LTBP Program's Literature Review on Weigh-in-Motion Systems

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Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This study was conducted as part of the Federal Highway Administration's Long-Term Bridge Performance (LTBP) Program. The LTBP Program is a long-term research effort, authorized by the U.S. Congress under the *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* legislation, to collect high-quality data from a representative sample of highway bridges nationwide that will help the bridge community better understand bridge performance. The products from this program will be a collection of data-driven tools, including predictive and forecasting models that will enhance the abilities of bridge owners to optimize their management of bridges.

This report presents a review of the literature related to regulations on truck weight limits, weigh-in-motion (WIM) technologies for pavements and bridges, WIM system specifications and accuracy, and experience from the Long-Term Pavement Performance Program with WIM systems relevant to the traffic load data collection goals for the LTBP Program. This report should be of interest to bridge program personnel from Federal, State, and local transportation departments as well as to parties engaged in bridge-related research.

Mark Swanlund
Acting Director, Office of Infrastructure
Research and Development

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FHWA Contacts: Susan Lane, HRDI-50 and Yamayra Rodriguez-Otero, HRDI-50
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16. Abstract

Truck size and weight are regulated using Federal and State legislation and policies to ensure safety and preserve bridge and high infrastructure. Weigh-in-motion (WIM) systems can capture the weight and other defining characteristics of the vehicles actually using the Nation's highways, providing important loading-related data that is essential for evaluating the performance of transportation infrastructure.

As part of the Federal Highway Administration's (FHWA) Long-Term Bridge Performance (LTBP) Program's Technical Assistance Contract, a literature review of the state of the practice was performed for WIM systems installed in pavements and on bridges. This literature review focused on the development of WIM systems, concepts for measuring axle loads, the applications of WIM sensors for pavements, and recent advancements in bridge WIM system. This review covers the types, installation, calibration, operations, accuracy, efficiency, effectiveness, and durability of WIM systems, in addition to current Federal and State truck load regulations. This review facilitates selection of the appropriate WIM technology systems for consideration and use to address LTBP Program needs. This literature review serves as a reference document for Pooled Fund Project Number TPF-5(283), *The Influence of Vehicular Live Loads on Bridge Performance*, which targets the impact of vehicle live loads on bridge component durability.

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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)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		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)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		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)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
AASHTO	American Association of State Highway and Transportation Officials
AVC	automatic vehicle classification
B-WIM	bridge weigh-in-motion
ESAL	equivalent single-axle load
FE	finite element
FHWA	Federal Highway Administration
FAD	free-of-axle-detector
GVW	gross vehicle weight
LCV	longer combination vehicle
LTBP	Long-Term Bridge Performance
LTPP	Long-Term Pavement Performance
NCHRP	National Cooperative Highway Research Program
NOR	nothing-on-road
OS/OW	oversize/overweight
PCC	portland cement concrete
SPS	Specific Pavement Study
STAA	Surface Transportation Assistance Act
TRB	Transportation Research Board
TS&W	truck size and weight
USDOT	U.S. Department of Transportation
WAVE	Weigh-In-Motion of Axles and Vehicles for Europe
WIM	weigh-in-motion

CHAPTER 1. INTRODUCTION

State and Federal highway agencies are responsible for safeguarding the expenditure of billions of dollars invested in highway infrastructure each year. As such, for the purposes of safety and infrastructure preservation, truck size and weight (TS&W) are regulated using Federal and State legislation and policies. However, data on the actual characteristics of the trucks using this infrastructure, including weights, volumes, and configurations, are necessary for many applications, including design, research, maintenance, and preservation. Weigh-in-motion (WIM) systems can capture and record the axle or axle group mass, capturing the gross vehicle weight (GVW) while the vehicle is moving.

As part of the Federal Highway Administration's (FHWA) Long-Term Bridge Performance (LTBP) Program's Technical Assistance Contract, a literature review of the state of the practice was performed for WIM systems installed in pavements and on bridges. This literature review focused on the development of WIM systems, concepts for measuring axle loads, the applications of WIM sensors for pavements, and recent advancements in bridge WIM systems. The literature review consists of the following five main topics:

- Regulations on truck weight limits.
- Permanent WIM systems installed in roadways.
- Bridge weigh-in-motion (B-WIM) systems.
- WIM system specifications and accuracy.
- Long-Term Pavement Performance (LTPP) Program's WIM experience.

SCOPE

This literature review outlines important topic areas related to WIM systems and the research performed by various agencies. One goal of the LTBP Program is to investigate the impact of truck loads on the performance and durability of bridges, and this review facilitates selection of suitable WIM technology systems to meet these data collection needs.

The review serves as a reference document for Pooled Fund Project Number TPF-5(283), *The Influence of Vehicular Live Loads on Bridge Performance*, which targets the impact of vehicle live loads on bridge component durability.(1) Currently, the participating agencies in the pooled fund study are FHWA and State transportation departments in Minnesota, Iowa, Pennsylvania, Georgia, Oregon, Wisconsin, and North Carolina.

The goals for the pooled fund study are highlighted by the following two fundamental questions:

- What are the current truck loads on the Nation's bridges? There have been changes in truck geometry, axle configurations, suspension, and tire characteristics. In some cases, common loaded truck weights have increased from 72 kips (design truck) to more than 110 kips.

- What are the impacts of increased truck loads on the durability of the Nation's bridges? The freight industry has been requesting increases in allowable truck loads on bridges.

> The bridge elements that are especially affected by increased truck loads need to be identified. Bridge owners need to address the effects of live loads on bridge component durability by using better tools and strategies to manage and operate bridges, given the constrained financial resources should traffic volumes and weights increase and truck configuration changes.

WIM OVERVIEW

WIM is the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle.(2) Efforts to develop and use WIM systems to collect truck weight data in the United States can be traced back to the early 1950s. One of the earliest examples was a WIM system developed in 1951 by Norman and Hopkins at the U.S. Bureau of Public Roads.(3,4) The WIM system used a floating reinforced concrete platform that was embedded in the roadway and supported at its corners by strain gage load cells, and the measurements were acquired by taking photographs of the traces from an oscilloscope.(3) Subsequent developments with the embedded weight sensors included different iterations on platform designs using steel plates and strain gage load cells, steel bending plates instrumented with strain gages, and strip sensors. The utility of the earliest WIM systems was severely limited by the sensing, signal conditioning, and data acquisition technologies available at the time. Modern WIM systems are largely unencumbered by the technology limitations of the past and typically consist of roadway sensors that classify vehicles by type and measure the vehicle weight and the supporting electronic hardware and software needed to process, sort, analyze, and transmit the recorded data. These WIM systems effectively capture and record the axle or axle group weights and the GVW while the vehicle is moving at normal highway speeds.

The operational principle of WIM sensors is based on measuring axle loads through the signals recorded by sensors, such as voltage, strain, and resistance. Typically, WIM sensors are embedded in the pavement surface. The accuracy of WIM systems is affected by the interaction between pavement and vehicle, which is dependent on pavement roughness, vehicle suspension, and speed. Other factors that influence the accuracy of WIM systems are the installation, calibration, and maintenance procedures of the sensor system.

WIM systems are used to determine vehicle characteristics, including GVW, speed, axle weight, and axle spacing. Common WIM sensor technologies used to measure weight include polymeric, ceramic, and quartz piezoelectric systems; bending plates; and load cells.

B-WIM was first used to measure vehicle weight in the 1970s; the data acquisition hardware and software of B-WIM have been continuously developed since then.(4,6) A B-WIM system uses the measured responses of a bridge (usually strain) to determine the weight and other characteristics of crossing trucks. B-WIM systems typically require more elaborate data analysis and interpretation procedures to determine the truck characteristics than are necessary for traditional WIM systems installed in a single lane of pavement. This is due to factors such as the possibility of multiple presences of trucks and other vehicles on the structure, changes in structural behavior due to environmental effects, geometric and structural complexity of the bridge, and dynamic interactions between trucks and the bridge.

CHAPTER 2. REGULATIONS ON TRUCK WEIGHT LIMITS

HISTORY OF FEDERAL TS&W REGULATIONS AND RELATED STUDIES

The *Comprehensive Truck Size and Weight Study*, published by the U.S. Department of Transportation (USDOT) in 2000, summarizes the chronology of developments in Federal TS&W limits.(7) The following section presents an abbreviated description of that chronology as it helps to frame the evolution of the Federal TS&W limits currently in place for the U.S. Interstate System.

The first limits on TS&W for vehicles operating on the Interstate System were imposed by the Federal Government in 1956.(7) The *Federal-Aid Highway Act of 1956* (Public Law 84-627) authorized construction of the National System of Interstate and Defense Highways (Interstate System) and established size and weight limits for commercial vehicles operating on this system.(8) The maximum weight limits were set at 73,280 lb for gross weight, 18,000 lb for single axles, and 32,000 lb on tandem axles. States that already had stricter weight or size regulations in place when the Federal limits went into effect were permitted to keep using them.

Both the allowable gross weight and axle weight limits for interstate highways were subsequently increased by Congress in 1975 when it enacted the *Federal-Aid Highway Amendments of 1974* (Public Law 93-643).(9) The legislation amended Title 23 United States Code (U.S.C.) § 127, increasing the gross weight limit to 80,000 lb, the single axle limit to 20,000 lb, and the tandem axle limit to 34,000 lb.(10) It also enacted the Federal Bridge Formula, limiting the weight-to-length ratio of any vehicle crossing a bridge.(11) The law still permitted States to adopt lower, stricter weight limits if they already had such regulations in effect in 1956.(7)

Congress later required States to adopt the Federal length and weight limits on the Interstate System with the passage of the *Surface Transportation Assistance Act of 1982* (*STAA*) (Public Law 97-424).(12) This legislation also required States to permit commercial vehicles with *STAA*-defined dimensions to operate on the Interstate System and other qualifying Federal-aid primary system highways. The last significant changes to Federal TS&W limits were made by the passage of the *Intermodal Surface Transportation Efficiency Act of 1991* (Public Law 102-240), which prohibited States from allowing expansion of longer combination vehicle (LCV) operations, and the Transportation Equity Act for the 21st Century (Public Law 105-178), which extended the prohibition of expanded LCV operations.(13,14)

In 1990, the Transportation Research Board (TRB) conducted a comprehensive study that quantified the potential impacts of 10 proposed truck weight regulations.(15) It was found that a 10 percent increase in the number of equivalent single-axle loads (ESALs) on the Nation's highways would trigger an annual need for additional $25 million for new and reconstructed pavements and $350 million for the resurfacing of existing pavements. It was also found when designing new pavements that the required pavement thickness slightly increases as a result of the increased traffic loadings.

In 1990, another TRB study assessed the costs of fatigue life reduction and substandard load ratings on bridges caused by a variety of proposed new truck weight limits.(16) The study covered bridges constructed according to current and older design standards. It was estimated that the proposed new truck weight limits and vehicle configurations would require an additional investment of several billion dollars per year for bridges depending on the scenario of the proposed truck weight limit. The cost for replacing substandard bridges as a result of strength rating was dominant among all the bridge cost impacts considered. This was the first effort made to include new bridges as a cost impact category.

In the *Comprehensive Truck Size and Weight Study* conducted by USDOT, several vehicle scenarios of truck weight limit changes were considered and compared with a base case to estimate the cost impacts.(7) Each scenario included seven or eight truck configurations. The factors considered in the study include infrastructure costs, safety, productivity, traffic operations, and intermodal competition. It was found that the impacts of TS&W depend on several factors, including GVW, axle weight, the distance between axle groups, pavement type, and bridge type and length. The analytical framework developed from this study is flexible and can be adjusted to assess specific proposals.

In 2002, TRB conducted Special Study 267 concerning the regulation of weights and sizes of commercial motor vehicles.(17) This study suggested that methods used in past studies had not received adequate estimates of the effect of changes in truck weights regarding bridge costs. It found that the efficiency of the highway system may be improved by reforming Federal TS&W regulations, which may involve allowing larger trucks to operate. The committee recommended a federally supervised permit program to allow the operation of heavier vehicles, provided that the changes applied only to vehicles with a maximum weight of 90,000 lb, double trailer configurations with each trailer up to 33 ft, and an overall weight limit governed by the Federal Bridge Formula.

A new comprehensive TS&W study is currently being conducted by USDOT under the *Moving Ahead for Progress in the 21st Century Act*.(18) The objectives of this study include evaluating safety risks, impact on infrastructure (pavements and bridges), levels of compliance and enforcement caused by trucks operating at different TS&W limits, and potential modal shift. Alternative configurations (including configurations that exceed current Federal TS&W limits) are being compared with the current Federal TS&W regulations, and the effects on freight diversion resulting from these alternative configurations will be analyzed. The results of this study were not available at the time this report was written.

CURRENT FEDERAL TRUCK WEIGHT REGULATIONS

Truck weight regulations significantly affect the design of transportation infrastructure and the efficiency of truck freight transportation operations. Truck weight regulations have evolved continually through fluctuations of the economy, vehicle technology advancements, pavement structural capacity changes, and emerging bridge structural designs.

Federal law currently limits single axles to 20,000 lb and tandem axles (axles closer than 96 inches apart) to 34,000 lb.(7) GVW is limited to 80,000 lb. Federal law also regulates that States cannot impose stricter weight limits than the Federal limits on interstate highways. In addition, Federal law regulates bridge formula weight limits, which control vehicle weights, to protect the Nation’s bridges.(7) In particular, it limits the weight on groups of axles depending on the distance between those axles. The limits are determined by using the Federal Bridge Formula (see figure 1).(11)

$$W = 500\left[\frac{LN}{N-1} + 12N + 36\right]$$

Figure 1. Equation. Federal Bridge Formula.

Where:

W = Gross weight on any group of two or more consecutive axles, to the nearest 500 lb.
L = Distance between the outer axles of any group of two or more consecutive axles, in ft.
N = Number of axles in the group under consideration.

For example, the weight limit on a tandem axle with an axle spacing of 9 ft is 39,000 lb (see figure 2).

$$W = 500\left[\frac{(9)(2)}{(2-1)} + 12(2) + 36\right] = 39{,}000$$

Figure 2. Equation. Example calculation of the weight limit for a tandem axle using the Federal Bridge Formula.

STATE REGULATIONS ON TRUCK LOADS

Generally, each State has a State-specific version of weight limits and regulations governing trucking activities. Detailed regulations may impose separate limits for certain classes of roads and bridges. Although basic Federal TS&W limits have not changed since 1982 (with the exception of the LCV freeze), several States have been granted exceptions by Federal legislations to GVW or axle weight limits.(15) In addition, States are granting an increasing number of permits for oversize/overweight (OS/OW) trucks.(15) The *Comprehensive Truck Size and Weight Study* conducted by USDOT summarizes the following general State weight limits: single axle, tandem axle, bridge formula, and GVW.(7) These limits usually apply both on and off the Interstate System.

The following is a summary extracted from the National Cooperative Highway Research Program (NCHRP) Synthesis 453 on the States' legal loads:(19)

- A total of 36 of 50 States set limits for axle load at 20,000 lb, and 14 States set higher limits on axle load, with the highest being 24,000 lb.
- A total of 33 of 50 States set limits for load on tandem axles equal to 34,000 lb.
- A total of 17 States set higher limits for tandem-axle load. The highest limit is 48,000 lb.
- A total of 32 States set limits for GVW equal to 80,000 lb, the limit set in Title 23 U.S. Code.(10)

- A total of 9 States set GVW limits greater than 100,000 lb. The largest limit is 164,000 lb.
- States set limits on GVW in relation to axle count and wheelbase using the Federal Bridge Formula or using State-specific bridge formulas.
- Some States have seasonal provisions for exemption of legal loads. Vehicles are exempt for specific uses, specific commodities, or specific owners. For example, in North Dakota, agriculture-related loads receive a 10 percent increase over legal loads during harvest time.

OVERLOAD PERMITS

Trucking accounts for approximately 80 percent of freight transportation expenditures in the United States. An OS/OW permit is required for trucks traveling with a size or weight exceeding the legal limits for dimension and weight regulated by State agencies. The state-of-practice of OS/OW vehicle permitting systems varies at different State and local agencies in terms of permit type, fee structure, and operation process. The trucking industry has expressed its concern over the multiple permit application processes and permits fee structures available across the States in an interstate trip, which may cause truck fleets to change their vehicle configurations or pay loads when transporting the same goods through different States.(20)

According to FHWA, any vehicle with a total GVW exceeding the legal weight of 80,000 lb (Title 23 Code of Federal Regulations (CFR) Part 658.17) requires an overweight permit.(7,21) It has been noted that an 80,000-lb truck does as much damage to the road as 9,600 cars do.(22) The stress level for pavement is mainly determined by truck wheel loads. However, bridge stress levels are controlled by weight distribution. Hence, the weight per axle and axle spacing must also be monitored. FHWA limits the allowable single axle weight to 20,000 lb for overweight vehicles. In addition, a bridge weight formula was developed and applied to commercial vehicles to determine the total gross weight.(11)

In some cases, a permit cannot be issued if a bridge is determined to be overstressed when carrying the excessive weight. Therefore, the load capacity of bridges might control the issuance of permits.(20) For example, an old bridge may need to be improved in case of repeated overweight loading.

Many State agencies issue superload and oversize permits in addition to annual or routine permits. Threshold dimensions or threshold weights for the extra-legal loads are specified by each State agency. For example, Indiana issues oversize and/or overweight permits for a load that exceeds legal dimensions but does not exceed the following upper threshold dimensions: 16 ft wide, 110 ft long, 15 ft high, and 120,000 lb.(23) The resulting fee for an oversize and overweight permit is the larger of the calculated overweight or oversize fees, and a superload permit is required if the load exceeds the upper threshold dimensions and does not fall under any other permit type.(23) In certain States, the number of axles is considered in conjunction with superload thresholds. In Illinois, for example, the threshold of 120,000 lb is valid only for trucks with six or more axles.(24) However, it is unknown how the thresholds were established among the various States; they might have been primarily based on expert judgments that considered the load capacity of pavements and bridges in that State.

PERMIT FEE STRUCTURE

Typically, permits can be divided into several categories based on cargo, load, truck configuration, trip, and time. Based on loads, permits can be divided into divisible load-related permits and non-divisible load-related permits. According to Title 23 CFR Part 658.5, *non-divisible* means any load or vehicle exceeding applicable length or weight limits which, if separated into smaller loads or vehicles, would compromise the intended use of the vehicle, affect the value of the load or vehicle, or require more than 8 work hours to dismantle using appropriate equipment.(25) It is noted that the number of non-divisible trip permits issued in each State significantly exceeds the number of divisible trip permits.

Based on trips, permits can be divided into single-trip permits and multi-trip (annual) permits for a given time period. Single-trip permits are valid from one point of origin to one specific destination, and the hauler is allowed to make the move during the times specified on the permit (usually 4 to 6 consecutive days). Recently, annual or multiple trip permits have become more commonplace, which has become a concern for FHWA, presumably because the larger loads and their increased frequency may not be adequately represented by the notional load model used for bridge design.(26)

Though there are a variety of permits in each State, the fee structures in overweight single-trip permits, oversize single-trip permits, and annual permits can be representative of the fee structure in each State agency. An extensive review of the permit fee structure of each State shows five major fee considerations when issuing single-trip permits: number of axles, distance and weight (combined), distance, weight, and flat rate.

The number of States in each fee structure is shown in table 1. Most States in the West, including California, Arizona, Oregon, Washington, Utah, and Nevada, use a flat fee for their single-trip permit structure. Single-trip permits are very attractive for truckers in the West because flat-rate fees are generally much less expensive than distance-based fees.

Table 1. Factors considered in single-trip permits in 50 States.

Factors	Number of States
Number of axles	4
Distance and weight	13
Distance	2
Weight	9
Flat rate	22

In terms of the difference between single-trip permit fees and annual permit fees, it can be concluded that fees associated with multi-trip permits are only slightly more expensive than those associated with single-trip permits. Most States have adopted single-trip permit fees that scale by weight or distance but still assign flat-rate fees to annual permits.

Agencies issue permits for the purpose of ensuring the safe travel of loads on State highways. It is difficult to effectively assess the damage done to the infrastructure as a result of permitted vehicle travel. Currently, in Oregon, a value is periodically assigned to the damage caused by trucks to both pavements and bridges, and that cost is used to establish a weight-mile tax structure.(27) Another trend in permit issuance is that some highway agencies switched from single-trip permit systems to annual, blanket flat-fee permit systems after the early 1990s. It is reported that while these agencies benefited from the convenience of reduced monitoring of single trips, they lost significant revenue because there was no limit for the number of trips they made in 1 year on an annual permit.(28)

CHAPTER 3. WIM SYSTEMS OVERVIEW

WIM SYSTEMS DEVELOPMENT

There have been many initiatives contributing to the development and improvement of WIM systems. In the United States, the American Association of State Highway and Transportation Officials (AASHTO) Technology Implementation Group designated WIM as a concept of focus technology in 2004. The work conducted under FHWA's LTPP Program resulted in the development of a field operations guide for WIM sites.(29) The guide contains recommendations for WIM system installation, calibration, operation, and data validation procedures that enable these systems to collect research quality data. Activities targeting WIM system development in Europe include the *Weigh-In-Motion of Axles and Vehicles for Europe (WAVE)* project and the European Cooperation in Science and Technology 323 project: *Weigh-In-Motion of Road Vehicles*.(30,31)

A significant challenge associated with WIM systems is installing sensors in the roadway pavement. This requires temporary roadway closures and pavement cuts for placing sensors. The condition of the existing pavement at the installation site may also create challenges for installation and for obtaining reliable truck weight measurements. The pavement at the site must be sufficiently smooth for a minimum distance before and after the location of the weight sensor to minimize the influence of vehicle dynamics on the weight measurements. In practice, existing pavement sections often do not meet the minimum smoothness specifications for WIM system installations. This can require rehabilitation or replacement of the existing pavement at the WIM site to achieve the required smoothness. Maintaining the required smoothness at the WIM site throughout the lifespan of the WIM installation also poses a challenge.

The ASTM E1318 standard for WIM systems classifies WIM systems according to the following four distinct types (Type I through Type IV), depending on the application and functional performance requirements:(2)

- **Type I and Type II systems:** Suitable for traffic data collection purposes, with Type I systems having slightly more stringent probability of conformance requirements. Vehicle speed range to meet functional performance requirements is 10 to 80 mi/h.

- **Type III systems:** Suitable for screening vehicles suspected of weight limit or load limit violations and have stricter functional performance requirements than Type I and Type II systems. Vehicle speed range to meet functional performance requirements is 10 to 80 mi/h.

- **Type IV systems:** Not approved for use in the United States but intended for use at weight enforcement stations. Vehicle speed range to meet functional performance requirements is 2 to 10 mi/h.

The following discussion is limited to WIM systems for traffic data collection applications because weight enforcement applications are beyond the scope of this project. It is important to note that the functional performance requirements for Type I and Type II systems can be satisfied by most of the WIM system technologies currently available on the market, but the initial cost, installation, maintenance, calibration requirements, and long-term performance characteristics for the different available technologies can vary significantly.

COMPONENTS OF A WIM SYSTEM

Although there are some portable WIM systems currently under development, using these devices for traffic data collection has revealed many installation and calibration challenges that make their use problematic for traffic data collection on high traffic routes or for extended durations.(32) The vast majority of traffic weight data collection has been and is currently performed using permanent WIM systems.

The major components of permanent WIM systems include various sensors embedded in the roadway surface to detect, weigh, and classify vehicles; software and electronics to control the WIM system sensors and collect, analyze, and store the sensor measurements; and communications hardware used to transmit the vehicle measurements offsite. The electronics and communications devices are usually located in a roadside cabinet adjacent to the WIM site, and the system is powered by either a direct AC power connection or by batteries charged by a solar panel array.

Weight Sensor

The weight sensor is the most fundamental and important component in the WIM system because it directly measures the force applied by the vehicles passing over the sensor. The principal weight sensor types used extensively for permanent WIM system installations include bending plate, load cell, and piezoelectric. These weight sensor types primarily differ according to their principle of operation. Each sensor type also has its own advantages and disadvantages with respect to its use for WIM systems.

Bending Plate Sensors

Bending plate weight sensors utilize strain gages that are mounted to the underside of high-strength, rectangular steel plates called weighpads. The strain gages are wired in a Wheatstone bridge circuit configuration, and when a wheel passes over the weighpad, the WIM system software uses the measured strains to back-calculate the force. The weighpads are covered in vulcanized rubber and are attached to a shallow steel foundation frame embedded in a concrete foundation. Bending plate weighpads are available in a number of different sizes, ranging from 20 by 49 inches to 20 by 77 inches.

When used in a WIM system for traffic data collection, two individual weighpads are usually installed in each traffic lane being monitored. The two weighpads are installed in either an inline (side-by-side) or staggered arrangement. All bending plate WIM systems include an inductive loop installed in the pavement some distance before the location of the weighpads in order to detect the presence of a vehicle and initiate the WIM system measurements. A second inductive loop is usually installed in the pavement after the weighpads to detect when a vehicle has moved beyond the weighpads. The staggered installation arrangement permits the vehicle speed to be calculated directly from the two bending plate measurements. The use of the inline arrangement requires an independent axle detection sensor (usually a piezoelectric strip sensor) to compute vehicle speed. The second inductive loop can also be used for this purpose but is generally less accurate for this purpose. The need for a dedicated axle detection sensor for the inline configuration makes this arrangement less desirable from a cost and long-term maintenance perspective than the staggered configuration. Figure 3 shows a bending plate WIM system installation employing a staggered weighpad configuration.

Figure 3. Photo. Staggered bending plate installation and inductive loops.(33)

Load Cell Sensors

Load cell-based WIM systems use load cells for the weight sensor. A load cell is a transducer that converts an externally applied force into a proportional electrical signal. Although a load cell can be a hydraulic device with a piston and cylinder arrangement, most currently available WIM systems with load cells use strain gage-type sensors. The sensing element of these load cells typically consists of pairs of strain gages mounted to both sides of the web of a specially machined shear beam. When a force is applied to the sensing element, the strain gages measure the principal strains on the beam web, which are used to determine the applied load. The sensing element is capable of measuring high forces, is insensitive to the point of loading, and offers good resistance to side loads.(34)

One type of load cell-based weight sensor used in WIM systems has a single load cell mounted to a steel frame under the center of a rectangular steel loading plate. The weighing unit employs a torque tube that transmits any weight applied to the surface of the load plate to the single load cell. Another type of load cell-based weight sensor used in WIM systems has a total of four load cells installed between a steel frame and each corner of a rectangular steel loading plate. The weight of a wheel located at any position on the loading plate is determined by summing the forces measured by each individual load cell. The rectangular load plates in these systems are approximately 30 by 72 inches, which is large enough to enable each wheel set of a given axle to be weighed individually. Load cell-based systems require a reinforced concrete vault or foundation to support the scales. These vaults are expensive and time-consuming to construct.

As with bending plate systems, load cell-type scales can be installed in a given traffic lane using either an inline or staggered configuration. Inductive loops are usually installed in conjunction with these systems to activate the vehicle measurement sequence. An axle detection sensor may also be used in conjunction with the scales if they are installed using the inline configuration. The load cell-based WIM sensors are the most expensive of the available weight sensor technologies, considering the procurement and initial installation costs; however, they are also considered to be the most accurate WIM technology and are very durable, resilient systems. Figure 4 shows a load cell-based WIM system installed using an inline configuration.

Figure 4. Photo. Inline configuration of load cell-based weight sensors.(33)

Piezoelectric Sensors

Piezoelectric technology can also be used for the weight sensor in a WIM system. Piezoelectric sensors may either be used for measuring weights and vehicle classification or only for vehicle classification purposes (e.g., axle detection and vehicle speed). The sensors used as weight sensors require stricter manufacturing and performance characteristics than those used only for vehicle classification purposes.

Piezoelectric sensors are available in different forms, but they all operate on the principle that when force is applied to a piezoelectric material, a voltage is generated in proportion to the force.(33) The relationship between the applied force and the generated voltage can be quantified and used to determine the weight of a wheel or axle crossing the sensor. This transduction principle only works with dynamically applied loads; weight sensors based on this technology are not suitable for measuring loads applied to them very slowly and cannot be used for static weight measurements. As with bending plate and load cell WIM systems, inductive loops are also used in a WIM application with piezoelectric weight sensors to initiate the measurements when a vehicle's presence is detected. Many WIM system designs using piezoelectric weight sensors employ two separate lines of the sensors, spaced some distance apart, and installed perpendicular to the lane direction (double threshold system) to increase the accuracy of the weight measurements and to collect vehicle classification data.

There are three basic types of piezoelectric sensors available for WIM applications: piezoceramic sensors, piezopolymer sensors, and piezoquartz sensors.

Piezoceramic Sensors: Piezoceramic sensors consist of ceramic powder compressed between a solid copper core and an outer copper sheath. The sensors have small diameters and are similar in size to regular coaxial cables. When they are used as a weight sensor in a WIM system, they are typically placed in a rigid metal channel filled with a glass fiber-reinforced epoxy resin. The top of the sensor must be installed level with the top of the pavement, which requires it be placed in an approximately 2-inch^2 slot cut into the pavement surface and grouted in place. These sensors are available in standard lengths of 6 or 12 ft. Piezoceramic sensors provide weight measurements of average quality and are most suitable for vehicle classification purposes.(33)

Piezopolymer Sensors: Piezopolymer sensors consist of piezoelectric polymer material surrounded by a flat brass casing.(33) The sensor can be installed in a 1-inch-deep by 0.75-inch-wide slot cut into the pavement surface. Installation brackets are placed in the slot at 6-inch intervals to position and support the sensor; once installed, the sensor is surrounded by grout which can be ground flush with the pavement surface after hardening. These sensors have some limitations that reduce the quality of the weight measurements and are more commonly used as axle detectors for vehicle classification purposes.

Piezoquartz Sensors: Piezoquartz sensors are the newest of the piezoelectric sensors available for collecting weight measurements in a WIM system. The piezoelectric material used in this sensor is not sensitive to temperature changes.(33) The design of the sensor packaging is also fundamentally different from the other types of piezoelectric sensors. They are more expensive than the other types of piezoelectric sensors but have been found to be capable of providing good-quality weight measurements. The piezoquartz sensors are installed in an approximately 2-inch-wide slot cut into the surface of the pavement and grouted in place. The sensors are available in different lengths, including 5, 6, and 6.5 ft. Multiple sensors must be installed end-to-end on the same line to cover the full width of a traffic lane. A WIM system design using these weight sensors typically includes a single line of the sensors and two inductive loops, or two separate lines of these sensors and one or two inductive loops. The use of two separate lines of these sensors separated by some distance constitutes a double threshold setup that improves the quality of the weight measurements and collects measurements that can be used for vehicle classification. Piezoquartz sensors were used extensively in the LTPP Specific Pavement Study (SPS) Traffic Data Collection Pooled Fund, TPF-5(004) and found to be capable of providing research-quality traffic load data.(34,36) Figure 5 shows a double threshold installation with these sensors for a WIM system.

Figure 5. Photo. Double threshold WIM system setup with piezoquartz sensors.(33)

Fiber-Optic Sensors

Fiber-optic sensors have also been explored for use as weight sensors for WIM systems. They can function at high speeds, have low temperature dependency, do not require an electric supply, and have the ability to process data in real time.(36) Although fiber-optic WIM systems have been demonstrated in the field, there are currently no commercially available systems.

Weight Sensor Summary

The different weight sensor technologies described in this report have different advantages and disadvantages with respect to their initial cost, installation requirements, and maintenance needs. To select an appropriate WIM sensor, it is important to consider various criteria, including the following:(38)

- Purpose of application.
- Desired data accuracy.
- Traffic flow characteristics.
- Output data requirements.
- Calibration effort.
- Maintenance cost.
- Frequency and level of effort of recalibration.

Table 2 provides a comparison of weight sensor technologies used with WIM systems for traffic load data collection with respect to their initial cost, expected life, applicability, reliability, and sensitivity of the sensing element to temperature changes from a study published in 2007.(38) The costs for each sensor type have increased since then, but the table provides a valid, relative comparison between relative costs and the advantages and disadvantages of the different systems. In general, bending plates are expensive to procure and install, but they can produce research-quality traffic data. Load cell-based WIM systems are the most expensive to procure and install, but they can provide the most accurate weight data. Conventional piezoelectric sensors provide the lowest accuracy with the lowest relative cost. Quartz-piezoelectric sensors have been shown to provide accurate weight data, but the sensors can be expensive. WIM systems using bending plates and quartz piezoelectric sensors were both shown by the LTPP SPS Traffic Data Collection Pooled Fund Study, TPF-5(004) to be capable of providing high-quality traffic data over a period of years if certain site selection and installation procedures are followed and if periodic maintenance, validation, and calibration of the systems are performed. (34,36)

Table 2. WIM sensors comparison.(38)

Characteristic		Bending Plate	Single Load Cell	Piezoelectric Sensor	Quartz-Piezoelectric Sensor
Cost	Initial installation cost per lane (USD)	Medium (~$20,000)	High (~$50,000)	Low (~$9,000)	Medium (~$20,000)
	Annual maintenance and operation costs (USD)	Medium (~$6,000)	High (~$8,000)	Low (~$5,000)	High
Accuracy (GVW 95-percent confidence)		±10 percent	±6 percent	±15 percent	±10 percent
Sensitivity		Medium	Medium	High	None to temperature, but high to roughness
Expected life (years)		6	12	4	Expected > 15
Reliability		Medium	High	Low	Medium

Vehicle Classification and/or Identification Sensor

Vehicle classification data are needed for pavement and bridge design and rehabilitation as well as for traffic analysis. Most WIM systems also collect data used for vehicle classification. Vehicle classification can be accomplished from the measurements recorded by the weight sensors (if they are configured in a double threshold setup or a staggered configuration) or using a combination of the measurements from the weight sensors (inline or single line of sensors) and a dedicated axle detector also installed in the pavement. The inductive loops used in conjunction with WIM systems to detect vehicle presence and to start and stop the measurement sequence can also be used in order to classify vehicles; however, the loops cannot provide information on vehicle characteristics with the same level resolution that is possible with the other approaches previously described.

Regardless of the WIM system used, identifying vehicle configuration involves careful manual analyses of WIM data, including the use of photographs or video to match the load indications with known or feasible truck axle configurations. Identifying realistic truck configurations is critical for performing certain types of traffic/loading analyses. Typical WIM vehicle classification data validation efforts can successfully identify more than half of the wheel loads recorded.

Inductive Loop Detectors

Inductive loop detectors are typically used to determine the entry and passage of the vehicle from the WIM system. The detectors can also provide various information, including vehicle speed, axle spacing, and vehicle length as the vehicle passes over the WIM station.(39) The primary role of loop detectors in WIM systems is to trigger the system to start and stop the weight measurement and classification sequence for each passing vehicle.

From a technical point of view, an induction loop is an electromagnetic system that uses the relative movements of metal over a wire loop that changes the inductance of the loop. An inductive wire loop is installed in the pavement while an electronics unit transmits energy into its wire loops at certain frequencies, depending on the application. When a vehicle passes over or is stopped within the loop, the vehicle induces currents in the wire loops, decreasing the loop's inductance and causing the controller connected to the loop to detect the vehicle. A single-loop detector can capture information such as the presence, counts, flow, and lane occupancy of the passing vehicles. Dual-loop detectors (which often use a pair of loops deployed a few feet apart in the same traffic lane) can be used to determine vehicle speed, axle spacing, and average vehicle length. Inductive loops are generally better suited for vehicle detection than they are for providing high-quality vehicle classification information.

Cameras

Some WIM systems incorporate automatic number plate recognition or license plate recognition cameras to read vehicle registration plates to catalog passing vehicles. They can use existing closed-circuit television or road-rule enforcement cameras or ones specifically designed for vehicle surveillance. Such systems commonly use infrared lighting to compensate for headlights and poor weather conditions that might affect recognition any time of day.(40) Pattern recognition technologies for optical characters are applied to images taken by cameras. The processing of these images can be performed entirely at the lane location in real time or later after images for many lanes are transmitted to a remote computer location. The pattern recognition technology tends to be region-specific, owing to plate variation from place to place.

Another type of camera that may be used for WIM systems is the Internet protocol camera, which is a type of digital video camera used to capture a photograph of an entire vehicle from its side and send and receive data via the Internet. Such systems provide high-resolution color images or video that may require a central network video recorder to handle the recording and storage. Photo imaging systems such as these are sometimes integrated with WIM systems used for screening purposes in weight enforcement applications, such as Virtual WIM. Video cameras are not commonly used with WIM systems designed for traffic data collection purposes, although they can be used to evaluate and validate vehicle classification algorithms employed by the WIM system in these instances.

Laser Scanning

Laser scanning technology is used not only for vehicle presence detection, but also for three-dimensional (3D) vehicle shape recognition and classification (width, length, height, shape, etc.). Such systems, often mounted over the traffic lane, typically emit two eye-safe laser beams to scan the roadway and passing vehicles in order to create a 3D image of the object. Unlike traditional cameras that collect color information about surfaces within its field of view, a 3D scanner collects distance information about surfaces within its field of view. These distances are then used to reconstruct the 3D position of each point on the subject vehicle. When a vehicle enters the beam, the measured distance decreases, and the corresponding vehicle height is calculated based on simple geometry. As the vehicle moves along, the second beam is broken in the same manner. The vehicle speed and length are estimated by measuring the time difference between the breaking of the two beams. Data collected by the sensor are processed and transmitted in real time. This technology can be incorporated with a WIM system design for truck screening in enforcement applications but may be considered too expensive to employ with WIM systems used for traffic data collection.

Automatic Vehicle Classification (AVC)

AVC equipment uses a series of inputs that usually include vehicle presence, number of axles, and the spacing between axles to categorize vehicles into different classes. WIM systems also use these inputs and the axle weights to categorize vehicles. The calibration reexamines the process tests to ensure the algorithm using these inputs correctly classifies the vehicles in WIM stations. Depending on the results, adjustments are made to the algorithm until the output meets the acceptance criteria.

Vehicle weight and classification measurements are made by WIM sensors and AVC systems under challenging, dynamic conditions, and their accuracy and reliability are affected by actual traffic and site conditions at a particular WIM location. No single, standard calibration values exist for these systems that can be valid for all possible locations and traffic conditions. As a result, site-specific calibration and validation procedures must be used for each system. Standardized calibration and validation procedures must be executed following the initial installation of AVC and WIM systems before they can be used to collect reliable traffic data measurements.

AVC calibration involves comparing vehicle classification counts with independent measurements of those same vehicles for a sufficient time period to capture representative data. Independent counts are done manually or by using a video recording technology and then converting the recorded information to classification information. These field tests of the system are the primary means for validating that the AVC equipment and its associated software algorithms are accurately classifying vehicles at a given installation site.

Processor and Data Storage Unit

A processor and data storage unit receives and analyzes the signals from the weight sensors and vehicle classification and/or identification sensors to generate the axle load and vehicle type information that can be used directly by the end user. In most cases, the processor and data storage unit also provides power to the WIM system through a power supply connected to external alternating current power or direct current batteries.(41)

User Communication Unit

The user communication unit provides a communication link between the processor and data storage unit and the user interface. The communication link can be connected directly to a personal computer at the field site or remotely accessed through a wired or wireless modem connection for controlling the systems and transmitting the measurement data offsite. The processor and data storage unit can also directly display the collected data and serve as the user communication unit.(41)

CHAPTER 4. B-WIM SYSTEMS

DEVELOPMENT OF B-WIM SYSTEMS

B-WIM systems use the bending deformations of a bridge caused by vehicles crossing over the structure. These deformations are typically measured using strain sensors attached to the structural members and are analyzed to estimate the GVW and axle loads of passing traffic. Two main approaches to B-WIM have been used. The first approach uses strain sensors mounted on the bridge and a separate axle detection sensor installed on the road. The second approach uses only strain sensors installed on the bridge for both axle detection and weight measurements. The second approach is the more desirable since it simplifies the overall design, installation, operation, and maintenance of the B-WIM system as compared to the first approach.

One potential advantage of B-WIM systems is that the sensors can be removed and reinstalled on a different structure. The portability of the sensors provides some flexibility regarding where the system is installed to collect traffic data that is not available with permanent WIM systems installed in the roadway. Another advantage of B-WIM systems is the potential for using the measured bridge responses for traffic data collection and for evaluating the performance of the structure itself. In many cases, the same sensors on a structure can provide data that can be used for both objectives. In other cases, additional sensors of the same type and with the same signal conditioning requirements can be added to the structure to supplement the sensors needed for traffic characterization. Some examples of such applications could include prescreening, bridge rating, remaining fatigue life evaluations, and bridge condition monitoring.(42–44)

Fred Moses conducted a field test of a B-WIM system and reported 11-percent error at a 95-percent confidence interval as compared with the GVW of calibration trucks.(6) This proves the feasibility of using strain measurements for weight estimation for the first time. Snyder and Moses developed an inverse matrix solution to calculate individual axle weight based on the influence lines of bridges.(42) The influence lines for an in-service bridge require rigorous modeling of the bridge structure. O'Brien et al. made the transition from requiring an actual influence line for each bridge to only requiring a theoretical influence line for B-WIM.(45)

Ojio and Yamada developed an approach that allowed them to avoid using influence lines for data analysis and to determine GVW using integration of strain data with adjustment factors for speed and truck type.(46) In a separate study, Cardini and DeWolf demonstrated the feasibility of this method in a field test on a multi-span steel girder bridge.(47) Advanced computing methods, such as neural network and wavelet-based analyses, have been used for truck classification and analysis of strain signals to estimate vehicle speed, axle spacing, axle weight, and GVW.(47–49)

Note that the accuracy of B-WIM systems using strain sensors can be affected by the presence of multiple trucks, whether in parallel or serial configurations, and by other traffic on the bridge. The analysis of measurements collected under such circumstances would require the construction and calibration of a 3D finite element (FE) model by controlled load testing in order to evaluate the measured strains. Given the complexities of the strain measurements that can be produced by the random nature and mix of heavy truck and automobile traffic that may be crossing a bridge at any given time, the use of B-WIM systems can be overly complex and inefficient for continuously characterizing every vehicle crossing a particular bridge in the same manner as permanent WIM systems installed in roadways. The system operation and data analysis can be simplified if measurements are only recorded on a triggered basis, using threshold strains corresponding to trucks crossing the structure. Controlled load testing of the structure is usually necessary to establish the threshold values. Photographs of the actual traffic on the structure when the strain measurements are triggered can also be useful for validating the measured strain results and interpreting them in conjunction with a calibrated FE model of the structure.

MOVING FORCE DETECTION IN B-WIM

Moving force detection is based on minimizing the differences between measurements and the corresponding strains calculated from theoretical models. The original B-WIM algorithm developed by Moses assumes that the bending of bridge is in proportion to the product of the load magnitude and the influence line of bridge.(6) The measured strain is the result of all axle forces on the bridge; therefore, it is difficult to distinguish the contribution of each axle. Accordingly, this method would provide better accuracy for calculating GVWs than axle weights. In this method, the influence of bridge and vehicle dynamics on the influence line is not considered.

Solving the minimization problem is difficult even when multiple sensor data are used. The theoretical approaches used in the B-WIM model can be divided into two categories: the FE method and the exact solution method coupled with the system identification technique. The approach using an exact solution method is generally subject to large fluctuations in the predicted force at the start and end of the time history. The method of Tikhonov regularization has been employed to provide an error-bound and smoother solution.(50–52)

Many alternatives have been proposed such as the Culway WIM system and Matui’s method.(53,54) The Culway WIM system weighs trucks using culverts that minimize the vehicle dynamics as a result of the damping effect caused by the interaction between the culvert and the surrounding soil. Rowley proposed a regularization procedure to improve the accuracy of the least square approach for identifying axle weights originally developed by Moses.(55) Field test results showed that the modified algorithm and the experimentally calibrated influence line could generate accurate results for axle weights.

The use of one-dimensional beam models to represent the dynamics of the bridge may not be accurate because torsional and lateral modes of vibration also contribute to the overall dynamic behavior of a bridge structure. Zhu and Law modeled a bridge deck as an orthotropic plate subject to moving forces and idealized as a group of moving forces representing each wheel load.(56,57) The principle of modal superposition is used to solve the equilibrium equation of motion in the time domain. Quilligan et al. developed two-dimensional (2D) algorithms for orthotropic steel decks that were validated using FE models and experimental tests.(58) A number of researchers have developed approaches that specifically consider the dynamics of the system.(59,60)

Gonzalez et al. solved the moving force identification problem using the FE method and first-order Tikhonov regularization on a 2D orthotropic plate bridge model.(61) Strain measurements were simulated using a 3D vehicle and bridge interaction system. The problem was solved by performing a least squares minimization of the difference between measured and theoretical strains. In this process, it is assumed that vehicle velocity, number of axles, and axle spacing are known from axle detectors on the road, and deterioration of bridge stiffness is negligible with the passage of the vehicle.

It is desirable to develop B-WIM systems that do not require separate axle detectors on the road surface because this helps simplify the design, installation, and maintenance. For example, a commercially available B-WIM system developed within the framework of the WAVE project uses a free-of-axle-detector (FAD) or nothing-on-road (NOR) configuration. The FAD or NOR systems are prevailing types of B-WIM used in Europe. FAD and NOR configurations have been applied on different types of bridges and with sensors installed on different bridge components, including web stiffeners of steel girders and the underside of the concrete deck slabs.(45) The accuracy of FAD or NOR is greatly dependent on the time histories of strain signals produced by moving vehicles. A recorded strain time history can be affected by the dynamic characteristics of the structure, the structural stiffness, the axle spacing, and the vehicle speed.

CHAPTER 5. WIM SPECIFICATIONS AND ACCURACY

ASTM SPECIFICATION

ASTM has established a standard specification for highway WIM systems. The latest revision of ASTM E1318 was published in February 2009, "Standard Specification for Highway WIM Systems with User Requirements and Test Methods."(2) The ASTM E1318-09 standard has specifications covering definitions, four various types of WIM systems, site specifications, testing and calibration requirements, data recording, and ESALs calculations. This standard is used as a guideline by most WIM users around the world.

The ASTM E1318-09 standard defines WIM as "the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle."(2)(pg.1) In addition to tire-load information, a WIM system is capable of recording traffic data such as speed, lane of operation, date and time of passage, number and spacing of axles, and classification of each vehicle.

A WIM standard specification includes the following elements:

- Terminology.
- **Type/classes:** Can be classified according to application or accuracy class.
- **Performance requirements:** Include features/functions, applications, and tolerances (estimated tire loads, speed, and axle spacing).
- **User requirements:** Include site conditions (such as road geometry, surface smoothness, pavement structure, temperature ranges, etc.), recalibration procedure, and acceptance test.
- **Test methods (to be specified by user):** Include reference tire loads and axle spacing for static vehicles, calibration procedure, type-approval test, and onsite acceptance/ verification test.

FACTORS AFFECTING WIM ACCURACY

Many factors can affect the accuracy of a WIM system, such as site condition, vehicle characteristics, and environment condition.

Temperature

Temperature and humidity can affect the accuracy of each sensor used in a WIM system and the accuracy of the overall WIM system. Temperature is a critical parameter because it can change the performance of many of the sensors and the pavement material properties. This can cause the contact force measured by the WIM sensor to vary at different temperatures. WIM sensors embedded directly into asphalt pavements have greater temperature variations than the sensors embedded in concrete pavements because asphalt material becomes soft in hot weather. The condition of the pavement located before and after the WIM site is also influenced by temperature, which can affect the dynamics of a vehicle as it crosses over the WIM sensors. The use of concrete pavement at the WIM site can help mitigate these effects, and WIM sensors installed in frames or housings that isolate the sensor from direct contact with the surrounding pavement are also less sensitive to temperature influences on pavement material properties. Since temperature influences on WIM system performance can never be completely eliminated, the operation of a WIM system should be validated over the full range of temperatures expected at a given WIM site. The specifications for a WIM site should include the full range of ambient temperatures that can be expected for a particular installation site, and sensors must be supplied for the WIM that are capable of providing reliable measurements while operating within the specified temperature limits.

Roughness

Conditions such as road geometry, slopes, and surface condition at the location where the WIM sensor is installed can affect the WIM measurement. Among these factors, road surface roughness has the most significant effect on the accuracy of a WIM sensor. *Pavement roughness* is defined as the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality.(62) Short wavelength roughness affects the axle motion, and long wavelength roughness causes vehicle body motion.(38) This can cause variation of the dynamic axle force measured by the WIM sensor. The ASTM E1318-09 standard requires that the surface of the paved roadway 200 ft in advance and 100 ft beyond the WIM system sensors shall be smooth before sensor installation.(2) The standard further stipulates that the surface smoothness shall be maintained such that a 6-inch diameter by 0.125-inch-thick circular plate cannot pass under a 16-ft-long straightedge that is swept across the lane at different distances from the WIM sensors.(2) Recently, AASHTO published a provisional standard for pavement smoothness requirements in the approach to WIM systems.(63) The field operations guide developed for LTPP WIM sites specifies pavement smoothness criteria applicable for the 900-ft approach to the WIM sensors and for 100 ft after these sensors.(29) Longitudinal smoothness can be checked using a straightedge procedure in the 400-ft approach to the WIM sensors and for 100 ft beyond the sensors to determine if short wavelengths of dynamic vehicle motions are within acceptable limits.(29) The guide also has specifications for checking the transverse smoothness of the pavement at the WIM sections using the straightedge procedure.

Vehicle

Many vehicle characteristics, including speed, tire type and inflation pressure, suspension system, and axle configurations, affect the dynamic tire force, thus affecting WIM sensor measurement as well. The effects of vehicle characteristics on WIM sensor accuracy is interconnected with the effect of road surface roughness as the dynamic tire force is dependent on both factors.

INSTALLATION AND CALIBRATION OF PERMANENT WIM SYSTEMS

Best practices for WIM installations are available in the *States' Successful Practices Weigh-in-Motion Handbook*.(63) *The LTPP Field Operations Guide for SPS WIM Sites* updated these recommendations based on the experience gained from the pooled fund study on traffic data collection.(29,34) Some of these important recommendations are as follows:

- Installation must be done in good weather, not wet, freezing, or hot conditions.
- The sensors must be flush (within 0.04 inch) with the road surface.
- The top of the sensor must be separate from the road surface.
- The equipment must be protected from water and dust.
- The equipment cabinet must protect the system electronics from extreme temperatures, dust, humidity, and insect and rodent infestation.
- The equipment must be protected from lightning and power surges.
- The equipment must be installed so that routine maintenance can occur without disruption of data collection.

The *States' Successful Practices Weigh-in-Motion Handbook* also summarizes the installation procedures for the WIM system for bending plates, load cells, and piezoelectric sensors.(63)

The following is the installation process for a bending plate:

1. Initial test.
2. Prepare the road.
3. Install scale frames in the scale pit.
4. Install scale pads in the scale frame.
5. Final test.

The following is the installation process for a load cell:

1. Initial test.
2. Prepare the road.
3. Prepare the pit to receive the scale frames.
4. Prepare the scale frames.
5. Install scale frames in the scale pit.
6. Clean up the frame installation.
7. Prepare the single load cell scale pads.

8. Install the single load cell scale pads into the frame.

9. Test the operation of the load cell.

10. Final test.

The following is the installation process for a piezoelectric sensor:

1. Initial test.

2. Preparing the road.

3. Install sensor in the main slot.

4. Final test.

The measurements by WIM systems are made under dynamic conditions. This can result in difficulties associated with determining the reference value for the calibration procedure and developing a method for a WIM system's accuracy assessment. A system calibration must be applied immediately and repeated periodically after the initial installation of a WIM system.

In order to ensure that WIM systems give estimated weights that are as close to the actual static weights as possible, a calibration procedure is required. Factors such as pavement temperature, vehicle speed, and pavement conditions affect the estimated weight. ASTM 1318 procedures recommend the following process to calibrate WIM systems:(2)

1. Adjust all WIM system settings to the vendor's recommendations or to a best estimate of proper setting based on previous experience for the initial calibration.

2. Force vehicles that go through the system for calibration purposes to enter into the static scales at the site or a nearby facility to obtain static weight data. With a radar gun or other means, take speed data to measure the speed of the truck over the WIM sensors.

3. Record wheel loads and/or axle weights and axle spacing at the static scales.

4. Calculate the difference between the WIM system estimate and the reference value for speeds, wheel loads, axle loads, axle group loads, GVWs, and axle spacing measurements. Express the differences in percent, and obtain a mean value for each set of measurements.

5. Enter the calibration factors into the WIM system.

6. Determine whether the calibrated system can be expected to perform at the necessary tolerances. If the differences are greater than the ASTM specified tolerance values for a specified system, then the system is not expected to perform well.

7. Note precision and bias information, although no procedure has been developed to determine what effect this data has on WIM system performance at this time.

Calibration procedures for WIM systems are summarized in *NCHRP Synthesis 359: High Speed Weigh-in-Motion System Calibration Practices*.(65) *The LTPP Field Operations Guide for SPS WIM Sites* provides recommended field validation and calibration procedures and guidance for determining how often they should be performed to ensure that the WIM system data are reliable.(29)

The calibration of WIM scales must be checked and, if necessary, revised to be in accordance with the LTPP procedures.(29) According to this guide, the LTPP Program anticipates that a maximum of three validation sessions (installation verification or calibration and with two additional validations) is needed for the first year of operation at most scale sites. The LTPP Program recommends that a minimum of two validations be performed each year for WIM sites where the environmental conditions did not change significantly during the year. The LTPP Program recommends that only one validation test would be needed per year if the testing proved that a given scale system (as installed) was operating accurately under the full range of environmental and highway operating conditions. A remote office monitoring process for the WIM systems is used to detect whether there is calibration drift for a given system, requiring additional system calibration tests.

The main function of WIM scale systems is to estimate the static weight of different vehicles within specific tolerances (see table 3).(2,66) In order to determine these tolerances, the percentage of weight difference between static and dynamic loads must be calculated. The errors must then be converted into percentage form for evaluation. The standard deviation of that error can then be used to determine the 95-percent confidence limit.

Table 3. WIM scale tolerance limits.

SPS-1, -2, -5 and -6 Sites	95-Percent Confidence Limit
Single axles	±20
Tandem axles	±15
GVWs	±10
All Other Test Sites	
Single axles	±30
Tandem axles	±20
GVWs	±15

Minimum requirements are important for these calibration steps and must follow the manufacturers’ calibration instructions. Different vehicle speed ranges, temperatures, and/or GVWs may require separate calibration factors for some systems but not for others. The system must work correctly at all times under different traffic and climatic conditions.(67)

Examining the influence of vehicle classification is the second stage of WIM equipment calibration. Field checks are necessary for all WIM system parts, such as AVC and automatic vehicle identification systems, to check the status of the algorithm status. This calibration review involves extensive testing of the algorithm itself. In addition, it is important to test the classification results of the WIM system against those produced by an agency’s AVC equipment to ensure that the results from these alternative devices are compatible.

LTPP PROGRAM'S WIM EXPERIENCE

A significant objective of the FHWA's LTPP Program is to develop a comprehensive understanding of the relationship between pavement performance, truck volumes, and axle loadings. The LTPP Program implemented a traffic pooled fund study, TPF-5 (004), Long-Term SPS Traffic Data Collection, to fill in gaps and improve the quality and quantity of monitored traffic data.(32) The objective of the pooled fund study was to improve the quality and increase the quantity of monitored traffic data.(34) The knowledge gained from a series of pilot studies conducted prior to implementing the LTPP Program pooled fund study is summarized in a report, *SPS Traffic Site Evaluation—Pilots Summary and Lessons Learned*.(65) The following significant conclusions were made:

- The ASTM E-1318 Type I WIM system performance specification is achievable with current technology and practices.
- The recommendation of bending plate sensors in smooth portland cement concrete (PCC) will meet the performance specification.
- The minimum two trucks with a 3-by-3 matrix of temperatures and speed is sufficient to determine whether the weight data is of research quality.
- Smoothness is an important factor in determining variability of weights.
- The current acceptance criteria for straight edge and profiler measurements is inappropriate.
- The straight edge and the profiler smoothness methodologies are not equivalent.
- A better definition of "smooth enough" must be developed for both the straight edge and profiler evaluations.
- Attention needs to be paid to PCC/asphaltic concrete interfaces where they exist on the site.
- A go/no-go standard needs to be established to determine which sites are suitable for evaluation and which will not produce research quality data without prior remedial work.
- A greater emphasis on vehicle classification and a measure of the quality of that aspect of the data is needed.
- The ability to do the analysis of data on site is needed.

The objective of the pooled fund study was to improve the quality and increase the quantity of monitored traffic data (i.e., volumes, classifications, and weights) at the LTPP Program SPS test sites. The study was divided into two concurrent phases due to the scale of the work performed. The scope for phase I of the study included assessing existing WIM equipment for its potential to meet the LTPP Program's precision requirements and performing annual field validations of new and existing WIM equipment. The scope of phase II included evaluating the suitability of sites for installing new WIM systems; installing, calibrating, and maintaining new WIM systems; collecting and validating WIM data; and maintaining WIM systems in accordance with a 5-year warranty period.

SPS Traffic Site Evaluation—Pilots Summary and Lessons Learned also indicates that the 500-ft length of slab at the PCC sites was found to be a reasonable minimum, but this should be considered a minimum criteria rather than a fixed length specification.(68)

The knowledge gained related to collecting research quality traffic data from the LTPP Program WIM sites in phase 2 of the study is reflected in the *LTPP Traffic Data Collection and Processing Guide, Version 1.3* and the *LTPP Field Operations Guide for SPS WIM Sites*.(69,29) The former document presents the processes and procedures used by the LTPP Program to collect and store the traffic data that is used to estimate pavement loadings, while the latter document contains the guidelines for traffic data collection at SPS sites. The second report covers all aspects of the process in the field and is divided into six major operational sections: (1) Site Assessment, (2) Site Validation—Weight, (3) Site Validation—Classification, (4) Pavement Smoothness, (5) WIM Equipment Installation & Calibration Auditing, and (6) Data for Use in LTPP Activities. The LTPP Program pooled fund research project demonstrated that research-quality traffic load and characterization data can be collected from WIM systems for an extended period of time.(34,36) These guide documents serve as important references for guiding the selection, installation, operation, validation, and maintenance of a WIM system expected to provide reliable traffic data.

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