calibration report
     c. WIM inventory form
     d. WIM inspection form
     e. Manufacturer warranty information
     f. As-built sketch
     g. Site photographs

SECTION 3 – WIM SYSTEM CALIBRATION

Purpose

Calibration is the process of evaluating the measured weight and distance values reported by the WIM system against known weights and distances and making necessary adjustments to the WIM system operating parameters to minimize measurement errors. Periodic WIM calibration is performed to ensure that the data accuracy remains consistent and within the performance specification. As a result of the calibration, the mean error in WIM measurements should be as close to zero as possible and the spread of errors within acceptable tolerance limits.

Personnel Requirements

WIM system calibration shall be performed by a qualified WIM technician familiar with the WIM manufacturer's specifications and the requirements and guidelines described in ASTM E1318-09.

WIM System Performance Requirements

The ASTM E1318-09 performance specifications for Type I and Type II WIM Systems are provided in Table 50.

Table 50. Functional Performance Requirements for WIM Systems per ASTM E1318-09

Function	**Tolerance for 95% Compliance**	
	Type I	**Type II**
Wheel Load	25%	N/A
Axle Load	20%	30%
Axle-Group Load	15%	20%
Gross Vehicle Weight	10%	15%
Speed	1 mph (2 km/h)	
Axle-Spacing and Wheelbase	0.5 ft (0.15 m)	

Reference Documentation

Available reference sources for WIM system calibration include:

- WIM manufacturer's operations manual or WIM vendor maintenance guides
- ASTM E1318-09 — Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM 2009)
- LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
- FDOT Calibration Instructions for New and Existing WIM Sites (see Appendix D)
- IRD 2008b Calibration Spreadsheet (see Appendix D)
- TXDOT Calibration Worksheet (see Appendix D)
- ARA WIM Calibration Tool Snapshot (see Appendix D)
- VDOT WIM Calibration Procedures (see Appendix D)

Tools and Equipment

- Manufacturer's operations manual
- Communication equipment for connecting to the WIM system
- Laptop computer
- Multimeter
- Jeweler's screwdriver

- 100-ft measuring tape
- Flashlight
- Tire pressure gauge
- Tire depth gauge
- Cabinet key
- Temperature gauge
- Laser speed gun

Recommended Supporting Forms and Documentation

A WIM calibration form should be used by the WIM technician to record information about the WIM site, static weights, test truck length measurements, data collected for the test truck runs, operational characteristics of the on-site equipment, pavement assessments, existing and new WIM compensation factors, classification study data, and photograph logs.

In addition, a WIM site maintenance and inspection form should be used to record test data from the pre-calibration WIM system electronic and electrical checks.

A WIM calibration summary report template should be used by WIM personnel for all WIM site calibrations for reporting consistency and to keep a historic record of WIM site performance.

If vehicle classification accuracy testing is desired during WIM calibration visits, an ADOT vehicle classification algorithm implemented at the WIM site should be provided to the calibration field crew.

In addition, a semi-automated spreadsheet application is recommended to aid in the calibration process, such as ARA's WIMCal tool. This application should keep track of WIM weight and axle spacing measurements from the test truck runs, compute statistics necessary to determine whether WIM performance parameters have been met, and compute new values for WIM compensation factors if calibration is needed.

Scheduling WIM System Calibration

To maintain consistent WIM accuracy and, therefore, uniform data quality throughout the year, it is important to check WIM system performance periodically and use WIM calibration activities to systematically compensate for the WIM system biases that tend to develop over time. To assist with scheduling, WIM data processing and quality assurance personnel may provide inputs on when a WIM site needs to be calibrated, basing these inputs on a comparative analysis of truck and axle loading statistics developed from the downloaded WIM data samples against statistics based on a CDS collected after the last successful calibration. The performance characteristics of the piezo-quartz and piezo-polymer sensors are different, so the approaches calibrating these systems will vary, as described in the following sections.

Calibration of WIM Systems with Piezo-Quartz Sensors

WIM systems using piezo-quartz sensors should be calibrated every 12 to 18 months. However, the frequency of calibrations may be increased if the system is affected by factors including:

- Recent maintenance or hardware changes
- Demonstrated WIM measurement error dependence on pavement roughness
- Seasonal changes in pavement stiffness that would affect sensors in pavement
- Increases over time in the drift from past calibrations
- Changes in commodities transported by trucks
- Changes in truck classification distribution
- Changes in average truck speed
- Changes by more than 5 percent from benchmarks in key weight statistics (such as Class 9 GVW), in which case the system should be calibrated more frequently

Calibration of WIM Systems with Piezo-Polymer Sensors

The accuracy of weight measurement for WIM systems with piezo-polymer sensors is affected by temperature changes. Therefore, these systems should be calibrated seasonally or should have other means for consistently compensating for the effects of temperature on weight measurement accuracy. If seasonal calibrations cannot be scheduled, the ADOT users of WIM data should understand how weight measurements are affected by daily and seasonal temperature deviations. When seasonal calibrations are not feasible, calibrate every 12 months during a time when the daily temperature is as close to the average annual temperature as possible to avoid introducing an extreme temperature-induced bias.

For most WIM systems with piezo-polymer sensors, an auto-calibration feature is used to maintain weights within a reasonable accuracy. Typically, the auto-calibration feature is set up by using a predetermined class of vehicle, one to three GVW ranges for the type of vehicle selected, and expected front-axle weights for each of the GVW ranges.

Once a set number of samples in a particular range or ranges has passed over the scales, the average front-axle weights for the samples and the set averages for the auto-calibration feature are compared. The system adjusts auto-calibration factors based on the difference between the sample and the auto-calibration values to bring front-axle weight measurements close to the reference values.

For example, the Peek Sabre WIM unit uses an expected front-axle weight for Class 9 vehicles. After a set number (typically 25) of Class 9 trucks passes over the system, the average front-axle weight for the samples is compared with the auto-calibration factor. If the average front-axle weight for the sample set is lower than the current auto-calibration factor, the system automatically changes the current auto-calibration factor. The auto-calibration factor is updated each time the required number of samples is collected.

The main limitation of auto-calibration is that, while it maintains a high accuracy for measuring moderately loaded steering axles (10,000-12,000 lb range), it does not provide a means for assuring accuracy of the heavy single-axle measurements (18,000 lb or more) or weight measurements of heavy axles in axle groups (tandem, tridem quad, etc.). This is because the relationship between the front (steering) axle weight and the weight of the other axles is unique for each site; dynamic forces induced by different axles and axle configurations on the sensor result from differences in truck body type and configuration, pavement roughness or local distresses, and roadway geometry. High accuracy and consistency in steering axle measurements resulting from the auto-calibration feature does not automatically translate into high accuracy of heavy axle measurements or GVW measurements.

Calibration Procedure

The calibration of each type of WIM system consists of three parts: pre-visit, on-site, and post-visit activities. The pre-and post-visit procedures for each type of WIM system are similar. As summarized in the outline below, the on-site procedures (Part 3.2) are similar for both piezo-quartz and piezo-polymer systems, except for Steps 3.2.4 (disable auto-calibration feature) and 3.2.7 (adjusting the compensation factors). Step 3.2.4 applies only to the piezo-polymer WIM systems with an auto-calibration feature. The procedures for calibrating piezo-quartz systems are provided in Step 3.2.7a, and the procedures for calibrating the piezo-polymer WIM systems are provided in Step 3.2.7b.

Calibration Outline

- Part 3.1 – Pre-Visit Activities, including:
    - Step 3.1.1 – Pre-Visit WIM Data Analysis
    - Step 3.1.2 – Pre-Visit Pavement Profile Analysis
    - Step 3.1.3 – Selection of Test Trucks
- Part 3.2 – On-Site Activities, including:
    - Step 3.2.1 – Site Assessment
    - Step 3.2.2 – Measurement of Test Trucks
    - Step 3.2.3 – Verify Communications with Test Truck Driver
    - Step 3.2.4 – Disable auto-calibration feature (piezo-polymer WIM systems only)
    - Step 3.2.5 – Pre-Calibration Test Runs
    - Step 3.2.6 – Test Truck Run Data Analysis to Evaluate WIM Performance
    - Step 3.2.7 – System Calibration, including:
        - Step 3.2.7a – Piezo-Quartz WIM System Calibration
        - Step 3.2.7b – Piezo-Polymer WIM System Calibration (Utilizing Auto-Calibration Feature)
    - Step 3.2.8 – Post-Calibration Test Runs and Evaluation
    - Step 3.2.9 – Speed and Classification Accuracy Validation
- Part 3.3 – Post-Visit Activities, including:
    - Step 3.3.1 – Post-Visit Data Analysis
    - Step 3.3.2 – Comparison Data Set (CDS) Development
    - Step 3.3.3 – Reporting of Results

Part 3.1 Pre-Visit Activities

The activities performed prior to the on-site visit provide the field team the information needed to establish the requirements for the test truck vehicles, including type, weight, and speed.

Step 3.1.1 – Pre-Visit WIM Data Analysis. A pre-visit data analysis provides information on the current operational status of the WIM system and possible deviations of weight and length measurements from the values recorded in the CDS. Information gained from this analysis is also used to select the truck body type and the operational speeds for the calibration test trucks, using the following criteria.

Criteria:

- The range of the test truck speeds should represent a 10 to 20 mph range of typical truck speeds that includes the 85th percentile speed for trucks at the site. Testing at three different speed points is recommended to minimize speed-induced error.
- Test truck body type, suspension, axle spacing, and loads should be representative of the trucks observed at the site.

Actions:

- Prior to the site visit, collect/download a recent data sample (two to four weeks of WIM data) from the WIM system and analyze the data to determine the current site characteristics that will be used to determine the types of trucks, loads, and speeds for the calibration.
- From the pre-visit data analysis, record the following information on the WIM calibration form:
    - Most common heavy truck type for the site (typically FHWA vehicle Class 9) to be used as a test vehicle
    - 85th percentile truck speed and a range of speeds for calibration test truck runs
    - GVW distribution for the prevalent truck type (typically FHWA vehicle Class 9) and target weight of calibration truck
    - Axle spacing for the prevalent truck type
- Compare the traffic characteristics computed from the data collected immediately after the previous validation/calibration (the CDS) with the traffic characteristics based on the recently collected WIM data. Use the results to estimate the extent of calibration needed and to establish the likely range of compensation factors to be applied in the field.
- Record the following information on the WIM calibration form:
    - Changes in the GVW of the most common heavy vehicle type
    - Changes in vehicle class distributions
    - Changes in average truck speeds

Step 3.1.2 – Pre-Visit Pavement Profile Analysis. Analysis of pavement surface profile is used to infer whether pavement condition is likely to have an adverse effect on WIM measurement accuracy.

Criteria:

- When all values are less than the lower WIM smoothness index threshold shown in Table 51 (repeated from Table 48), it is unlikely that pavement conditions will significantly influence sensor output.
- Values between the smoothness index threshold values may or may not influence the accuracy of the sensor output.
- Values above the upper smoothness index threshold may lead to sensor output that would preclude achieving the research-quality loading data.

Table 51. Recommended WIM Smoothness Index Thresholds

Index	Lower Threshold (m/km)	Upper Threshold (m/km)
Long-Range Index (LRI)	0.50	2.1
Short-Range Index (SRI)	0.50	2.1
Peak LRI	0.50	2.1
Peak SRI	0.75	2.9

Actions:

- ➢ If available, analyze the most recent profile data (i.e., IRI data) from the WIM site location.
- ➢ Process profile data using the *LTPP WIM Smoothness Index* software and compare the software outputs with the threshold indices provided in Table 51 to provide an indication of whether or not the pavement roughness may affect the operation of the WIM equipment.
- ➢ Process profile data using ProVal or similar software to identify locations of highest IRI values within the WIM scale approach section (200 ft before WIM scale location) and the WIM scale departure section (100 ft after WIM scale location).
- ➢ Record findings on the WIM Calibration Form.

Step 3.1.3 – Selection of Test Trucks. When calibrating a WIM site, it is very important to accurately represent the population of the dominant heavy trucks (i.e., trucks in vehicle Classes 4 and 6-13) for that particular site. For instance, if the most frequently observed vehicles in the heavy-truck categories are Class 9 and Class 10 trucks, it is vital that a Class 9 and a Class 10 truck be used for the calibration. Additionally, if 40 percent of the trucks at the site are fully loaded Class 9 trucks, and 35 percent are partially loaded Class 9 trucks, both types of loadings must be represented during the calibration. Lastly, if the dominant speed for trucks is 65 mph at a particular site, it is important that the test trucks make several runs at this speed, or as close to this speed as possible without exceeding the speed limit.

Criteria:

- The test truck should represent the heavy truck type (Classes 4 and 6-13 as defined by the 13-bin FHWA vehicle classification scheme) observed most frequently at the site.
- The truck configuration is an important consideration. It should not introduce adverse truck dynamics into the test.
- The load must be evenly distributed along the trailer, firmly secured to prevent sliding or shifting, and covered to prevent the introduction of moisture in rainy weather conditions.
- The suspension must be in good operating condition to ensure the airbags are not leaking and the springs are not cracked or broken.
- The test truck tandem-axle spacing for the primary (heavily loaded) truck must be standard—typically 4.0 ft to 4.4 ft apart for the truck and trailer.
- The tandem spacing for the secondary (partially loaded) truck must be standard for the truck; however, the trailer tandem may be split if it represents a large percentage of the truck population for the site. It is important to note that the split tandem configuration on the trailer may induce different dynamic effects, and its behavior will be different from that observed for a group of axles, thus making the calibration more difficult.

Actions:

- ➢ Determine the type of test truck to be used for the calibration, including classification, weight, and suspension configuration.
- ➢ Determine test truck speeds (based on 85th percentile speed for trucks and speed limit).
- ➢ Whenever possible, use more than one calibration truck to better calibrate to the variety of loading conditions encountered at the site.
- ➢ Locate the certified static weight scale closest to the WIM site. This scale is used to measure the true static weight of test truck(s) before calibration.

Part 3.2 On-Site Activities

The on-site activities include verifying the WIM system operation, measuring and evaluating the weight and distance measurement accuracies of the WIM system, and calibrating the site based on test truck(s) runs.

Step 3.2.1 – Site Assessment. The site assessment helps determine the possible effect of pavement, equipment, and site conditions on the accuracy of WIM weight and distance measurements.

Actions:

Pavement Inspection

- Conduct a visual pavement distress survey from the shoulder to identify surface anomalies that may affect truck motions across the sensors.
- Identify such items as potholes, patches, rutting, and asphalt-concrete transitions. In addition, use the information from the most recent pavement profile data to determine specific locations that may need to be more closely examined during the on-site calibration activities.
- Record on the WIM calibration form and photograph any pavement distresses that may affect the accuracy of the WIM scale measurements.

Vehicle-Pavement Interaction

- Observe several trucks while they pass over the site to determine whether truck traffic is showing adverse characteristics such as bouncing, swerving, braking, or accelerating within 200 feet of the sensors.
- If feasible, determine whether the truck tires are in full contact with the sensors.
- Document observed truck dynamics on the WIM calibration form, noting any adverse movements observed within the WIM scale approach and departure roadway segment. This information may help explain issues with measurement accuracy of the WIM system. Include location from the WIM scale area.

Equipment Inspection

- Perform a visual inspection and static electrical and electronic tests of all WIM site support components.
- Identify and record deficiencies involving the equipment that will require repair.
- If any discrepancies or deficiencies exist that will affect the measurement accuracies and that cannot be remedied on-site, postpone the calibration.
- Identify all items whose present or deteriorating condition will eventually adversely affect the operation and/or accuracy of the WIM equipment.
- Turn off the system's auto-calibration routine, if present, during calibration.
- Document findings on the preventive maintenance form.

Step 3.2.2 – Measurement of Test Trucks. This activity involves the use of certified static scales. Certified scales should have been tested by the relevant agency within the past three years. Axle-weight scales are preferred to platform scales.

Actions:

- ➢ Use certified scales to obtain static weights, axle spacings, and overall lengths of test trucks. Measure each calibration truck twice at a certified truck scale. Measure a third time if any of the measured weights (axle, group, or GVW) differ by more than 2 percent.
- ➢ Inspect the truck tires and suspension for defects.
- ➢ Record all measurements on the WIM calibration form.

Step 3.2.3 – Verify Communications with Test Truck Driver. Effective communications with the test truck driver will help ensure proper test truck movements across the WIM sensors.

Criteria:

- The test truck must not accelerate or decelerate in the WIM approach and departure areas.
- The test truck must travel down the center of the travel lane.

Actions:

- ➢ Review the calibration procedures with the truck driver, including proper speeds and turnarounds. Review safety procedures.
- ➢ Establish communications with the test truck driver.
- ➢ Instruct the driver to make at least 10 runs over the WIM scales at three different speeds.

Step 3.2.4 – Disable Auto-Calibration Feature (applies to systems with piezo-polymer sensors only). For WIM Systems using the auto-calibration feature, ensure that it is disabled for each lane prior to making test truck runs. For these systems, perform Steps 3.2.5 and 3.2.6, and then go to Step 3.2.7a.

Step 3.2.5 – Pre-Calibration Test Runs. Pre-calibration test runs are conducted to quantify any potential system bias and overall measurement errors. They consist of 10 or more test truck runs over the range of speeds determined during the pre-visit analysis. After initial pre-calibration test truck runs, the system should be calibrated to minimize bias, and then the same number of post-calibration test truck runs should be performed to validate the system and quantify measurement data accuracy.

Criteria:

- The test truck runs must be conducted at the widest possible ranges of speeds and temperatures observed at the site.
- A sufficient number of pre-calibration runs should be performed to quantify WIM measurement error percent: at least 10 test runs per truck, per lane.

Pavement Temperature Consideration

If the WIM system shows a measurement accuracy dependence on temperature, it is important to collect test truck data over the greatest possible range of temperatures to minimize temperature-induced measurement bias. Although it is anticipated that all of the pre- or post-calibration test truck data will be collected in one day, weather conditions may necessitate collection of the test truck data over the course of two days. The best way to complete testing is to begin early in the afternoon on the first day, and then to resume as early as possible on the second day.

Criteria:

- A 30° F minimum pavement temperature range is the target for calibrating WIM performance under varying pavement temperatures.
- For WIM systems utilizing the auto-calibration feature, the temperature range requirement does not apply unless the temperatures measured during calibration will be used to adjust the WIM system's temperature compensation feature.

Actions:

- ➢ For each pass of the test truck, take a pavement surface temperature reading at a location near, but not on, the WIM sensor and record it on the WIM calibration form.

It is recommended that, for WIM sites that use the piezo-polymer sensor for weight measurement, and for any other WIM sites that demonstrate measurement error dependence on temperature, a review of prior calibration be performed to assist in determining the proper calibration of the WIM system based on seasonal temperatures. Data collected over seasons can be used eventually to fine-tune the WIM systems temperature compensation curve, a procedure typically performed by the WIM manufacturer.

Test Truck Runs

The number of test truck runs depends on the data variability observed at a given WIM site. Sites with consistent measurements (i.e., low error variability) require fewer test runs than sites with high error variability to collect a representative sample. Use the following criteria to determine the required numbers of test truck runs.

Criteria:

- At least four test truck runs at each of the three WIM system speed points (12 test runs) for WIM systems utilizing speed-based compensation factors (FHWA 2012 [LTPP]).
- At least 10 runs for sites that have a GVW error range (percent error between static and WIM-measured GVW) of 5 percent or less after 10 truck runs (FDOT, NMDOT, VDOT, PennDOT).
- At least 20 test runs for sites that have a GVW error range over 5 percent after 10 truck runs or that demonstrate measurement error dependence on pavement temperature.

In addition, if the WIM system demonstrates measurement error dependency on pavement temperature, perform test truck runs over a 30-degree temperature range or the widest temperature range possible (FHWA 2012 [LTPP]).

Data Collection and Recording

Actions:

- For each pass of a test truck, obtain the WIM system's output for axle weights and axle spacing.
- When the test truck is crossing the sensor, use a laser or radar gun to obtain the truck's speed for comparison with the WIM system's output.
- After each test truck passage over the sensors, use a hand-held laser temperature device positioned approximately 30 inches from the pavement surface to collect pavement surface temperature.
- Record the following data from the WIM system for each test truck pass on the WIM calibration form:
    - The sequence number of the test run
    - The date of the test run
    - The time of the test run
    - Axle weights of the test trucks as they pass over the scale
    - Spacing between each axle on the test truck
    - Speed of the test truck
    - Pavement temperature at the time of each test run

Step 3.2.6 – Test Truck Run Data Analysis to Evaluate WIM Performance. Once the data have been collected in the field, the WIM system performance parameters can be evaluated using one of the two methods described below. The LTPP method is based on statistical analysis and typically requires larger samples to draw sound conclusions. This method is preferred when data quality is of utmost importance. The ASTM E1318-09 method is simpler to implement but may result in false positive and false negative outcomes when small samples (i.e., fewer than 20 test truck runs) are used.

Actions:

- Compute measurement error statistics to determine whether the WIM site meets the required accuracy parameters stated in the WIM performance specification, which is typically the ASTM E1318-09 specification.

LTPP Method

The basic statistic required for this test is the error expressed as a percentage error of the known value (known value is the static weight of the test truck or the static weight/load of the test truck axles). The percentage of error is calculated from the data collected for each run and then used to compute a series of summary statistics. These summary statistics are used to infer whether the scale produces data of acceptable data quality. To calculate the summary statistics, use the following procedure.

Actions:

- Using a sample of test truck runs, compare weights reported by the WIM system with the known static weights for each test truck run.
- Compute percentage errors between the known static weights and the WIM weight measurements and determine the mean error, standard deviation (use a t-distribution for sample sizes smaller than 38) and the statistical confidence interval (that represents the range of errors for a 95 percent confidence level).
- Combine the mean error and confidence interval values (mean error ±2 standard deviations of error) to compute the overall error.
- Compare the resulting overall error range with the tolerance levels specified in ASTM E1318-09 for Type I or Type II systems (select appropriate values from Table 50 in Section 3 based on the type of installed WIM system) to check whether the WIM system is producing weight measurements within specified tolerances.
- If the overall error is within the tolerance levels specified in ASTM E1318-09 for a given WIM system type and the mean error (i.e., system bias) is close to zero (i.e., less than 2 percent) for GVW, axle groups, and front-axle weight measurements, then the system does not require calibration. Otherwise, calibration is required.
- Note on the WIM calibration form:
    - The WIM system measurement bias (i.e., the mean error between static weights and WIM weight measurements)
    - The computed overall errors for GVW, axle groups, and front axle for each of the test truck speed groups
    - Conclusion on whether the WIM system requires calibration

ASTM E1318-09 Method

The test method for determining compliance with these requirements under prevailing site conditions includes the following actions.

Actions:

- For each test vehicle pass, calculate the percent difference in the WIM-system value and the corresponding reference value (i.e., static measurement) for each parameter listed in Table 50 in Section 3 (select appropriate values from Table 50 based on the type of installed WIM system [Type I or Type II]).
- Using all passes of the test vehicles over the sensors, determine the number of test truck runs with calculated differences that exceeded the tolerance value shown in Table 50 for each data item and express this number as a percent of the total number of observed values of this item

(i.e., percent of all test measurements [percent of test truck runs] for a given data item [like GVW] that exceed the tolerance).

- If more than 5 percent of the calculated differences for any applicable data item from Table 50 exceed the specified tolerance for that item, declare the WIM system failed.
- If the mean error for each measurement (like GVW mean error) calculated from all test passes significantly deviates from zero (user-specified value, 2 percent or less is recommended), then the WIM system may be considered to have a systematic bias, and the calibration should be repeated. If mean errors continue to stay above the user-specified value after three successive calibration attempts, the system or WIM sensors are malfunctioning and require corrective maintenance.
- Document findings on the WIM calibration form.

Step 3.2.7 – System Calibration. The purpose of WIM calibration is to reduce the WIM system's measurement error dependence on speed, temperature, or, in the case where multiple test trucks are used, truck type. The primary focus of calibration should be on reducing the measurement error for free-flow truck traffic observed at the site. To accomplish this, the test truck runs are conducted over a range of speeds typically observed at the site (a minimum of three test speeds are recommended for calibration), as well as over the widest range of temperature conditions observed on the day of calibration (for WIM systems with temperature-dependent sensors). The dependence of WIM error on temperatures beyond those observed during calibration typically cannot be addressed during a routine calibration, as this requires access to the temperature compensation algorithm embedded in the WIM system's firmware, which is not usually available to the WIM operator without manufacturer assistance or specialized training. Also, unless multiple test trucks are used, the WIM system's accuracy as a function of truck type cannot be effectively improved. Because WIM systems with piezo-quartz sensors typically do not exhibit error dependency on temperature, and systems with piezo-polymer sensors do, the following two steps describe different calibration procedures that apply to WIM systems with these sensors.

Step 3.2.7a – Piezo-Quartz WIM System Calibration (no auto calibration feature is used)

Actions:

- Based on the WIM system measurement error calculated during pre-calibration runs, calculate the adjustments to the current WIM system weight and distance error compensation factors using the formulas provided in the manufacturer's user manual.
- Record all changes to the WIM system compensation factors on the WIM calibration form.
- Enter the new compensation factors into the WIM system firmware.

Step 3.2.7b – Piezo-Polymer WIM System Calibration (systems using an auto-calibration feature)

Many WIM systems with piezo-polymer sensors utilize an auto-calibration feature. Auto-calibration typically uses pre-set front-axle weight values to compare with the average values from a sample of vehicles of a predetermined truck class (typically Class 9 trucks) collected from the traffic stream observed at the site. These values are used to compute weight measurement errors for the front axles and to regularly adjust the WIM auto-calibration factor to minimize these errors. The pre-visit procedures described above provide an estimate of whether the current setting is producing higher or lower than expected GVW values.

Unfortunately, the relationship between the front-axle weights and GVW for a particular site is difficult to define. The percent error for GVW and front-axle weights for trucks may differ by as much as 20 percent. For piezo-polymer WIM systems, this would mean that an auto-calibration feature that uses a front-axle weight factor between 10,000 and 11,000 pounds may demonstrate GVW values that are 20 percent heavier or lighter than the static weight. For these systems, it is vital to understand and apply the site-specific relationship between the front-axle weight and GVW and to set the auto-calibration feature for the front axle in such a way that it will provide more accurate GVW and heavy-axle-group weights, which are much more critical than front-axle weights for most WIM data users.

To properly adjust the auto-calibration compensation and front-axle auto-calibration factors, complete the following actions.

Actions:

- Based on the difference between the GVW and front axle WIM system measurement error calculated during pre-calibration runs, calculate adjustments to the current WIM system auto-calibration and distance error compensation factors using the formulas provided in the manufacturer's user manual.
- Enter the new compensation factors into the WIM system firmware.
- Apply the difference measured in the first step to adjust the WIM system's auto-calibration front-axle factor(s). For example, if GVW is being measured with a negative bias of 5 percent, and the front axle is being measured with a positive bias of 5 percent, the auto-calibration factor must be reduced by 10 percent to align the measurement bias for the two parameters, and then the compensation factor must be raised by 5 percent to account for the GVW bias.
- Record all changes to the WIM system compensation factors on the WIM calibration form.

Step 3.2.8 – Post-Calibration Test Runs and Evaluation. The number of post-calibration test truck runs may be reduced to 10 if all of the following apply, otherwise perform 20 post-calibration test truck runs:

1. The WIM measurement accuracy does not show temperature dependency.
2. Weather conditions observed during testing include a wide range of temperature changes.

3. The data from the test runs demonstrate that the speed dependence at each speed point has been eliminated or minimized (less than 2 percent average error for each speed point).
4. The overall system bias computed based on the data from the available test runs is as close to zero as possible (i.e., less than 2 percent error for the mean error).
5. None of the individual runs is outside the ASTM E1318-09 tolerance range for 95 percent conformance, or the 95 percent confidence range computed based on the test data is within the acceptable LTPP WIM performance tolerances.

Actions:

- ➢ Repeat Steps 3.2.5 through 3.2.7 until the WIM system performance parameters meet the tolerances specified in Table 50 of Section 3. The calibration protocol may be repeated up to three times if needed.
- ➢ After a set of satisfactory compensation factors has been established and WIM system performance has been verified, record the final values of each WIM system performance parameter listed in Table 50, and final changes to the WIM system compensation factors, on the WIM calibration form.
- ➢ Ensure that the final compensation factors have been stored in the WIM system firmware.
- ➢ For WIM systems utilizing the auto-calibration feature, re-enable auto-calibration for each lane.

Step 3.2.9 – Speed and Classification Accuracy Validation. To determine whether the equipment is classifying vehicles correctly at the site, use a sample of vehicles to compare the classifications based on the visual observations to the classification based on WIM system output. This sample should include a minimum of 100 heavy vehicles (FHWA Classes 4, 6–13), unless such a sample would require more than three hours of collection effort (use a three-hour collection period if there will be fewer than 100 heavy vehicles).

Criteria:

- The number of classification errors in vehicle Classes 4, 6 and higher should be less than 2 percent of the truck volume for the same set of vehicles.
- The percentage of “unclassified” vehicles should also be no greater than 2 percent.

Actions:

- ➢ Conduct a comparison of observed classifications for a sample of 100 heavy vehicles (FHWA Classes 4, 6–13) with the classifications provided by the WIM system.
- ➢ Record the percentage of error for heavy trucks (in Classes 4, 6–13) and for all trucks (Classes 4–13) and record the percentage of unclassified vehicles in these classes, if any.
- ➢ Document findings on the WIM calibration form.

Part 3.3 Post-Visit Activities

The post-visit activities include a comparison of the WIM data samples from just prior to and immediately following the calibration. It is conducted to evaluate the effectiveness of the calibration. The post-calibration sample will be used to develop CDS benchmark values for future data evaluation.

Step 3.3.1 – Post-Visit Data Analysis. This analysis is used to evaluate and confirm the effectiveness of the calibration. For this analysis, a traffic data sample, consisting of weight and distance measurements over 14 days (30 days for low truck-volume roads) immediately following the calibration, is collected. This sample is used to compute truck weight and length statistics that are compared with the CDS values from the previous calibration and the pre-visit data sample.

Actions:

- Download a data sample for the period of two to four weeks immediately after the calibration visit.
- Compute and compare the following parameters among the CDS from the previous calibration, the pre-visit data sample, and the post-visit data sample.
    - Class 9 average GVW and GVW distribution by load bins
    - Class 9 average front-axle weight and front-axle weight distribution by load bins
    - Class 9 tractor average tandem-axle spacing
- Based on a comparison of pre- and post-visit computed parameters with CDS values, note whether the differences from the previous CDS observed in the pre-visit data set have been resolved or reduced based on post-visit data set values.
- Determine whether the calibration had the desired effect on the data values by comparing the change in the computed parameters with the changes made to the WIM system calibration factors.
- Document findings in a WIM calibration summary report.

Step 3.3.2 – Comparison Data Set Development. The CDS is used as a basis for evaluation of WIM data quality. It should be computed based on the data sample of weight and distance measurements collected over 14 days (30 days for low truck-volume roads) immediately after each calibration. The old CDS should be replaced with the new CDS after each calibration. The data sample used for computation of CDS values represents the most accurate WIM data collected at the site. The CDS should be compared with the current WIM data periodically (bi-weekly or once a month) and prior to scheduling calibration visits. Changes in average weight and/or length measurement values or shifts in the weight distributions over 5 percent may be used as triggers for calibration.

Actions:

- Use the two- to four-week WIM data sample collected immediately after the successful calibration to develop statistics for the CDS:
  - Average Class 9 GVW
  - Average Class 9 front-axle weight
  - Average Class 9 tractor tandem spacing
  - Class 9 GVW distribution
  - Class 9 front-axle weight distribution
  - 85th percentile speed for heavy trucks
  - Vehicle class distribution (FHWA Classes 4–13)

Step 3.3.3 – Reporting of Results. Prepare the WIM calibration summary report no more than two weeks after Step 3.3.2 and include the following information:

- Test date
- Equipment status
- Pavement condition and temperature during testing
- Calibration truck characteristics
- WIM system weight and distance measurement accuracy before and after calibration, including mean error, two standard deviations, and overall error range (mean error ±2 standard deviations) for 95 percent confidence level
- Calibrate/do not calibrate decision and reasoning
- Changes made to WIM system parameters
- Pre-visit and post-visit data analyses and findings
- Required corrective actions and recommendations
- Vehicle classification evaluation, if conducted
- Supplemental documentation including photographs

SECTION 4 – WIM EQUIPMENT MAINTENANCE

Purpose

To maximize the life of the WIM system, a comprehensive maintenance program must be put into practice. It is important to perform routine preventive maintenance every six to 12 months and to develop a schedule and event procedure to facilitate timely operational checks and repairs of system failures. This section includes a scope of recommended maintenance activities, recommended schedules, description of field checks, and recommendations for field logs, acceptance testing, and maintenance reports.

Personnel Requirements

WIM maintenance must be performed by trained, experienced WIM technicians. Most WIM vendors provide on-site certification programs for agency personnel. Alternatively, the maintenance function could be outsourced. Most WIM vendors provide maintenance schedules and procedures for maintaining and repairing their WIM systems in user maintenance and operation guides.

Reference Documentation

Valuable information for conducting preventive and corrective maintenance is available in FHWA's *Traffic Detector Handbook* and *WIM Field Inspectors' Troubleshooting Guide* (Klein et al. 2006, Quinley 2009). Additional available resources include:

- WIM manufacturer's operation and maintenance guides
- LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
- PennDOT WIM Maintenance Contract Statement of Work (see Appendix E)

Materials, Tools, and Equipment

An effective WIM maintenance program must provide the proper tools, materials, and spare parts to enable performance of regular preventive maintenance and quick resolution of system problems without significant down time and lost data. Manufacturers' maintenance guides typically contain a list of required spare service parts, tools, and equipment necessary to properly maintain the vendors' WIM systems.

Recommended materials include:

- Clipboard
- Shop rags or clothes
- Cleaning solvent
- Pens and pencils
- Electrical tape
- Splice kits
- First aid kit

Recommended hand tools include:

- Digital camera
- Screwdriver set – slotted and Phillips
- Jewelers' screwdrivers – slotted and Phillips
- Small-socket driver set
- Pliers – long-nose, round-nose, and curved (both smooth and serrated types are useful)
- Adjustable wrench, small
- Cutters – diagonal and flush
- Lineman's pliers

- Wire strippers – fixed and adjustable
- Wet/dry vacuum cleaner
- Crimp tool
- GPS receiver
- Power inverter
- Tape measure
- Measuring wheel
- Small shovel
- Pry bar

Recommended testing equipment products include:

- Digital multimeter with well insulated test probes
- Megger (loop insulation tester)
- Oscilloscope – dual-trace, 10 to 20 MHz minimum vertical bandwidth and 10x/1x probes
- Logic probe—for quick activity checks of digital circuitry
- Kistler® Sensor Test Kit, including insulation tester (for piezo-quartz WIM sensors only)

Recommended computer software products include:

- WIM System connectivity and data download software
- Modem setup script files and/or setup guide

Recommended Supporting Forms and Documentation

The following forms and documentation should be used by the WIM maintenance team:

- WIM site as-built plans showing locations of WIM components
- WIM system manufacturer's service manual
- WIM site maintenance and inspection form—to record preventive or corrective maintenance activities and repairs or replacements performed at the site and the results of WIM system operational tests performed before and after maintenance activities.
- WIM system troubleshooting form—to record investigative activities performed at the site to identify problems with the equipment, including steps taken to identify and resolve system problems.
- WIM site maintenance log—to keep a historical record of site visits and work completed; to be kept in the WIM cabinet.
- Examples of these forms and logs are provided in Appendix E. In addition, the WIM program manager or the WIM maintenance supervisor should implement a WIM site maintenance management tool, in the form of a spreadsheet or a maintenance management software application, to keep track of scheduled and completed WIM site maintenance visits, along with a brief summary of work performed during each visit.

Safety

When working on site, several safety procedures must be followed.

Actions:

- Park any vehicles off the road in a safe area away from traffic.
- Equip all vehicles with a safety strobe.
- Always wear a reflective safety vest, hard hat, steel-toed shoes, and weather-appropriate clothing.
- Always use a traffic spotter when working near the roadway.
- Carry adequate amounts of drinking water.

Procedure

Part 4.1 Scheduled Preventive Maintenance

Preventive maintenance is performed to prevent future equipment and site problems. During each preventive maintenance visit, all in-road sensors should be checked for proper electronic values. The entire WIM system should be visually inspected, including the pull boxes, in-road sensors, telephone and power service equipment, and the roadway leading up to and within the WIM scale area. All deficiencies should be recorded and reported for correction. Each item to be checked is described in detail in the following sections.

Pavement Inspection. A visual inspection of the pavement in the WIM scale approach/departure roadway segment will provide an indication of whether the pavement condition may be contributing to any inaccuracies of the WIM system. Any pavement distresses that appear to influence truck dynamics at or near the WIM scale approach/departure roadway segment must be documented on the WIM site maintenance and inspection form.

Actions:

- From the shoulder, walk from the WIM sensor installation to a distance 200 ft ahead of the WIM sensors and 100 ft past the WIM sensors.
- Photograph and record any distresses that may influence truck dynamics, including bumps, severe level cracking, potholes, rutting, pavement transitions, and dips.

Visual Equipment Inspection. As part of preventive maintenance, a visual inspection of all the WIM system components is important. It is recommended that a lane closure be set up so that a close inspection of the roadway and the in-road sensors can be performed.

Actions:

- Carefully inspect each WIM system component and record any deficiencies on a WIM site maintenance and inspection form.

- Check around WIM sensors for cracks and broken pavement.
- Check the cabinet interior for broken components, such as thermostats, lights, shelving, heaters, terminal panels, battery, and modem.
- Remove the covers to each pull box and inspect the interior. Inspect the exterior for cracks and ensure that all hardware is in place.
- Inspect service pole, pedestal, and foundation for cracks and make sure that the pole is plumb.
- Visually inspect power service equipment for structural deficiencies. Do not touch broken wires and do not open any live service boxes.
- Inspect telephone and cellular service equipment for damage, cut or damaged wires, or broken antennas.
- Check exposed conduit for extensive rust, breaks, or cracks.
- Record all readings and inspection details on the WIM site maintenance and inspection form.

Equipment Cleaning. The interior and exterior of all WIM components should be cleaned.

Actions:

- Remove dust and debris with a heavy-duty wet/dry vacuum cleaner.
- Wipe down components with cleaning solvents, avoiding directly spraying components with solvent by instead spraying the rag or cloth away from the equipment.
- Clear out clogged drainage pipes.
- Perform vegetation control around the cabinet, pull boxes, and solar panels.
- Replace the cabinet filter.

Electronic and Electrical Checks. As part of the preventive maintenance process, perform electronic and electrical checks of all WIM system components to confirm that each is operating within the manufacturer's tolerances.

Actions:

- Check the following components:
  - WIM sensors — capacitance, insulation leakage, and output amplitude
  - Loop sensors — resistance, insulation leakage, and inductance
  - Electric power connections
  - Telephone service
  - System grounding capability
- If any equipment gives a reading that appears to be outside the specified tolerances, double-check the readings against the manufacturer's maintenance manuals and begin troubleshooting the system, if necessary, to determine the cause.
- Record all readings on the WIM site maintenance and inspection form.

Firmware Upgrades. Once the electronic values for the WIM sensors and support equipment have been verified as correct, perform any scheduled software upgrades.

Actions:

- Follow the instructions provided in the manufacturer's operations guide to protect the equipment from damaging electronic surges or improper installation of the firmware.
- After installing the latest firmware, re-enter all default values and system parameters to ensure proper operation.
- Verify that each of the following system settings is correct:
  - Date/time
  - Site information
  - Weight compensation factors
  - Axle and loop spacings
  - Loop sensitivities
  - Lane configurations, sensor assignments, and sensor spacings
  - Violation settings
  - Communication settings
  - Data logging information
  - Password information
  - Auto-calibration settings
- Record that the firmware was replaced and note the current version on the WIM site maintenance and inspection form.

Operational Testing and Verification. After local, direct communications with the WIM system user interface have been established, run a series of operational checks to verify the proper operation of the WIM equipment, including the following checks.

Actions:

- Vehicle capture and reporting check: Verify the proper operation of the WIM sensors and inductive loops by observing the individual vehicle reports provided by the WIM system after vehicles pass over the WIM scale. Determine that the speed, distance measurement, and vehicle weight is reasonable and that each axle is reported. Verify using several different types of vehicles, including passenger cars, buses, delivery trucks, and semi-tractor trailers.
- Classification check: Observe several vehicles as they pass over the WIM scales and verify that they are being classified properly according to the classification algorithm that is installed in the WIM system.
- Weight check: Record the front-axle weight over a sample of at least 50 Class 9 trucks. The average front-axle weight for the Class 9 trucks is typically between 10,000 and 11,000 pounds. If the front-axle weight average is less than 9,000 pounds or greater than 12,000 pounds, a calibration of the system may be necessary.
- Record findings on the WIM site maintenance and inspection form.

Communications Checks. As part of the preventive maintenance routine, a communications check is important to prevent a return trip to the site.

Actions:

- Prior to leaving the site, and after all other preventive maintenance activities have been performed, contact office personnel by phone and request that they remotely connect to the WIM site using the appropriate communication application to verify that the WIM system is communicating with the host computer.
- Record findings on the WIM site maintenance and inspection form.
- Complete a WIM site maintenance log and leave it in the cabinet.

Part 4.2 Scheduled Corrective WIM Maintenance

Corrective maintenance is performed after a problem is detected with the system or when a scheduled part replacement or upgrade is due. Corrective maintenance could include changes to system parameters, adjustment to sensor operating parameters, firmware upgrades, calibration, or replacement of parts.

Many factors must be considered when determining the corrective action: cost, potential loss of data, availability of replacement parts, and degree of difficulty of the repair. The repair must be cost-effective, i.e., a component should be replaced if the cost of repair is nearly the same as the replacement. Many circuit board components are not readily available for replacement. The technician should have replacement parts on hand for high-failure items.

Actions:

- After all repairs have been completed, perform preventive maintenance to ensure that the whole system is fully operational.
- Clearly mark all replaced parts as “bad” so that they are not re-used.
- Complete a WIM site maintenance and inspection form.
- Complete a WIM site maintenance log and leave it in the cabinet.

Part 4.3 Unscheduled Corrective WIM Maintenance and Troubleshooting

Unscheduled maintenance is performed after a problem is detected in the system that prompts a visit to the site. If the source of the problem is unknown, routine preventive maintenance according to the procedure described in Part 4.1 should be performed to attempt to identify the problem’s source. Once the problem has been found, it must be investigated to identify a solution. Solutions may involve changes to system parameters, adjustment to sensor operating parameters, firmware upgrades, system calibration, or replacement of parts.

The goal of system troubleshooting is to identify, investigate, and resolve equipment deficiencies to ensure successful WIM system operation throughout its design life. This section provides a general guide for troubleshooting and repairing affected systems and components. It includes an overview of the information presented in FHWA's *WIM Field Inspectors' Troubleshooting Guide* and *Traffic Detector Handbook*, and includes:

- Basic troubleshooting tips
- Specific troubleshooting, repair, and replacement procedures related to each system component
- Electronic and electrical safety

In addition, the *LTPP WIM System Troubleshooting Outline—Traffic Sheet 23 of LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])*—is a valuable tool that guides users through a systematic troubleshooting routine.

Read this section in its entirety before beginning work. Information from one section may directly assist efforts in another. Refer to manufacturers' guides for specific troubleshooting techniques and procedures related to WIM system components, including common problems and associated solutions.

Troubleshooting Tips. The first requirement in troubleshooting is developing a logical, methodical procedure of narrowing down the cause of the problem. It is important to recognize the fault correctly, find the cause, determine the proper corrective measure, and repair or replace the faulty system component(s). Additionally, it is important to consider the following:

- Always begin the troubleshooting process by checking WIM system settings.
- Many WIM system vehicle capture problems are created by incorrectly set loop frequencies.
- Intermittent problems are typically due to bad connections and can be fixed by removing, inspecting, and replacing connectors or circuit boards.
- Problems that result in a completely non-functional system or affect a number of different functions or components are usually related to power. Oftentimes, just turning the system off and back on will fix the problem.
- If a power problem is suspected, use sight and smell to search for evidence of burnt components.

Whenever working on the system, a WIM system troubleshooting form, similar to the *LTPP WIM System Troubleshooting Outline—Traffic Sheet 23 of LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])*—is useful for tracking troubleshooting steps and taking detailed notes. Completing the form will assist technicians in remembering what they have already checked. It also provides a visual way of investigating and fixing the problem rather than trying to remember what has already been found and what remedies have already been tried. The following steps describe the troubleshooting process.

Step 4.3.1 – Problem Description. The identification of WIM system problems typically begins with an inability to communicate with the system or download system data. Other signs of a troubled WIM system are questionable or incorrect data. In either case, it is important to obtain very specific and detailed problem descriptions and symptoms.

System malfunction may also be detected during any regular maintenance routine, such as periodic preventive maintenance, system upgrade, or equipment replacement or repair. Again, it is very important to write down exactly what the problem is and the problem's characteristics.

Before proceeding further, refer to the troubleshooting section in the manufacturer's maintenance or operational manual, if available, to see if the reported problem is listed. If it is not, or the recommended corrective action is not successful, proceed with Step 4.3.2.

Step 4.3.2 - System Data Collection. The first step in properly diagnosing a system malfunction is to accumulate all system operating information, including system data and current operating parameters.

Actions:

- Prior to visiting the site, check to see whether a remote connection with the site is possible.
- If connection is possible, call the site and record all operator interface-mode information prior to traveling to the site.
- While connected to the site, use a WIM system troubleshooting form to record all system characteristics, including:
    - Weight compensation factors
    - Lane configurations, sensor assignment, and sensor spacing
    - Violation settings
    - Communication settings
    - Data logging information
    - Real-time view (collect several samples of as many types of vehicles as possible)
    - Vehicle classification and speed data from the past hour
    - Time and date
    - Password information
    - Self-calibration settings
- Download data from the day before or within the time frame in question. Compare data values with the CDS values. This process may narrow down the problem to a particular function, such as weight measurement or distance and speed measurement.
- Use the WIM system menu to enter the equipment diagnostic mode.
- Record all system sensor values available in the system diagnostics mode. Compare current system settings with historical records.
- Double-check all measurements that appear incorrect or out of tolerance.
    - If any system parameters are found to be incorrect, fix the problem by simply inputting the correct parameter. If the number is off by a small amount, or if the number appears to have been typed incorrectly, it is likely that the problem is user-related. Type the number in as it should be, and restore the system firmware parameters according to the manufacturer's instructions.
    - If a number is drastically incorrect, the problem was probably created by a system "glitch," and if one exists, many may exist. The best way to fix these numbers is to perform a hard

reset of the system that will reset all system operational parameters to their default settings. Download all the data files from memory. Follow the manufacturer's instructions for performing a system reset and restoring the default parameters.

- After reviewing the site operating parameters, site data, and sensor analog values, add any additional information to the "Problem Description" portion of the WIM system troubleshooting form.
- A site visit is required if contacting the site remotely is not possible, the system data already collected indicate the problem, or the problem discovered through system data cannot be fixed remotely.

Step 4.3.3 – Finding the Source of the Problem. During this step, use the information gathered from the previous steps to determine the probable faulty function. Consider during this process that multiple problems are rare, and that all symptoms should be considered the result of one problem.

Actions:

- Using the information gathered in Parts 4.1 through 4.3.2, determine the probable faulty function. Any WIM system has five separate primary functions:
    - Power – Most power problems are the result of dead battery, blown fuse, or tripped circuit breaker. Investigate these possibilities first.
    - Classification and Weight (including speed and spacing) – Problems related to the measurement of vehicle characteristics are usually caused by improper system settings. Verify that all settings are correct before further troubleshooting. The second most common problem associated with misclassification of vehicles is the loop frequency and sensitivity settings. Verify that all loop frequencies and sensitivities have been set in accordance with the manufacturer's setup routine. If the problem persists, refer to the Weight and Classification troubleshooting section of this Guide for assistance.
    - Communications – Communication problems are usually caused by disrupted cellular or landline service, corrupt modem settings, or power problems with the modem.
    - Data Storage – The inability of the WIM system to store collected data is typically associated with an improper system setting or corrupt system memory.
    - Data Download and Processing – The failure of the WIM system to properly download data is typically a result of a communication error. Investigate deficiencies associated with the communication devices first.
- Based on the above investigation, determine the probable faulty function and record results on the WIM system troubleshooting form.
- Once the faulty function has been determined, follow troubleshooting flow charts and step-by-step guides provided in the manufacturer's maintenance manual to determine the faulty component.
- If the faulty component cannot be determined, contact the manufacturer and provide the gathered information. Many times the manufacturer can suggest additional checks to perform or advise the technician of the probable faulty component without further troubleshooting.

Part 4.4 Maintenance Reports and Records

Almost as important as the maintenance itself, proper recordkeeping is an essential function of the WIM system maintenance program. Data from previous maintenance actions can be invaluable for determining high-failure-rate components and best practices for correcting common problems. Most importantly, past records can provide the WIM program manager with valuable information on predicting the failure of WIM system components so that they can plan and budget for upcoming maintenance and prepare the technician with replacement parts before the system fails.

Maintenance records should include preventive and troubleshooting efforts, as well as final analysis and repair actions performed. Please refer to the beginning of Section 4 in this Guide for a list of recommended reports and documentation.

SECTION 5 – WIM DATA QUALITY ASSURANCE AND ANALYSIS

Purpose

This section describes recommended off-site data QC checks used to remotely monitor and evaluate WIM system performance between field visits. The data QC checks covered in this Guide are focused on ensuring that data collected by the WIM equipment is within tolerances specified for that type of WIM equipment. They do not cover QC checks that ensure accuracy of the statistics computed based on the WIM data.

Personnel Requirements

The evaluation and analysis of the data collected from the WIM site must be performed by trained WIM data analysts experienced with WIM data download, data processing, and data analysis tools and functions. The WIM data QA-QC function may be performed by in-house personnel or outsourced in whole or in part.

Reference Documentation

- WIM Data Analyst's Manual (Quinley 2010)
- *LTPP Traffic QC Software Volume 1: User's Guide* (FHWA 2001, available at http://www/fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/reports)
- FDOT Telemetry Site Quality Control Comments (see Appendix F)
- FHWA Traffic Monitoring Guide – Appendix J: TMAS 2.0 Quality Control Checks (see Appendix F)

The *WIM Data Analyst's Manual*, produced by FHWA, provides a comprehensive description and proven methodology for evaluating the operational status of a WIM system in real-time view and for performing WIM data quality checks on data that is downloaded from the site (Quinley 2010).

Tools and Equipment

- Host desktop computer or laptop computer
- WIM manufacturer's system user interface software
- WIM manufacturer's data downloading and processing software installed on a host computer
- CDS tool to generate CDS statistics and supporting graphs and tables (See Step 3.3.2 of this Guide for CDS definition and instructions for computing CDS values.)

In addition, several traffic data vendors offer WIM data processing software.

Recommended Supporting Forms and Documentation

ADOT should implement the following documentation and procedures to be used by WIM program personnel to analyze WIM data during calibration, maintenance, and scheduled data analyses:

- WIM data QA-QC checklist
- WIM data QA-QC form
- Procedure/tool to compute CDS values and conduct WIM data analysis (See Step 3.3.2 of this Guide for CDS definition and instructions for computing CDS values.)

Procedure

Two methods may be used to remotely evaluate the WIM system's ability to provide accurate WIM data: Periodic WIM Data Review and Analysis (see Part 5.1) and Real-Time Operational Review (see Part 5.2).

Part 5.1 Periodic WIM Data Review and Analysis

The WIM data QA-QC review and analysis process provides a means to evaluate data downloaded from the WIM system against a CDS of known quality for a particular site. Notable differences between the CDS and recent data may indicate an operational deficiency with the WIM site that needs to be addressed through remote operational checks or an on-site validation.

Depending on resource availability and the frequency of use of the collected WIM data, the following checks may be performed daily, weekly, bi-weekly, or monthly.

Actions:

- Download a two- to four-week sample of recently collected WIM data for Class 9 trucks.
- Compare the downloaded data with the most recent CDS benchmark values from the latest CDS obtained during the two- to four-week period immediately following the last successful calibration.

Truck Distribution Analysis. Analysis of the most recent data against the CDS provides information about the truck distributions and may indicate possible deviations from that distribution.

Actions:

- Compare the truck class percentages for the current data with the truck class percentages for the CDS.
- Flag or provide comments for data that indicate a greater than 5 percent difference for any truck class.

GVW Data Analysis. This analysis is especially important for the sites that use the auto-calibration feature. Analysis of the most recent data against the CDS provides information about the Class 9 GVW distribution and the possible deviations from that distribution. A significant change in the weight value corresponding to loaded or unloaded peaks (5 percent or more) indicates a possible drift from the previous calibration and a need for re-calibration. Other than calibration drift, these changes could be attributed to changes in goods moved by Class 9 vehicles at a given WIM site; therefore, a good understanding of the nature of the goods being moved by the trucks is highly beneficial.

Actions:

- Analyze the downloaded data sample to determine whether there is a discernable shift (over 5 percent) for the unloaded or loaded peaks or the average GVW weight of Class 9 vehicles between the CDS and the most recent sample dataset (use a two- to four-week sample).
- If WIM data indicates a shift of the unloaded or loaded peaks or of the average GVW by more than 5 percent, flag the data and WIM site ID for field WIM site evaluation and possible re-calibration.

Class 9 Front-Axle Weight Data Analysis. Analysis of recent data against the CDS provides information about the average front-axle weight for Class 9 trucks and any possible deviations from that weight. This analysis may not yield accurate information about the accuracy of weight measurements (especially for the heavy loads) for the sites that utilize the auto-calibration feature. A change of over 5 percent in the average weight or in the peak loads of Class 9 front-axle weight may indicate that the data are biased due to a likely calibration drift.

Actions:

- Compare the average front-axle weight from the current data sample with the expected average front-axle weight average from the CDS.
- Evaluate the data for any significant changes in the percentage of lighter axles (9.0 to 10.0 kips), the percentage of heavier axles (12.0 to 13.0 kips), and the percentage of overloads (no weights over 20,000 lb should be expected). Note any changes in front-axle weights that represent the greatest percentage of trucks.
- Flag any data that indicate a significant change (over 5 percent) in front-axle weights from the values provided by the CDS, and provide comments on a WIM data QA-QC form.

Class 9 Tractor Tandem Spacing Data Analysis. This analysis provides a basis for the evaluation of the accuracy of the equipment distance and speed measurements and vehicle classification. A discernable change in the tandem spacing (±12 inches) may indicate sensor degradation or failure that must be addressed before a calibration visit.

Actions:

- ➢ Compare the observed average tractor tandem spacing from the recent sample data with the expected average tractor tandem spacing from the CDS.
- ➢ Flag any data that indicate a significant change (over 5 percent) in tandem-axle spacings from the values provided by the CDS and provide comments on the WIM data QA-QC form.

In addition to the above checks, the following checks of polled WIM data, identified through the survey of successful WIM practices, are recommended as part of routine WIM data checks done in the office:

- Polling errors checks: number of error vehicles, status-clear vehicles, and good-weight vehicles per day
- Data file size check
- Site identification, lane, direction, date, time, and location description checks
- Volume, class, and speed errors based on site-specific traffic volume, class, and speed averages
- Number of vehicles with invalid weight
- Class 9 hourly or daily volume checks
- Check of Class 9 front-axle weights against a minimum weight
- Right- and left-wheel weight comparison for the front-axle of Class 9 vehicles
- Check of the average Class 9 GVW against the historical data
- Check of the percentage of overweight vehicles against historical data
- Minimum/maximum axle weight and GVW check for Class 9 vehicles
- Minimum/maximum axle spacing check for Class 9 vehicles
- Total wheelbase check based on vehicle class

Actions:

- ➢ If data analysis indicates that any of the elements listed above seem unreasonable (i.e., out of typical range established for the site), notify the WIM program manager so that the proper corrective actions may be taken.

Part 5.2 Real-Time Operational Review

If any regular data reviews identify suspect data, a remote connection to the WIM system may be performed to determine whether the system is operating properly. For the real-time operational review, perform the following.

Actions:

- Connect to the WIM system remotely using the manufacturer's communication software.
- Select the real-time view from the user menu to view vehicles passing over the WIM scales in present time.
- From the real-time view, verify that the following data elements appear to be reasonable for each lane (less than 3 to 5 percent different from the latest CDS or typical range established for the site):
    - Classifications – misclassified or unclassified (Class 15s)
    - Axle spacings
    - Speeds
    - Weights
    - Vehicle lengths
    - System error or warning flag codes
    - If the real-time observation indicates that any of the elements listed above seem unreasonable (i.e., out of typical range established for the site), notify the WIM program manager so that the proper corrective actions may be taken.

Many issues detected by the WIM data analyst may be remotely corrected by verifying and correcting one or several of the WIM system's operational parameters, including sensor spacings, detection thresholds, or compensation factors.

SECTION 6 – WIM PROGRAM SUPPORT STAFF

The program staff may include in-house staff, or some of the program functions may be outsourced. To properly staff a WIM program, the agency needs the following personnel.

WIM Program Manager

Qualifications

The WIM program manager shall have a Bachelor of Science degree in engineering, math, information technology, or business management/administration as a minimum. This individual must also have specialized training and experience in program management, traffic engineering, and traffic monitoring.

Duties

The WIM program manager will supervise all WIM program in-house or contracted personnel, including data analysts and field technicians. Additionally, the WIM program manager should be responsible for the following:

- Submitting program reports
- Scheduling WIM installation processes, including site selection, pavement smoothness analysis, installation, and acceptance
- Managing calibrations, maintenance, and repairs

- Managing contracts for outsourced WIM operations
- Overall WIM equipment and data QA-QC

The WIM program manager should be the primary point of contact with WIM data customers.

WIM Field Technician

Qualifications

The WIM field technician should have a high school diploma as a minimum. The technician should have received specialized training in electrical engineering technology or electronics. He or she should have experience with traffic equipment installation, traffic monitoring, and control systems, and have received certifications in WIM maintenance by WIM vendors.

Duties

The WIM field technician should be responsible for the following:

- Maintaining, calibrating, and repairing WIM systems
- Providing on-site QA of WIM installations and repairs
- Assisting with on-site WIM site selections

The WIM field technician will report to the WIM program manager.

WIM Data Analyst/Office Technician

Qualifications

The WIM data analyst/office technician should possess a high school diploma and specialized training in data processing, database applications, computer programming, and data analysis as a minimum. A Bachelor of Science degree in math, statistics, engineering, or information technology is preferred.

Duties

The WIM data analyst/office technician should be responsible for the following:

- Downloading and processing the WIM data and performing data QA-QC
- Summarizing the data and compiling it for reporting
- Serving as an alternative point of contact for WIM data customers

The WIM data analyst/office technician will report to the WIM program manager.

WIM QA Inspector/WIM Specialist

Qualifications

The WIM QA inspector/WIM specialist should have a high school diploma and specialized training in electrical engineering or engineering technology as a minimum. Experience with weigh-in-motion equipment, including installation, calibration, and maintenance, is required. He or she must have received maintenance and installation certifications from WIM vendors. A Bachelor of Science degree with a major in electrical engineering, electrical engineering technology, or mechanical engineering and control systems is preferred.

Duties

The WIM QA inspector/WIM specialist will oversee and manage WIM system installations, maintenance, and calibration. He or she will report to the WIM program manager.

Summary

WIM program support staff could be dedicated to the WIM program, shared with other ADOT programs, or outsourced. The most frequently outsourced WIM program function is installation, which is typically performed by qualified contractors or WIM vendors. Maintenance and calibration functions, when performed by staff outside the agency, are typically performed by qualified traffic monitoring system installation and maintenance companies or by the WIM vendors themselves. Data functions are typically carried out by in-house staff. The WIM program manager is an in-house position.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

This study focused on identifying best practices for collecting vehicle weight data using WIM systems with piezoelectric sensors. Of specific interest to ADOT were experiences of other highway agencies with WIM piezo-polymer and piezo-quartz sensors, especially under climatic conditions similar to those in regions within Arizona.

The project tasks included a literature search, a survey of other agencies' practices related to WIM data quality assurance, and the development of a guidebook with recommendations for managing WIM installation, calibration, maintenance, and data quality assurance. Study findings were used to develop guidelines for ADOT to ensure the accuracy of their WIM data.

CONCLUSIONS

Literature Search Conclusions

The literature search identified many studies addressing accuracy of the piezo-polymer and piezo-quartz sensors. In each of these studies, it was determined that the piezo-quartz sensors performed much better than the piezo-polymer sensors because of their consistent reliability, reduced calibration requirements, and relative temperature insensitivity. The piezo-quartz sensors worked well in both asphalt and concrete pavements. All literature findings supported a conclusion that piezo-quartz WIM sensors should provide accurate axle and truck weight measurements in Arizona. However, to achieve longevity of the sensor, special attention should be given to proper installation and site location selection, including selection of pavement that provides sufficient structural support and is not susceptible to changes in stiffness due to changes in ambient temperature.

It was also concluded that use of the piezo-polymer sensors to consistently collect accurate axle and truck weight data in Arizona may be very challenging, primarily because of a known issue of piezo-polymer sensor temperature sensitivity and limitations of auto-calibration and temperature compensation technologies in environments where pavements are subjected to high seasonal temperatures and rapid day/night temperature changes. The piezo-polymer sensors should perform well in Arizona for vehicle classification, traffic volume, and speed studies because these data are obtained using a different data-processing algorithm that is not related to weight data. The piezo-polymer sensors are not recommended for applications that require accurate weight data collection.

In addition, the literature search identified critical elements of a WIM system installation and maintenance program that must be considered. These elements, in combination with a quality assurance program, are vital to sustainable, long-term WIM system reliability:

- The WIM site should have access to power and telephone, sufficient space for the controller cabinet, adequate drainage, free-flowing traffic conditions, and easy and safe site access for maintenance and calibration.

- The roadway geometric design should provide favorable conditions for accurate estimation of static loads from dynamic load measurements, including horizontal curvature, the longitudinal gradient, the cross (lateral) slope, and the width of the paved roadway lane.
- The roadway should be smooth to reduce adverse vehicle dynamics that lead to greater variations in the system accuracy.
- The agency should establish a systematic preventive and corrective maintenance program for the site to help to ensure that the expected "site design life" is attained.
- The agency should perform routine WIM system calibration involving test trucks, preferably heavy Class 9 trucks.
- The agency should perform routine and systematic WIM data quality control checks, including both field validations and routine office data checks, to ensure WIM data quality.
- The agency should recognize that proper installation of sensors is key to both WIM system performance and life span.

Survey Conclusions

The purpose of the survey was to review WIM practices implemented by the selected highway agencies that use WIM system technologies similar to those desired by ADOT and to identify successful practices applicable to ADOT's WIM program. Most of the critical elements for developing a successful WIM program were identified, as summarized in the following subsections.

WIM Site Location Selection and Assessment

The selection of a WIM site location that is conducive to accurate weight measurements is of upmost importance. If the desired location is provided by the WIM data user, the WIM data provider must make an assessment as to whether the site conditions of the selected location are favorable for collection of accurate WIM data. If site conditions would negatively affect WIM data quality, an alternative site location must be selected in collaboration with the WIM data user and data provider.

The primary objective of selecting the location of the WIM sensor installation is to minimize weight errors due to site characteristics that may directly affect the quality of WIM data collected. The most important aspects to consider when evaluating a candidate WIM site, in order of importance to the respondents, are:

1. Traffic conditions (free-flow, no nearby intersections or traffic signals)
2. Pavement condition (other than smoothness)
3. Safe access for technicians
4. Pavement smoothness
5. Roadway geometrics
6. Roadway gradient

Several reference resources developed by ASTM, FHWA, and state DOTs are available to provide guidance when selecting WIM site locations, including:

- ASTM E1318-09 (ASTM 2009)
- LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
- WIM Data Analyst's Manual (Quinley 2010)
- Smoothness Criteria for WIM Scale Approaches (Karamihas and Gillespie 2002)
- *Distress Identification Manual for the Long-Term Pavement Performance Program* (Miller and Bellinger 2003)

It is a good practice to stipulate acceptable WIM site selection criteria in the WIM installation contract specifications. These criteria can be used to further ensure correct selection of WIM site location by the WIM installer along the road segment. Developing a WIM site selection report for each WIM site for record keeping and future reference is also recommended.

WIM Installation

The most critical element for WIM site installations is ensuring that the in-road sensors are installed in accordance with the manufacturer's specifications. This includes the proper sensor placement (spacing, layout, depth, etc.) and the proper mixing and application of the chemicals and binding agents that are used to install the sensors.

All personnel involved in the installation should be qualified and certified. An independent quality assurance inspector or other agent representing the highway agency should be on site to observe the installation and verify that procedures comply with contract and manufacturer specifications. They may also be tasked with taking measurements to verify critical dimensions and photographing and videotaping all WIM site installation activities. The QA Inspector would also observe final testing and calibration of the WIM system.

Once the WIM system is properly installed, an initial calibration of the equipment should be performed by a qualified WIM technician according to manufacturer's specifications and requirements and guidelines set forth in ASTM E1318-09.

It is a good practice to develop WIM installation inspection and WIM acceptance testing reports for record keeping and future references.

Several reference sources could be used by ADOT to ensure that its WIM systems are installed properly. These resources include:

- International Road Dynamics' (IRD) instructions for the use of AS-475 Grout
- Kistler Instrument's installation instructions for Lineas sensors
- LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
- LTPP WIM System Installation and Calibration Audit from *LTPP Field Operations Guide for SPS WIM Sites Version 1.0* (FHWA 2012 [LTPP])

- ASTM E2561-07a – Standard Practice for Installation of Inductive Loop Detectors (ASTM 2007)
- ASTM E2759-10 – Standard Practice for Highway Traffic Monitoring Truth-in-Data (ASTM 2010)
- ASTM E1318-09 – Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM 2009)

WIM System Calibration

After the WIM system has been installed and initially calibrated by the installer or manufacturer, it is imperative to routinely monitor WIM system performance (using remote data access from the office) and to systematically calibrate the WIM system, either at regular intervals or as determined from remote WIM data monitoring, to ensure that the data remains usable.

The first and/or second calibration after installation should include two tractor semi-trailer trucks (FHWA Class 9 truck) of differing weights (use 90 percent and 80 percent of allowable capacity or typical weights of loaded truck observed at the site). Test truck runs should be conducted at the widest possible ranges of speeds and temperatures observed at the site. A sufficient number of pre-calibration runs should be performed to quantify WIM measurement bias (i.e., mean measurement error percent): at least 10 test runs per truck, per lane. After initial pre-calibration test truck runs, the system should be calibrated to minimize bias (i.e., to have mean measurement error close to zero), and then the same number of post-calibration test truck runs should be performed to validate the system and quantify overall measurement data accuracy (expressed as mean percent error ±2 standard deviations of the percent error).

For the subsequent routine calibrations, one truck that is representative of the weights and types of trucks at the site may be used, unless the initial calibration determined that a second truck of different weight offers additional benefit in reducing measurement error. A reduced number of runs may be performed to “validate” the current calibration settings or to determine the bias that must be compensated for using the system calibration factors. A minimum of 10 test truck runs is recommended to avoid false positive and false negative conclusions. After compensation factors have been adjusted, the same number of runs must then be used to verify that the calibration had the intended effect on the system measurement’s bias, and that the biases for all weight, spacing, and length measurements are as close to zero as possible.

For systems that are using temperature compensation, the function should remain on. However, if the system uses an auto-calibration routine using temperature or free-flow traffic truck weights, the auto-calibration should be turned off during calibration and turned back on after successful calibration.

The WIM systems with piezo-quartz sensors should be calibrated every 12 to 18 months, at a minimum. WIM systems with piezo-polymer sensors should be calibrated seasonally or have other means for consistent compensation of temperature effect on weigh measurements. Generally, for climatic conditions observed in Arizona (i.e., high time-of-day and seasonal temperature differentials), piezo–

polymer systems are not well suited for weight data collection unless low-precision WIM data (±30 percent error in weight measurements) are acceptable for customer applications.

To monitor WIM system performance between calibrations, collect a sample of data covering two weeks immediately after each successful calibration (four weeks for low truck volume sites with fewer than 100 Class 9 trucks per day). The CDS should include average weights of the front axle and GVW for Class 9 trucks, the location of loaded and unloaded peaks in distributions of tandem axle loads and in GVWs, and the peak steering axle weight value for Class 9 trucks (for example, range of values corresponding to tandem axle loaded peak: 30-34 kips). Use these data to develop a comparison data set (CDS). The CDS should include truck weight summary statistics that can be used as benchmark values to compare to the future WIM data. If the future WIM data drifts more than 5 percent from the benchmark values for Class 9 GVW, the system should be calibrated out of normal cycle.

It is also important to keep a record of WIM calibration dates, test truck parameters, references to procedures or a protocols used for calibration, WIM performance parameters (mean error and range of errors corresponding to 95 percent confidence interval) computed before and after each calibration, and a record of WIM compensation factor adjustments. A standard form or report would ensure reporting consistency.

The available reference sources for WIM system calibration include:

- WIM vendor maintenance guides
- LTPP Field Operations Guide for SPS WIM Sites (FHWA 2012 [LTPP])
- ASTM E1318-09 — Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods (ASTM 2009)

Maintenance

To maximize the life span of the WIM system, a comprehensive maintenance program must be put into practice. It is important to perform routine preventive maintenance every six to 12 months and to develop a schedule and procedures for timely repairs of system failures. During each preventive maintenance visit, all in-road sensors should be checked for proper electronic values. The entire WIM system should be visually inspected, including the pull boxes, in-road sensors, telephone and power service equipment, and the roadway leading up to and within the WIM scale area. All deficiencies should be recorded and reported.

It is also important to maintain an accurate record of all maintenance activities performed at each WIM site, including maintenance reports and photographs. In addition, maintenance logs should be kept in the cabinet for easy reference by field technicians.

The FHWA published the *WIM Field Inspectors' Troubleshooting Guide* in 2009 to assist WIM technicians in adequately maintaining WIM systems and provide guidance on how to properly identify and repair system faults (Quinley 2009).

Data Quality Assurance

WIM data quality assurance should have both field measurement and office data analysis components. Field data checks are used to support field validation and calibration of WIM systems, while off-site office checks are used to remotely monitor and evaluate WIM system performance over time and to identify changes in WIM data parameters that may signal WIM system malfunction or calibration drift.

Field data QC is performed as part of WIM validation or calibration activities. It involves comparison of weights reported by the WIM system with the known static weights. Test trucks representing the most frequently observed heavy vehicles at the site (typically Class 9 trucks) are used for these checks. Using a sample of test truck runs, errors between known static and WIM weight measurements are computed and used to determine the mean error and the statistical confidence interval (that represents the range of errors for 95 percent confidence level). The mean error and confidence interval values are combined (mean error ±2 standard deviations of error), and the resulting range is compared with the tolerance levels specified in ASTM E1318-09 for Type I or Type II systems to determine whether the WIM system is producing inaccurate weight measurements.

The following data checks of polled WIM data are routinely done in the office (daily, weekly, bi-weekly, or monthly depending on staff availability and truck volumes at the WIM site):

- Polling error checks: review number of error vehicles, status-clear vehicles, and good-weight vehicles per day
- Data file size checks
- Site identification, lane, direction, date, time, and location description checks
- Volume, class, and speed errors based on site-specific traffic volume, class, and speed averages
- Invalid weight counts
- Average Class 9 hourly or daily volume checks
- Average Class 9 loaded/unloaded peak loads
- Average Class 9 front-axle weights against a minimum weight and CDS weight
- Average Class 9 front-axle weights against historical data
- Right- and left-wheel weight comparison on front-axle data for Class 9 vehicles
- Average Class 9 GVW against historical data
- Average percentage of overweight vehicles against historical data
- Minimum/maximum axle weight for Class 9 vehicles
- Minimum/maximum axle spacing for Class 9 vehicles
- Average tandem axle spacing of Class 9 vehicles against historical data
- Total wheelbase based on vehicle class

WIM Program Support Staff

Whether or not the work is performed in-house or is outsourced, it is very important to have at least the following personnel, either dedicated to the WIM program or shared with other agency programs:

- WIM Program Manager. Duties: supervise in-house or contracted personnel, including data analysts and field technicians; schedule installations, calibrations, maintenance, and repairs; manage contracts for outsourced WIM operations; take responsibility for overall WIM equipment and data QA-QC; submit data and program status reports; and be the primary point of contact with WIM data customers.
- Field technician. Duties: Maintain, calibrate, and repair WIM systems. May provide on-site QA of WIM installations and repairs. Prepare maintenance and calibration reports or fill out forms provided by WIM Program Manager or WIM Specialist.
- Data analyst. Duties: Download, process, and QA-QC WIM data and compile data for reporting; develop ad-hoc WIM data analysis routines and custom reports; upload processed WIM data and statistics to a designated database; serve as alternative point of contact for WIM data customers.
- WIM QA inspector/WIM Specialist. Duties: Technically oversee and manage WIM system installation, maintenance, and calibration. Prepare WIM installation, calibration, and maintenance reports or conduct a review if these reports are developed by technicians. Conduct field evaluation of sites proposed for WIM installation and present findings to management.

Most agencies share staff resources, including program supervisors and managers, data analysts, and technicians, with other sections within the traffic monitoring division. The most frequently outsourced WIM operation is installation, which is typically performed by qualified contractors or WIM vendors. Maintenance and calibration functions, when performed by staff outside the agency, are typically performed by qualified traffic monitoring system installation and maintenance companies or by the WIM vendors themselves. Most data functions are carried out by in-house staff.

WIM Program Supporting Documentation, Operational Manuals, and Tools

Successful WIM programs use standardized procedures, agency-specific instructions, and reporting tools to support different WIM operations. The following supporting documentation is used by the agencies, organized by the WIM operation supported:

- Site Location:
  - WIM site selection form or report
  - WIM site selection roadway plan drawing
  - WIM site design plan
- Installation:
  - Manufacturer’s specifications
  - WIM installation audit form
  - Non-compliance report

- Calibration:
  - WIM calibration form and/or report
  - Field operations guide or manual
- Maintenance:
  - WIM site maintenance and inspection form
  - WIM system troubleshooting form and/or guide
  - WIM site maintenance log (to be kept in the WIM cabinet)
  - Manufacturer's specification
  - Field operations guide or manual
- Data QA:
  - Data QA-QC checklists
  - Templates for creating CDS values and graphs
  - In-house, FHWA, or off-the-shelf tools for data processing and reporting

RECOMMENDATIONS

WIM Sensor Selection

Higher-quality data comes at higher cost. Piezo-quartz sensors have higher initial costs compared to piezo-polymer sensors but much lower maintenance and calibration costs over the complete life cycle. Accuracy and reliability of piezo-quartz sensors is much higher than that of piezo-polymer sensors. Therefore, ADOT must determine the acceptable tradeoffs between the cost of equipment and its installation, the cost of calibration, the expected life span of the WIM sensor, and the application (i.e., data accuracy requirement) of the collected data. These trade-offs may be not acceptable when a data accuracy requirement cannot be met.

Typically, piezo-quartz sensors would provide more reliable and consistent data compared to piezo-polymer sensors. The main limitation of piezo-polymer sensors is measurement error sensitivity to temperature changes. This includes both same-day temperature changes and seasonal temperature changes. This sensitivity could be somewhat reduced by using an auto-calibration feature. However, this works only on roads with a high volume of Class 9 trucks and low intraday temperature changes.

Both types of piezoelectric sensors require regular calibration. WIM systems with piezo-quartz sensors may need calibration every 12 to 18 months. WIM systems with piezo-polymer sensors may require seasonal calibration in order to collect data within ASTM E1318-09 requirements for Type I or Type II systems. Auto-calibration may have limited success at locations subjected to rapid same-day temperature changes and low volumes of Class 9 trucks. Additionally, auto calibration is primarily focused on reducing weight error for the steering axle and does not have a direct effect on reducing error for the other axle groups or GVWs.

WIM Operation Support Tools

WIM Technician's Field Operations Manual

To ensure consistency of execution of ADOT's WIM operations and to maintain in-house knowledge, ADOT should consider developing a stand-alone WIM Technician's Field Operations Manual. The purpose of the manual would be to provide step-by-step instructions to ADOT's field personnel on how to perform various WIM operations. An example of such a manual is *LTPP Field Operations Guide for SPS WIM Sites* (FHWA 2012 [LTPP]).

This manual should cover the following operations:

- WIM Site Selection
- WIM Installation
- WIM Calibration
- WIM Maintenance
- WIM Malfunction Troubleshooting Guide
- WIM Data Quality Checks

The manual could be a single, comprehensive document or a series of pocket manuals, with each pocket manual covering one of the above bullet items. This second format may be more convenient for a technician reviewing relevant information in the field.

The manual should also include templates of the forms and reports to be used by ADOT's WIM program support personnel to track work being done and to report the results to ADOT's WIM program manager. These forms and reports should be available in both paper and electronic format. The recommended forms and reports include the following:

- WIM site selection summary report, including the following supporting forms:
    - WIM site evaluation form
    - Pavement distress survey form and map
    - WIM site selection roadway plan
    - WIM installation QA form
- WIM Installation and initial calibration summary report, including the following supporting forms:
    - WIM inventory form
    - WIM site as-built plan
    - WIM calibration form
    - WIM installation acceptance report
- WIM installation non-compliance report
- WIM calibration summary report, including the following supporting forms:
    - WIM calibration form
    - Pavement distress survey form and map

- WIM maintenance summary report, including the following supporting forms:
    - WIM maintenance and inspection form
    - WIM system troubleshooting form
    - WIM site maintenance log

In addition to the operations manual, some of the WIM operations could be significantly simplified and streamlined using automated tools and processes. The most beneficial tools are described in the following sections.

WIM Calibration Tool

The process of calibrating a WIM system may be performed more easily and with greater precision using a calibration tool. This tool automatically computes statistics needed to evaluate WIM performance parameters and aids in determination of WIM compensation factor adjustments. It also provides a means to analyze the relationship between WIM measurement error and speed, temperature, or test trucks (if more than one truck is used for calibration). Finally, this tool evaluates WIM performance parameters against user-specified acceptable values (typically ASTM E1318-09 values for Type I or II WIM systems) and determines whether the WIM system passed or failed calibration. To summarize, a WIM calibration tool should have the following functionality:

- Record site identification and general information from user entries.
- Record test truck static weight, axle spacing, and length data from user entries.
- Record test truck run data, including axle and axle group weights, GVW, axle spacing, overall length, speed, and pavement temperature from user entries.
- Record system weight and distance measurement compensation factors from user entries.
- Develop pre- and post-calibration test run statistics, including tabular and graphic information.
- Develop plots showing WIM measurement error relationship with speed, temperature, and test trucks (if more than one truck is used for calibration).
- Provide recommendations for WIM compensation factor adjustments based on weight and distance measurement biases, considering effects of speed, temperature, and truck type.
- Record pre- and post-calibration WIM performance parameters, such as mean percent error (or system bias), spread of error corresponding to 95 percent confidence interval, and overall error.
- Evaluate WIM performance parameters against user-specified acceptable values (typically ASTM E1318-09 values for Type I or II WIM systems) and determine whether the WIM system passed or failed calibration.

Data QC Tool

ADOT would benefit from the development of a CDS Tool. This tool will be used to compute reference values and statistics for each WIM system soon after the WIM system is calibrated. The CDS values will be used for periodic monitoring and assessment of future WIM data to determine whether the WIM system is producing consistent-quality data or if a site visit for corrective maintenance or calibration is required. This tool should have the following functionality:

- Import/Insert W-card data (recent WIM data).
- Compute and save CDS statistics.
- Display comparison graphs and tables for by-weekly or monthly WIM data comparison analysis with CDS (to use for monitoring WIM performance and scheduling calibration visits).
- Report whether WIM data passed or failed a check against CDS values. If failed, flag site for calibration or maintenance visit.
- Display comparison graphs and tables using CDS and recent WIM data for pre-visit data analysis (to be completed before calibration and included in the calibration report).
- Display comparison graphs and tables using old and new CDSs for post-visit data analysis (to be completed after calibration and included in the calibration report).

WIM Data Processing Tool

Typically, WIM data collected in the field is available for download in a Per-Vehicle Record (PVR) file format. This format represents the lowest level of data aggregation, where each line in the data file contains information about each vehicle passage, including time of vehicle passage over the WIM sensor, vehicle type (according to the FHWA vehicle classification scheme), number and spacing of axles, and weight of each axle. Depending on the level of traffic volume observed at a WIM site location over a year, this file or combination of downloaded files may contain millions of records. Therefore, an automated tool is needed to download, process, and summarize these data. Data summarization routines and data storage formats are a function of WIM data user requirements. It is recommended that ADOT work with its WIM data users to obtain data summarization and reporting requirements and use this information to identify proper tools for data processing and storage.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). 2012. *Standard Specification for Smoothness of Pavement In Weigh-In-Motion (WIM) Systems.* Standard MP 14-12. Washington, DC.

American Society for Testing and Materials (ASTM). 2007. *Standard Practice for the Installation of Inductive Loop Detectors*. ASTM E2561-07a. West Conshohocken, PA: ASTM International, doi: 10.1520/E2561-07A.

American Society for Testing and Materials (ASTM). 2009. *Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods.* ASTM E1318-09. West Conshohocken, PA: ASTM International, doi: 10.1520/E1318-09.

American Society for Testing and Materials (ASTM). 2010. *Standard Practice for Highway Traffic Monitoring Truth-in-Data.* ASTM E2759-10. West Conshohocken, PA: ASTM International, doi: 10.1520/E2759-10.

Burnos, Piotr. 2008. "Auto-calibration and temperature correction of WIM systems," in *Proceedings of the International Conference on Heavy Vehicles, 5th International Conference on Weigh-in-Motion of Heavy Vehicles*, 2008, 437–446.

Darter, Michael, Leslie Titus-Glover, and Dean J. Wolf. 2011. *Development of a Traffic Data Input System in Arizona for the MEPDG.* FHWA-AZ-13-672. Phoenix: Arizona Department of Transportation.

European Cooperation in Science and Technology (COST): Action 323. 1998. *Weigh-in-Motion of Road Vehicles*. Paris.

Federal Highway Administration (FHWA). 2001. *LTPP Traffic QC Software, Volume 1: Users Guide. Software version 1.6*. Washington, D.C.: Federal Highway Administration: 2001.

Federal Highway Administration (FHWA). 2002. *SPS Traffic Site Evaluation: Pilots Summary and Lessons Learned.* McLean, VA: Federal Highway Administration: 2002.

Federal Highway Administration (FHWA). 2012. *LTPP Field Operations Guide for SPS WIM Sites Version 1.0. Draft.* McLean, VA: Federal Highway Administration: 2012.

Federal Highway Administration (FHWA). 2012. *Manual on Uniform Traffic Control Devices for Streets and Highways*. 2009 edition including May 2012 revisions. Washington, D.C.: Federal Highway Administration: 2012.

Federal Highway Administration (FHWA). 2013. *Traffic Monitoring Guide*. Publication No. FHWA PL-92-017. Washington, D.C.: Federal Highway Administration: 2013.

Federal Highway Administration (FHWA). 2014. *LTPP 2014 and Beyond - What Is Needed and What Can Be Done?* Publication No. FHWA-HRT-15-017. McLean, VA: Federal Highway Administration: 2014.

Fernando, Emmanuel G., Dan Middleton, Todd Carlson, Ryan Longmire, Edward Sepulveda, Leonard Ruback, Tom Freeman, Jeongho Oh. 2009. *Deploying Weigh-in-Motion Installations on Asphalt Concrete Pavements.* FHWA/TX-09/0-5551-1. Austin: Texas Department of Transportation: 2009.

Gajda, Janusz, Ryszard Sroka, Tadeusz Zeglen, Piotr Burnos. 2012. "The Influences of Temperature on Errors of WIM Systems Employing Piezoelectric Sensors." *Metrology and Measurement Systems*, No 2: 171-182.

Hallenbeck, Mark and Herbert Weinblatt. 2004. *Equipment for Collecting Traffic Load Data*. Transportation Research Board: National Cooperative Highway Research Program (NCHRP) Report 509. Washington D.C.: 2004.

Jiang, Xiaohua, Shahram H. Vaziri, Carl Haas, Leo Rothenburg, Gerhard Kennepohl, Ralph Haas. 2009. "Improvements in Piezoelectric Sensors and WIM Data Collection Technology." Presented at the 2009 Annual Conference of the Transportation Association of Canada, Vancouver, BC, October.

Karamihas, S. M. and T. D. Gillespie. 2002. *Smoothness Criteria for WIM Scale Approaches*. Report No. UMTRI-2002-37. National Technical Information Service, Springfield, VA: 2002

Karamihas, S. M., G. R. Rada, B.K. Ostrom, A.L. Simpson, L. J. Wiser. 2004. "Pavement Smoothness at Weigh-In-Motion Sites: Developing Specifications for the Long-Term Pavement Performance Program." *Transportation Research Record: Data and Information Technology* 1870: 116-123.

Klein, Lawrence A., Milton K. Mills, David R.P. Gibson. 2006. *Traffic Detector Handbook: Third Edition—Volume I*. Publication No. FHWA-HRT-06-108. Washington, D.C.: Federal Highway Administration: 2006.

McCall, Bill, Walter C. Vodrazka, Jr. 1997. *States' Successful Practices Weigh-in-Motion Handbook.* Washington, D.C.: Federal Highway Administration: 1997.

Middleton, D., D. Jasek, and R. Parker. 1999. *Evaluation of Some Existing Technologies for Vehicle Detection*. FHWA/TX-00/1715-S. Austin: Texas Department of Transportation: 1999.

Middleton, D., R. White, J. Crawford, R. Parker, J. Song, and C. Haas. 2005. *Investigation for Traffic Monitoring Equipment Evaluation Facility*. FHWA/TX-06/0-4664-3. College Station: Texas Transportation Institute: 2005.

Miller, John S. and William Y. Bellinger. 2003. *Distress Identification Manual for the Long-Term Pavement Performance Program* (Fourth Revised Edition). Publication No. FHWA-RD-03-031. Washington, D.C.: Federal Highway Administration: 2003.

Nichols, Andrew P., Darcy M. Bullock. 2004. *Quality Control Procedures for Weigh-in-Motion Data.* Publication FHWA/IN/JTRP-2004/12. West Lafayette, IN: Purdue University.

Ostrom, Barbara K. 2009. *LTPP Traffic Data Collection and Processing Guide, Version 1.3*. Publication No. FHWA-HRT-09-051. Washington, D.C.: Federal Highway Administration: 2009.

Papagiannakis, A.T., R. Quinley, S.R. Brandt, 2008. *High Speed Weigh-in-Motion System Calibration Practices: A Synthesis of Highway Practice* Transportation Research Board: National Cooperative Highway Research Program (NCHRP) Synthesis 386. Washington, D.C.: 2008

Perera, R.W., S.D. Kohn, and G.R. Rada. 2008. *LTPP Manual for Profile Measurements and Processing*. Publication No. FHWA-HRT-08-056. Washington, D.C.: Federal Highway Administration: 2008.

Quinley, Rich. 2009. *WIM Field Inspectors' Troubleshooting Guide*. Publication No. FHWA-IF-10-003. Washington, D.C.: Federal Highway Administration: 2009

Quinley, Rich. 2010. *WIM Data Analyst's Manual*. Publication FHWA-IF-10-018. Washington, D.C.: Federal Highway Administration: 2010.

Ramachandran, Aditya N., Kent L. Taylor, John R. Stone, Soheil S. Sajjadi. 2011. "NCDOT Quality Control Methods for Weigh-in-Motion Data." *Public Works Management & Policy* 16 (1): 3-19.

Selezneva, Olga, A. Ramachandran, E. Mustafa, R. Carvalho. 2013. "Impact of Various Trucks on Pavement Design and Analysis: Mechanistic–Empirical Pavement Design Guide Sensitivity Study with Truck Weight Data." *Transportation Research Record: Journal of the Transportation Research Board* 2339: 120–127.

Selezneva, O. I., M. Ayres, M. Hallenbeck, A. Ramachandran, H. Shirazi, and H. Von Quintus. 2016. *MEPDG Traffic Loading Defaults Derived from Traffic Pooled Pooled Fund Study*. FHWA-HRT-13-090: McLean, VA: Federal Highway Administration: 2016.

Szary, P J, A. Maher, R. Panda, A. Safari. 1999. *Implementation of Advanced Fiber Optic and Piezoelectric Sensors: Fabrication and Laboratory Testing of Piezoelectric Ceramic-Polymer Composite Sensors for Weigh-in-Motion Systems.* Publication FHWA NJ 1999-029. Washington, D.C.: Federal Highway Administration: 1999.

Szary, Patrick, Ali Maher. 2009. *Implementation of Weigh-in-Motion (WIM) Systems.* Publication FHWA-NJ-2009-001. Washington, D.C.: Federal Highway Administration: 2009.

Tarefder, Rafiqul, James Brogan. 2011. "Review of Statewide Traffic Data Collection, Processing, Projection and Quality Control." *Transport Research Arena (TRA) 2014 Proceedings* 2014-4*.*

Vaziri, Shahram Hashemi. 2011. "Investigation of Environmental Impacts on Piezoelectric Weigh-In-Motion Sensing System." Doctoral thesis, University of Waterloo.

Walker, Deborah, David Cebon. 2011. "The Metamorphosis of Long-Term Pavement Performance Traffic." *TR News* 277*:* November-December 2011. 9-17.

Walker, Deborah, Olga Selezneva, Dean J. Wolf. 2012. "Findings from LTPP SPS WIM Systems Validation Study." In *Proceedings of the International Conference on Weigh-In-Motion (ICWIM 6),* ed. Bernard Jacob et al., Hoboken, NJ: John Wiley & Sons, Incorporated.

Yannis, George, Constantinos Antoniou. 2005. "Integration of Weigh-in-Motion Technologies in Road Infrastructure Management." *ITE Journal:* 75 (1): 39-43.