LOW-COST PIEZOELECTRIC WEIGH-IN-MOTION SYSTEMS IN OREGON: 1988-1993

Final Report

Experimental Features Project

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16. Abstract

In 1988, The Oregon Department of Transportation installed low-cost piezoelectric weigh-in-motion cables at three locations and in ten lanes on Interstate 5 and 205. This report documents the installation of the systems, problems, and results from 1988 to 1993.

The findings show that these systems are sensitive to pavement temperatures and need to be auto-calibrated.Their accuracies vary according to the pavement condition and type. Multi-sensor piezoelectric weigh-in-motion systems were evaluated with respect to improving accuracy. The results show that multi-sensors do improve weight accuracies. These systems should be used only in moderate to low traffic volume roads, rather than on the interstate or primary highways, and primarily for data collection purposes.

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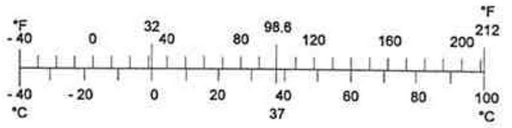
SI* (MODERN METRIC) CONVERSION FACTORS

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	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	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	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

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	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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1.0 INTRODUCTION

In 1987, the Federal Highway Administration (FHWA) gave the Planning Section, now the Transportation Development Branch (TDB), of the Oregon Department of Transportation (ODOT), a grant to test low-cost weigh-in-motion (WIM) systems. Specifically, the piezoelectric WIM (PWIM) cables and piezoelectric automatic vehicle classifiers (PAVC). ODOT installed these automatic weight and classification (AWAC) systems in ten lanes at three sites located on Interstates 5 and 205, eight lanes of PWIM and two lanes of PAVC. This report documents the background, installation, problems and findings from this demonstration project which started in 1988 and ending in 1993.

1.1 OBJECTIVES

The purpose of this demonstration project was to evaluate the potential of these low-cost AWAC systems for data collection and enforcement. The accuracy and durability of this WIM technology, including multiple sensors, was also evaluated.

1.2 BACKGROUND

The ODOT has been active in the application of WIM since 1983 (*1,2*). To date, most WIM systems in Oregon have been utilized for screening heavy vehicles at ports-of-entry (POE) and weigh stations by the weighmasters. In this capacity, the WIM systems interfaced with the automatic vehicle identification system and the Public Utility Commission (PUC) data base. They have effectively increased the capacity of the stations. At the same time, the WIM systems reduce the overall idle time of trucks at the POE, with very favorable results for both POE and vehicle operators (*3,4,5*).

WIM systems in Oregon are also used for data collection by the TDB at the sites. ODOT has been using heavy duty deep pit hydraulic load WIM scales. These are very durable and accurate, but are expensive and costly to install (*2*).

The Bridge WIM system was extensively tested during 1984-85 at some 25 sites in Oregon (*2*). Although the bridge WIM system worked successfully at many sites, its use was marred by being too labor intensive, data requiring detailed analysis, and the need for perfect bridge locations.

ODOT has held some field demonstrations with the WIM capacitance mats. Successful applications were very limited due to weather induced installation problems, studded tires, and traffic. Acceptable weight accuracies were sparingly obtained and limited in scope. Table 1.1 shows the advantages and disadvantages of various WIM systems.

Table 1.1 Advantages and Disadvantages of Various WIM Technologies.

Technology	Advantages	Disadvantages
Deep Pit, Load Cell Based Scales	High Accuracy High Reliability Long Life Cycle	Higher Costs Longer Installation Time Vault Required
Low Profile or Bending Plate Scales	Reasonable Accuracy Reliable No Vault Required (Install in Existing Pavement)	Medium Price
Piezoelectric WIM Systems	Low Cost Quickly Installed in Existing Pavements	Low Repeatability Short Life Cycle
Capitance Pad System	Portable System Similar Price to Permanent Piezo	Repeatability is Lower Than Permanent Piezo
Bridge WIM System	Portable System Install on Bridges	Labor Intensive Requires Good Bridges Repeatability is Questionable

WIM technology from Europe using piezoelectric cables offered a low-cost alternative to the present heavy-duty load cell WIM system currently in use. Oregon did test the French piezoelectric system at the Woodburn northbound weigh station in conjunction with the Washington State DOT in 1986.

Although the tests were inconclusive, enough positive results were obtained to justify a more comprehensive demonstration project. In addition, data requirements for current research projects such as the Strategic Highway Research Program (SHRP) and for traffic information/enforcement made it attractive to study and test low-cost PWIM.

The application of PWIM offers a low-cost system for highway application, filling a much needed role in the current highway data collection and enforcement programs. There is a definite need for WIM data collection on the state and interstate system. PWIM systems offer the ability to gather both classification and weight data for a cost not substantially higher than traditional classifiers. This data is useful for a variety of capacity, safety, pavement design studies, and enforcement programs.

2.0 DEMONSTRATION PROJECT

2.1 SITE LOCATION

Three sites were chosen for testing of the low-cost AWAC systems. Table 2.1 and Figure 2.1 shows the sites, their location, and the pavement type.

Table 2.1 Automatic Weight Classification Systems (AWAC) Site Locations

Highway	Mile Post	Number of Lanes	Location	Pavement Type	Type of PIezo System
I-205	25.5	5 NB[1]/SB[2] 1 NB	South of Jackson Bridge, by Airport Exit	10" CRC[3] 6" CTB[4]	PWIM[5] PAVC[6]
I-5	245.4	2 SB	North of Jefferson Exit	14" AC[7] 16" Agg[8]	PWIM
I-5	18.5	2 SB	South of Butler Creek Road	8" JRC[9] 12" Agg	PWIM

[1] Northbound
[2] Southbound
[3] Continuously reinforced portland cement concrete
[4] Cement-treated base
[5] Piezoelectric Weigh-In-Motion
[6] Piezoelctric Automatic Vehicle Classifier
[7] Asphalt concrete
[8] Aggregate
[9] Jointed reinforced portland cement concrete

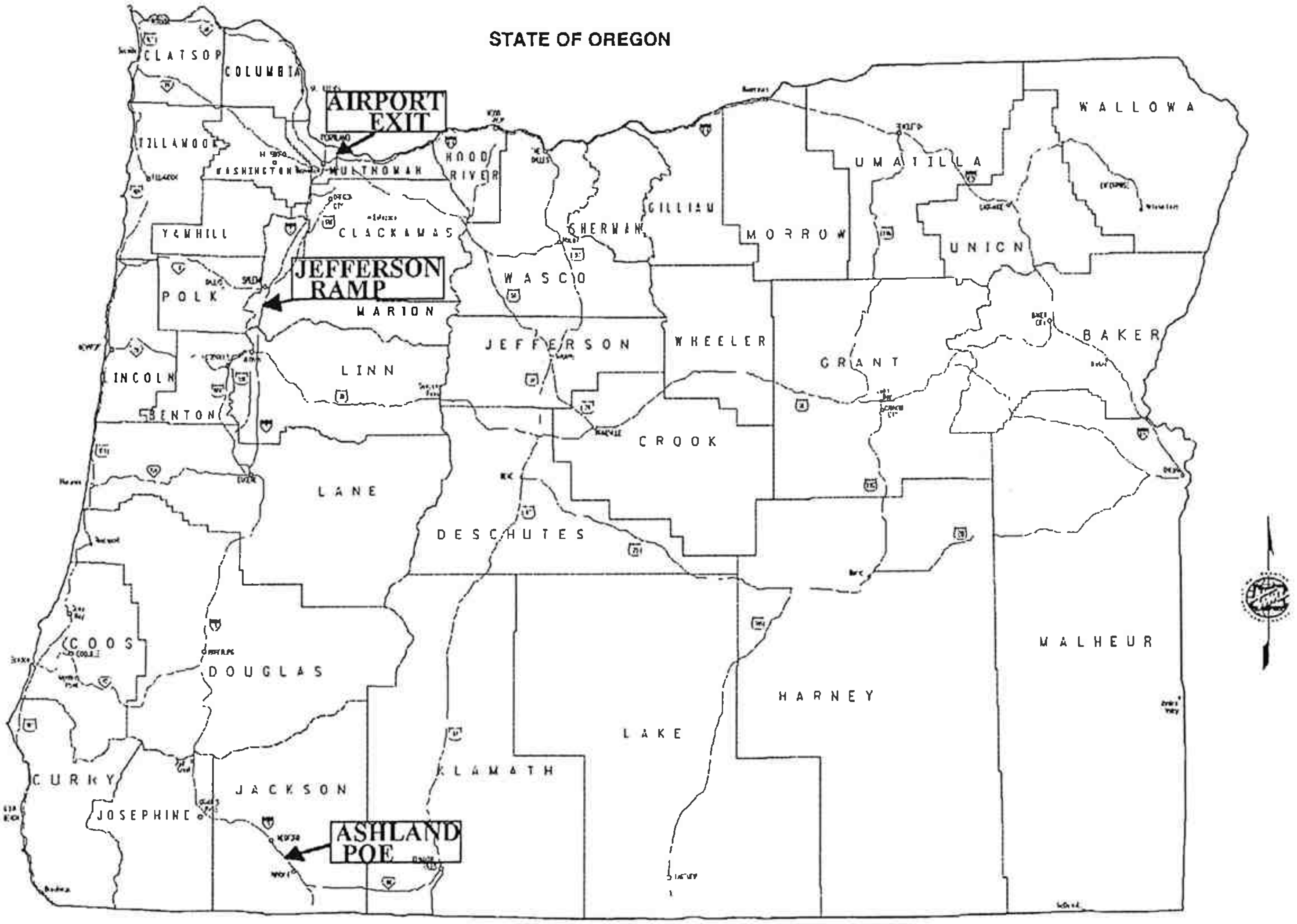
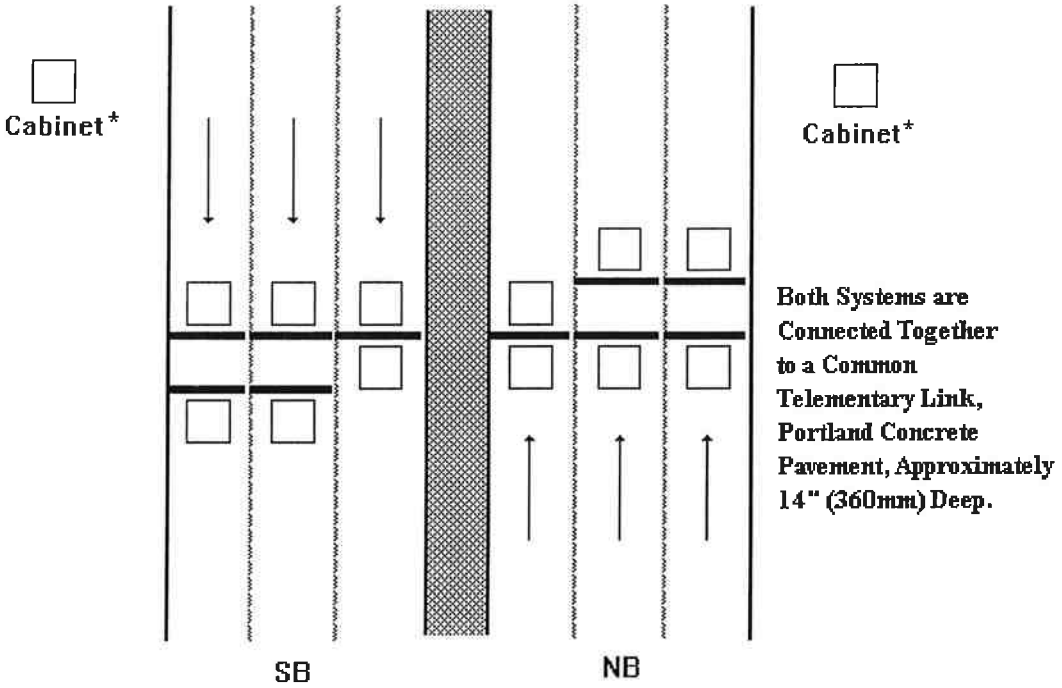


Figure 2.1 Vicinity Map

2.1.1 SITE 1: I-205 NORTHBOUND/SOUTHBOUND, AIRPORT EXIT

This site was chosen because there are no weigh stations on I-205. Commercial vehicles can use this route to Portland and Vancouver without getting weighed. There is also a lack of traffic data on these commercial vehicles. The Portland airport exit area of I-205 was chosen because sight, pavement condition, telephone and power requirements for WIM scales were met. In addition, this site gave ODOT an opportunity to test the PWIM systems in continuously reinforced concrete pavement, under urban traffic conditions, and in all six lanes. The original AWAC configurations installed at this site are shown in Figure 2.2.

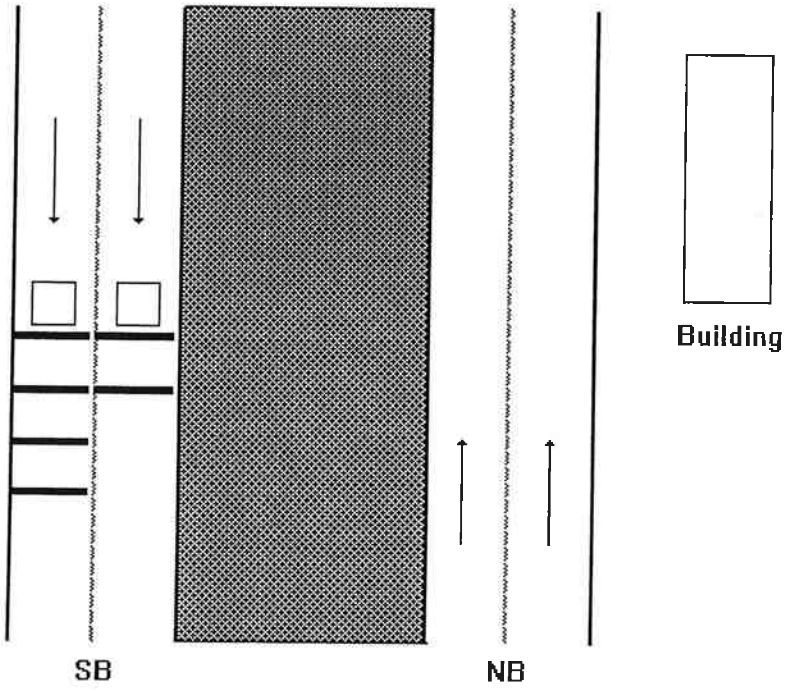


Both Systems are Connected Together to a Common Telementary Link, Portland Concrete Pavement, Approximately 14" (360mm) Deep.

Figure 2.2 Layout of Sites Near Portland, Oregon

2.1.2 SITE 2: I-5 SOUTHBOUND, BY JEFFERSON RAMP

This site was chosen because an existing WIM system was located in the northbound lanes of I-5. Power, telephone and a building existed and could be used, thus minimizing costs. In addition, the PWIM could be evaluated in asphalt concrete pavement in two lanes, using Woodburn southbound POE truck data. The original AWAC configurations installed are shown in Figure 2.3.

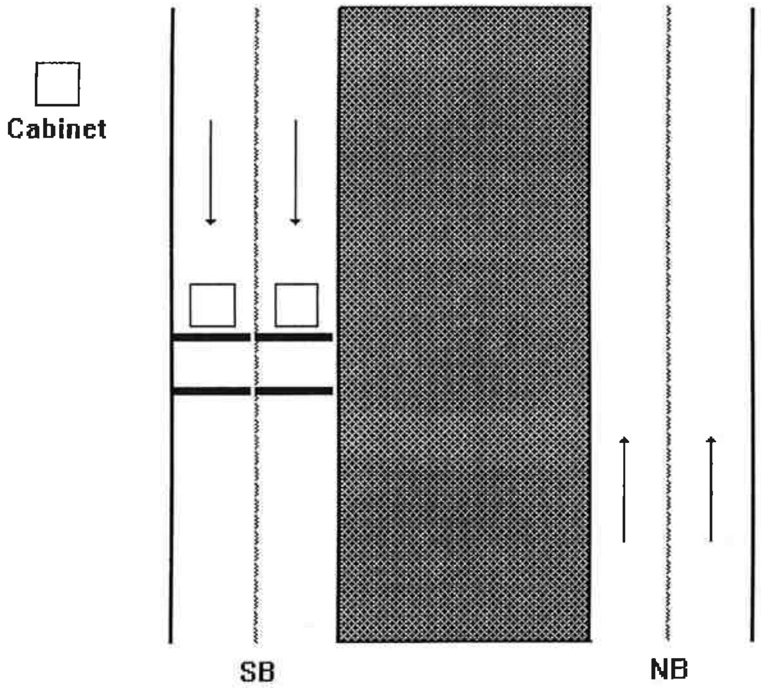


Asphalt Concrete Pavement, Approximately 9" (230mm) Deep, 4" (102mm) Inlay Extended 200' (61m) Either Direction from Sensors

Figure 2.3 Layout of Jefferson Site

2.1.3 SITE 3: I-5 SOUTHBOUND, ACROSS FROM ASHLAND POE

This site was chosen because the Ashland southbound weigh station was located about half a mile away, with available power and telephone sources. Data from the weigh station could be used to calibrate the PWIM systems, thus reducing calibration time and expenses. In addition, the PWIM system could be tested in reinforced portland cement concrete pavement. The AWAC configurations installed are shown in Figure 2.4.



Portland Concrete Pavement, Approximately 10" (250mm) Deep, Angled Joints

Figure 2.4 Layout of Ashland Site

2.2 AWACS CONFIGURATIONS

Configuration A is basically a classifier and was installed in Site 1. Figure 2.5 shows the layout.

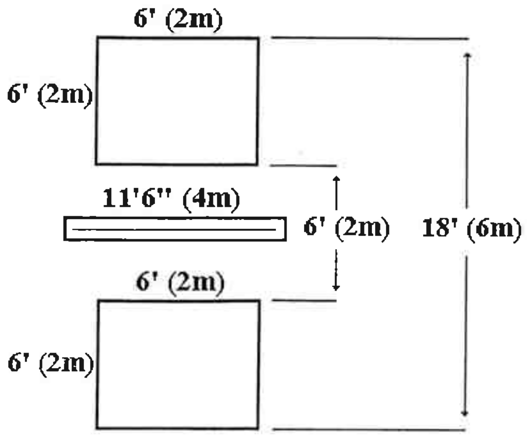


Figure 2.5 Configuration A: Two Inductive Loops, One Class 1 Piezo Cable (Loop Piezo Loop)

Configuration B, Figure 2.6, was for weight and classification, and were installed in Sites 1, 2 and 3.

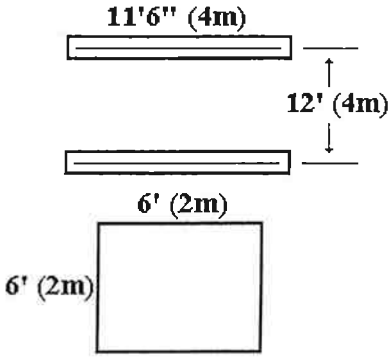


Figure 2.6 Configuration B: Inductive Loop, Two Class 1 Piezo Cables (Loop Piezo Piezo)

Configuration C, Figure 2.7 was installed at site 1 for weight and classification.

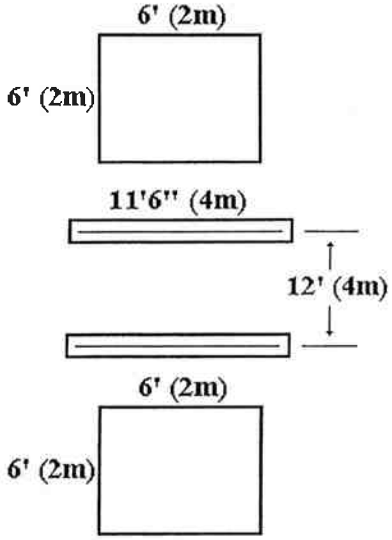


Figure 2.7 Configuration C: Inductive Loop, Class 1 Piezo Cables, Inductive Loop (Loop Piezo Piezo Loop)

Configuration D, shown in Figure 2.8, was installed in the inside lane on I-5 southbound Jefferson. The purpose of using multiple piezo cables was to compare the accuracy of Configuration C to Configuration B. The question to be answered was: Does multiple sensors increase the accuracy sufficiently to justify the addition expense?

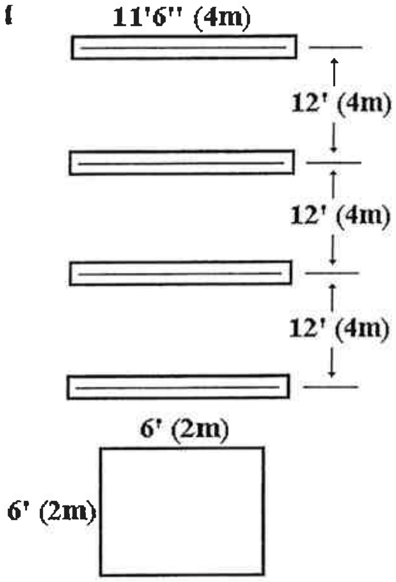


Figure 2.8 Configuration D: Inductive Loop, Four Class 1 Piezo Cables (Loop Piezo Piezo Piezo Piezo)

2.3 SENSOR INSTALLATIONS

2.3.1 PWIM SENSORS

The piezoelectric sensors were 12'(4m) Vibracoax Class 1 sensors manufactured by Thermocoax in France. These sensors were supplied pre-encased in an aluminum channel filled with an epoxy based material. The sensors were checked for linearity at the Thermocoax factory, and each came with a linearity certificate. The sensors were supplied with a single coaxial lead, installation brackets, and mounting grout.

The piezoelectric cables were installed in 1 1/4" (32mm) by 1 1/4" (32mm) grooves cut into the pavement. The mounting detail (Figure 2.9), was similar to that documented in the FHWA report FHWA-DP-88-76-006 with a few exceptions as follows:

The Hematite epoxy adhesive recommended in the FHWA report was replaced by the IRD AS-475 resin grout.

The sensors were not installed flush with the road surface, but were installed 3/16" (5mm) below the surface. It is felt that this may be beneficial as it adds protection.

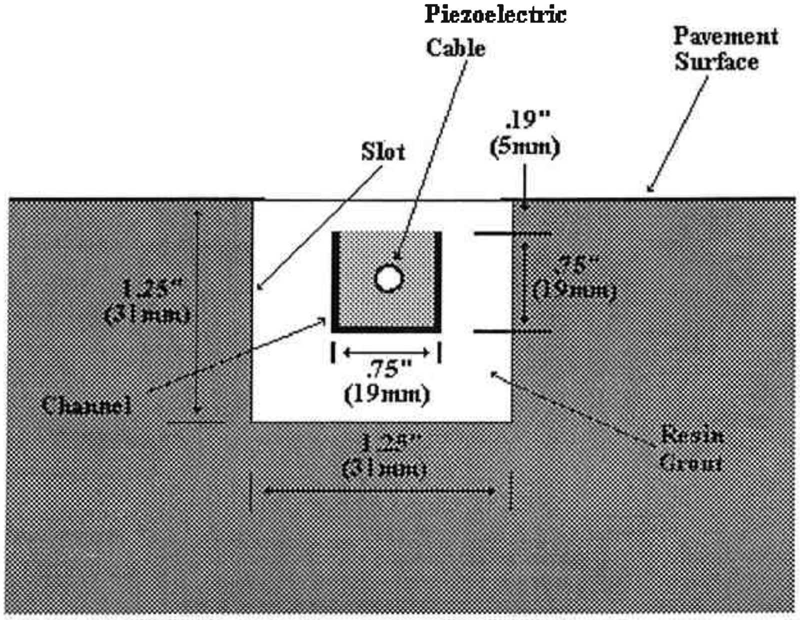


Figure 2.9 Piezoelectric Sensor Installation

The IRD grout is semi-flexible (about the same rigidity as asphalt concrete pavement) and allows the sensor to deform with pavement rutting. The only notable concern with the IRD grout is the intolerance of the grout to bond to damp or wet surfaces. In all cases, successful installations were performed with clean, dry slots.

Note that it is generally unclear as to what extent any axle sensor adhesive can tolerate wet surfaces. It may be of some use to adopt a dry installation practice where possible.

It was necessary to install the sensors and loops during the night time hours at the I-205 and I-5 Jefferson sites due to the heavy daytime traffic, and obvious safety reasons.

2.3.2 AUTOMATIC VEHICLE IDENTIFICATION (AVI) ANTENNAS

As part of the Heavy Vehicle Electronic License Plate (HELP) project AVI antennas were placed in each lane at each site. These were put in so that Mark IV Type II transponders could be read to identify the vehicle. This was part of the HELP project and not part of this project.

2.4 SYSTEM OPERATION

The equipment used for the demonstration was the IRD Model 1060P WIM system manufactured by International Road Dynamics Inc. Figure 2.9 is a block diagram of the system. Note that the processor (Intel 80286) is used to both process the sensor signals and to generate on-site reports from the collected data. The vehicle records and the generated reports are stored on a 40 MB hard drive system.

The basic system can accept inputs from up to 8 piezoelectric cables and 8 inductive loops. This allows up to 4 lanes of sensors on one interface. The system comes complete with a 1200 baud telephone modem for remote operation. All units run off of 120 VAC line power.

A temperature sensor was installed to monitor pavement temperature at each site.

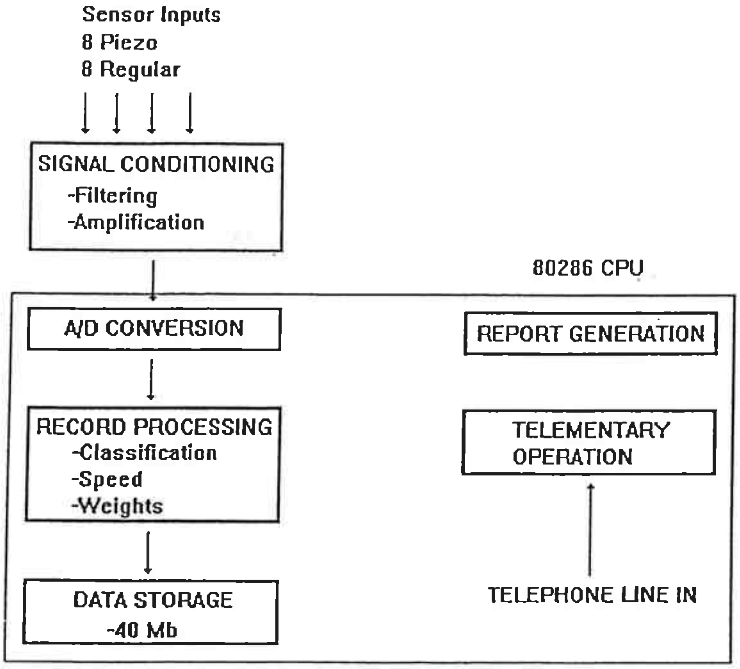


Figure 2.10 Block Diagram of the System

2.5 DATA STORAGE AND ANALYSIS FEATURES

The IRD 1060P system stores all information on a 40 MB hard disk in the central unit. Individual vehicle records can be stored in hourly files. Optionally, certain classes can be configured to be only counted. In this manner, only hourly totals of the light vehicle classes are stored, while individual raw vehicle records are stored for the heavy truck classes. This allows more efficient use of the available memory. All files are stored in a compressed binary data format to minimize the transmission time and memory requirements.

The system can be operated on site using a computer. Alternately, the system can be operated remotely via telephone modem connection.

The system features a menu driven software interface that allows the user to fully configure and operate the system. All setup parameters and calibration information is permanently stored in the system (even during power outages) and can be changed by the user. The system is protected by three levels of passwords.

The 40 MB hard disk is capable of storing more than 800,000 individual raw vehicle records. In general, this allows a two lane system to save 40 days of data. A unique feature of the IRD equipment is that the data can be processed on site. If the report parameters are selected, via modem, the modem disconnects and the report generation proceeds. All reports are stored on the hard disk system for future retrieval.

Appendix A presents some of the typical reports which can be generated. Note that the user can select the start and end date for the report, as well as the reporting interval (hourly, daily, monthly, or none).

The system classifies vehicles primarily based on the number and spacing of axles. Also, classification can be based on axle or axle group weights. The system allows the user to define up to 32 individual vehicle types, and place these vehicles into 24 individual vehicle classes.

2.6 SYSTEM COSTS

The total contractor costs of $170,540 are summarized in Table 2.2.

Table 2.2 System Costs

Item	Cost
Low Cost WIM Sensors	$39,950
Electronics and Hardware	24,160
WIM Software	5,500
Training	2,500
Monitoring	2,590
Site Installation	92,840
Site Changes	3,000
TOTALS	$170,540

Costs per site are shown in Table 2.3. These costs are subdivided into equipment, installation and inspection. The total costs are $179,540 which include inspection charges by state forces.

Table 2.3 Costs per site

Site	Equipment[1]	Installation[1]	Inspections[2]	Total
Ashland I-5 SB	$18,770	$37,600	$3,000	$58,920
Jefferson I-5 SB	27,460	24,110	3,000	54,750
Airport Way I-205 SB/NB	23,200	39,670	3,000	65,870
TOTALS	$69,610	$100,930	$9,000	$179,540

[1] Consultant

[2] State Forces

The funding sources are shown in Table 2.4. These are split between federal and state. The FHWA gave ODOT a $162,786 grant for the project. The remainder of the federal funds come from HPR and construction. The state funds were used for inspection, salaries and wages. The total project costs were $278,020.

The differnce in the total system and inspection costs and total project costs were mainly due to the pavement failures at the Jefferson Site, which is described in section 3.1.

Table 2.4 Funding sources

Funding Source	I-5	I-205	Total
Federal	$192,856	$60,738	$253,594
State	19,294	5,132	24,426
TOTALS	$212,150	$65,870	$278,020

2.7 CONTRACTOR

Specifications were written by ODOT staff and bids were requested. Two bids were received. The successful bidder was International Road Dynamics, Saskatoon, Saskatchewan, Canada with Diamond Scale Construction, Oakridge, Oregon.

3.0 PROJECT FINDINGS

3.1 INSTALLATION PROBLEMS AT THE JEFFERSON SITE

Piezo sensors were first installed at Jefferson during the fourth quarter of 1988. In December of the same year, the sensors started to come out of the asphalt concrete. This included the AVI antennas, which had been installed by state forces. There were several reasons for the failures (*6*).

Pavement Condition - The asphalt concrete pavement was badly rutted, with ruts of over 0.75 inches (20mm). Under rutting conditions of 0.50 inches (13mm) or less, the sensors and their frames can be contoured to the pavement surface. This was only partially achieved due to the depth of the ruts. About 0.25 inches (16mm) of the piezo sensor was above the pavement surface. Vehicle tires impacted the sensors. This caused the epoxy and the sensor frame to crack, become loose, break up into small pieces and come out of the pavement. This occurred in both lanes and included the piezo sensors and AVI antennas.

Adhesive - The adhesive used to grout the sensor frames in the asphalt pavement was found to be somewhat hydrophobic. The presence of water in the cut slots may have resulted in less than desirable adhesion. The contractor did attempt to dry the slots before installing the sensor, but the weather could have added to the problem. The AVI sensors were placed using a different epoxy, they also failed. One can conclude that although the adhesive used may have contributed to the failures, it was not the primary cause of failure.

Installation Techniques - It is possible that installation techniques used by the contractor may have contributed to the failures. There was some sloppiness and a lack of coordination of efforts observed at the site. However, the contractor used similar techniques at the Ashland and I-205 sites where there were no failures. Slightly different installation techniques were used by state forces in the installation of AVI antennas and these failed at Jefferson. The conclusion is; although the installation techniques may have contributed to the failures, it apparently was not the major cause.

In April 1989 (*6*), a 3-inch (76mm) deep, 500 foot (150m) long, section of the asphalt concrete pavement was removed and replaced with an open-graded polymer asphalt concrete mix. The result was a smooth rut free pavement.

The epoxy for the grout was changed to a hydrophilic one, RD-10. Although the epoxy costs more, the ODOT laboratory staff felt that it would do a better job than the previous adhesive. This epoxy worked better than the previous epoxy used even though the ambient temperature was in the low 50's.

Installation techniques were modified. The various tasks were better coordinated and more systematically done. Some technical changes were made in curing the epoxy grout by changing the heating technique.

The end result was that no more problems occurred with the sensor installation and they were turned off in late 1993 due to repaving.

3.2 WIM CALIBRATION

Two calibration methods were used depending upon the sites.

3.2.1 METHODOLOGY

One procedure utilized nearby static scales. Five-axle vehicles were weighed at the static scales, identified, and then weighed at the WIM sites, at highway speeds, and the weights were compared. This was done at the Jefferson and Ashland sites.

Since the piezo scales were located about a mile north of the Ashland weigh station, it was relatively easy to identify and weigh the trucks. The inside lane proved more difficult because the trucks did not use this lane often.

The Woodburn southbound POE was used to calibrate the Jefferson site. Since the two sites were approximately thirty miles apart, some of the vehicles weighed and identified at the Woodburn POE never reached the Jefferson site. This time delay occasionally caused problems in identification and vehicle weight comparisons. Eventually, enough samples were obtained to calibrate the system.

The I-205 sites were more difficult to calibrate. Originally the plan was to weigh trucks travelling north at the Woodburn Weigh Station using their static weights for calibration. It was found that this was not feasible because the trucks travelled either on I-5 or via I-205 and turned off at I-84 east.

Similarly, trucks going I-205 southbound from Washington were going to be weighed statically at the Woodburn southbound POE. It was found that many trucks turned off at the I-84 eastbound exit, and made it difficult to get any kind of a sample. In addition, there was a serious difficulty in getting enough truck weights in the center and inside lanes.

The contractor’s solution was to hire a pre-weighed truck. The vehicle made a number of passes and the PWIM was calibrated. This was time consuming but necessary.

Pavement temperature effects were noticed at the Ashland site when calibration was attempted. The weights changed with pavement temperature. Apparently these temperature changes affected the system.

3.2.2 AUTO-CALIBRATION FOR PAVEMENT TEMPERATURE

Thermocouples were installed in the pavement to monitor the temperature. Software was developed for an auto-calibration system. This system acts as an expert system, continuously monitoring the weights of vehicles with changes in pavement temperature.

The weight monitoring routine automatically looks at the front axle weight of a particular vehicle class. At a user input interval (either daily, weekly, or monthly), the system breaks the collected data into bins based on pavement temperature. The system then compares the average of the front axle weights for each temperature bin. The user enters the front axle control weight. Then the program prepares a table of temperature compensation values. The data in the bin is then adjusted for temperature. This enables the system to self calibrate after a few days of unattended operation, and maintain the calibration over daily and seasonal temperature variations.

This system proved to be successful for most of the lanes. One problem is that a large sample of vehicles is needed to maintain the auto-calibration. This was difficult to obtain for the central and passing lanes where few trucks travelled.

3.2.3 TESTS

WIM System - The main tests used to evaluate system performance was the mean error and standard deviation of error. The WIM error (E) is:

$$E = \frac{\text{WIM Weight - Static Weight}}{\text{Static Weight}} \times 100\%$$

These errors were calculated for each vehicle that was weighed, and for each of the axles or axle groups.

The mean of the error for a particular sample represents how close the system is to being ideally calibrated. A system that is perfectly calibrated has a mean error of 0%. If the mean error is negative, it means that the system is reading low on average, and a positive mean error indicates the system is reading high on average. The auto-calibration system should keep the mean error within an acceptable range, typically +/-3%.

The standard deviation of error provides an indication of variability, or scatter, of the data. This standard deviation is a measure of the random influence of weighing in motion. The closer this value is to 0%, the more consistent the system is.

Speed - The speed error was calculated based on radar readings. The formula used was:

Speed Error = Radar-WIM

The results were used to calibrate the WIM speed.

Axle Spacings - The spacing between the axles was measured using a tape measure. The axle spacing formula was:

Axle Spacing Error = Tape-WIM

The WIM system was calibrated as closely as possible to the tape measurements to minimize the axle spacing error.

3.2.4 I-205 AIRPORT EXIT SITE, WIM CALIBRATION

Speed - Speed readings using a radar gun was attempted but it proved to difficult to isolate and focus on the test vehicle because of the multiple lanes and the traffic.

Axle Spacings - Tables B1 and B2, Appendix B, show the axle spacings data from all the lanes on I-205 northbound and southbound, respectively. In most cases, the error was less than six inches.

Weight - The weight calibration results for I-205 northbound and southbound are shown in Tables B3 and B4, respectively. The average error and standard deviation were better than expected for this type of sensor.

Comparison of two piezo configurations tested, Loop Piezo Piezo Loop versus Loop Piezo Loop, show that the former configuration is more consistent in weight measurements. The indication is that multiple piezo sensors give more consistent results than a single piezo sensor system.

3.2.5 I-205 ASHLAND POE SITE, WIM CALIBRATION

Speed - Table B5, Appendix B, shows the results from the speed calibration using a radar gun. The results demonstrate that the calibration is good considering the fact that the accuracy of the radar gun is ± 1 mph (1.6 Kmph).

Axle Spacings - Table B5 also shows the results from the axle spacing calibration. The axle spacing measurements are acceptable. Some adjustment could be made to eliminate the consistently high average error. The possibility of tape droop affecting the tape measurements may account for some of the error, particularly, on the longer distance.

Weight - Table B6 shows the weight calibration results. Note that lane 1 has a high standard deviation, while lane 2 has a high average error and a lower standard deviation.

The higher standard deviation in lane 1 is probably caused by a pothole in the wheel path located approximately 120 yards prior to reaching the sensor. This pothole occurs at a joint between the concreted slabs, where it is obvious that there have been prior problems as evidenced by an asphalt on either side of the hole.

This hole was approximately 6 inches deep, 18 inches long, and about 12 inches wide and could induced large dynamic impacts which would cause the high standard deviation. The pothole was later repaired.

The high average error in lane 2 is probably the result of the auto-calibration function. Since the number of trucks travelling in this lane is low, more time is needed for the system to auto-calibrate.

3.2.6 I-5 JEFFERSON RAMP SITE, WIM CALIBRATION

Table B7, Appendix B, presents the performance of single piezo sensors in the driving lane. Note that the sensors were reading low and the standard deviation was much higher in the asphalt concrete pavement than in the portland cement concrete pavements.

Both Tables B7 and B8 show that the sensors are consistently reading low on the gross vehicle weight. This is a function of the auto-calibration targeting front axle weights. Therefore, the mean error associated with the front axle weight is lower.

3.2.7 FINDINGS

Piezo sensor repeatability of weighings was poor.

Findings by several authors (*7,8,9*) show that multiple sensors will improve the accuracy. The findings from this report show:

1. Some sensors contribute more errors than others, thus affecting system performance.
2. System performance is enhanced by averaging the results of two or more sensors.
3. The overall system accuracy of a four sensor installation was not significantly better than a two sensor installation
4. The calibration procedure is more difficult with multiple sensors.
5. The piezo sensor data has been a relatively high variability.
6. Multiple sensors do improve weighing accuracy, but should be limited to two sensors. Additional sensors do not improve the weight accuracy that significantly.
7. Piezo sensors in portland cement concrete pavement tend to give more consistent and accurate results than those in asphalt concrete.
8. A piezo sensor will last at least 24 months.

Portland cement concrete pavements have better system performance.

Although the piezoelectric sensors utilized were not supposed to vary with temperature change, the systems did vary with changes in pavement temperature. It was necessary to provide temperature compensation.

The auto-calibration system automatically reduces the overall mean system error.

The piezo sensor system accurately measured axle spacing and speed.

At least a twenty-four month life from piezo sensors can be expected.

4.0 CONCLUSIONS AND RECOMMENDATIONS

1. The lack of consistent accuracy makes these sensors adequate for data collection purposes, but should not be used for sorting or enforcement purposes at highway speeds.

2. These systems can be used in less travelled roads for traffic data, vehicle classification and approximate weight measurements.

3. These sensors should not be used in high volume roads since they may need early replacing, which is expensive, due to traffic control.

4. Pavement temperature effects the accuracy of the piezo systems. Temperature compensation and auto-calibration is needed.

5. Installation techniques and pavement condition is very important to ensure that the piezo sensors last and work properly.

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Appendix A

VEHICLE REPORTS

Table A1 Classification Report

From: Sat Jul 01 00:00:00 1989, To: Tue Jul 11 23:59:00 1989
Classification: FHWA
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-1	0	1019	304	11	36	2	1	4	35	4	2	7	1425
1-2	0	544	169	3	31	1	1	3	38	3	1	7	801
2-3	1	289	123	4	17	2	2	6	47	3	0	11	505
3-4	0	274	134	7	14	4	1	3	36	5	2	4	484
4-5	0	393	214	7	37	3	3	0	51	16	0	6	730
5-6	1	853	479	17	65	21	0	7	113	59	0	2	1617
6-7	15	2838	1161	35	141	32	13	23	124	69	5	4	4460
7-8	15	4213	1390	48	158	49	8	47	142	131	5	3	6209
8-9	11	2749	1184	47	182	48	7	39	154	99	4	10	4534
9-10	9	2887	1296	42	194	49	11	42	208	122	4	2	4866
10-11	14	3625	1523	41	229	50	24	52	211	119	1	0	5889
11-12	14	4400	1815	46	223	55	15	47	209	106	3	2	6935
12-13	21	4874	1820	47	252	55	16	56	248	115	11	1	7506
13-14	28	5395	2282	69	253	65	13	72	266	125	3	2	8573
14-15	30	5777	2236	54	286	61	21	62	267	120	4	3	8921
15-16	29	6533	2522	34	278	50	11	57	223	56	3	1	9797
16-17	50	8719	3057	51	321	33	11	84	177	42	3	4	12552
17-18	25	7492	2661	40	267	44	14	49	180	37	0	4	10813

Table A1 Classification Report (continued)

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
18-19	23	5595	2135	33	228	34	12	55	178	24	1	4	8322
19-20	12	3928	1464	20	144	16	11	31	180	17	0	2	5825
20-21	15	3587	1268	14	109	12	4	28	147	17	1	11	5213
21-22	10	3232	1008	32	93	8	7	16	134	19	0	13	4572
23-24	3	1574	493	12	58	4	4	3	79	7	3	12	2252
TOTALS	331	83415	31596	720	3680	703	213	802	3528	1327	46	127	126488

Table A2 Speed Report

From: Sat Jul 01 00:00:00, 1989 To: Jul 11 23:59:00 1989
Classification: Report
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Km/Hr	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-30	0	0	0	0	0	0	0	0	0	0	0	0	0
30-40	1	2	0	3	5	1	0	2	2	1	0	0	17
40-50	27	7	2	5	3	3	0	1	2	2	0	0	52
50-60	66	25	9	0	2	4	1	0	3	0	0	0	110
60-70	72	122	52	9	14	12	0	9	11	6	0	0	307
70-80	82	489	276	17	79	41	12	30	81	22	3	1	1133
80-90	24	2503	1699	52	394	146	35	144	370	78	6	26	5477
90-95	7	3711	2211	91	437	114	39	136	490	107	9	43	7395
95-100	7	8239	3733	128	541	128	32	152	806	285	4	26	14081
100-105	15	15426	5934	141	602	132	35	144	963	341	4	19	23756
105-110	8	16463	5508	90	519	60	29	83	402	227	6	6	23401
110-120	11	28087	9357	157	757	54	27	84	356	234	3	5	39132
120-130	11	7113	2268	17	195	6	2	10	36	21	4	0	9683
130-140	0	1004	394	4	67	1	1	6	6	2	2	0	1487
140-150	0	220	141	5	62	1	0	1	0	1	4	1	436
150+	0	4	12	1	3	0	0	0	0	0	1	0	21
TOTALS	331	83415	31596	720	3680	703	213	802	3528	1327	46	127	126488

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Table A3 Front Axle Report

From Sat: Jul 01 00:00:00 1989, To: Tue Jul 11 23:59:00 1989
Classification: FHWA
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Tonnes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-1	328	83314	30468	19	2342	160	139	514	34	13	3	2	117336
1-2	0	82	1048	53	801	101	34	86	138	49	4	4	2400
2-3	1	9	55	130	292	183	7	95	1040	482	8	56	2358
3-4	1	5	16	202	154	119	4	56	1245	462	8	52	2324
4-5	1	3	6	155	73	70	3	31	628	157	5	6	1138
5-6	0	0	3	79	14	39	5	7	289	92	5	6	539
6-7	0	1	0	44	2	20	9	5	87	35	4	0	207
7-8	0	0	0	16	1	7	3	1	30	17	3	1	79
8-9	0	0	0	12	1	0	4	2	14	8	2	0	43
9-10	0	0	0	3	0	3	1	1	13	3	2	0	26
10-11	0	0	0	2	0	0	1	1	3	2	0	0	9
11-12	0	0	0	1	0	0	2	0	2	2	0	0	7
12-13	0	1	0	1	0	0	1	0	2	4	1	0	10
13-14	0	0	0	1	0	0	0	2	0	0	1	0	4
14-15	0	0	0	1	0	0	0	0	2	0	0	0	3
15+	0	0	0	1	0	1	0	1	1	1	0	0	5
TOTALS	331	83415	31596	720	3680	703	213	802	3528	1327	46	127	126488

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Table A4 Single Axle Report

From Sat:00:00:00 1989, To: Tue Jul 11 23:59:00 1989
Classification:FHWA
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Tonnes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-1	0	83833	28932	33	1440	251	59	979	27	246	25	19	115844
1-2	0	224	2814	14	803	22	67	150	7	639	2	10	4752
2-3	0	16	518	10	527	7	30	107	6	111	4	19	1355
3-4	0	5	125	15	321	3	14	66	3	27	15	49	643
4-5	0	6	47	9	198	2	3	52	8	18	13	64	420
5-6	0	0	17	13	158	0	4	40	13	9	21	81	356
6-7	0	1	15	8	106	0	4	39	7	15	8	56	259
7-8	0	0	7	7	65	0	2	35	15	13	6	15	165
8-9	0	0	2	3	30	0	1	22	8	11	3	8	88
9-10	0	0	3	1	10	0	1	7	1	7	4	1	35
10-11	0	0	0	1	5	0	0	5	1	9	1	0	22
11-12	0	0	0	0	2	0	0	3	0	6	1	0	12
12-13	0	0	0	1	3	0	0	1	1	4	1	0	11
13-14	0	0	0	2	1	0	0	0	0	2	0	1	6
14-15	0	0	0	0	0	0	0	1	0	0	2	0	3
15+	0	0	0	3	1	5	0	3	0	1	1	4	18
TOTALS	0	84085	32480	120	3670	290	185	1510	97	1118	107	327	123989

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Table A5 Tandem Axles Report

From Sat:00:00:00 1989, To: Tue Jul 11 23:59:00 1989
Classification:FHWA
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Tonnes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-1	321	383	581	0	1	13	88	4	13	12	0	0	1416
1-2	4	19	158	6	4	9	49	8	55	125	0	0	437
2-3	3	2	39	13	3	27	23	13	248	471	0	0	842
3-4	0	2	28	42	3	72	8	16	423	421	1	0	1016
4-5	0	2	13	77	1	95	4	25	489	383	0	0	1089
5-6	0	1	7	83	2	73	5	23	577	337	1	5	1114
6-7	1	1	7	33	3	52	1	24	608	181	2	4	917
7-8	0	1	3	41	3	29	1	17	507	81	2	11	696
8-9	1	0	1	36	1	18	3	26	451	39	7	8	591
9-10	0	0	2	58	0	29	0	19	407	36	3	19	573
10-11	1	0	0	55	1	9	0	15	405	34	2	11	533
11-12	0	0	3	52	0	23	0	21	427	21	2	14	563
12-13	0	0	2	35	3	19	1	11	407	28	0	17	522
13-14	0	0	0	23	1	13	0	7	444	36	0	18	542
14-15	0	0	0	25	0	14	0	7	381	39	3	20	489
15+	0	0	1	54	1	65	2	11	1160	204	8	27	1533
TOTALS	331	411	845	633	26	560	185	247	7002	2448	31	154	12873

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Table A6 GVW Report

From: Sat Jul 01 00:00:00 1989, To: Tue Jul 11 23:59:00 1989
Classification: FHWA
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Tonnes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-5	328	83383	31174	26	2709	156	86	444	2	1	2	1	118312
5-10	2	26	374	202	761	282	73	21	33	21	0	0	1895
10-15	1	5	36	223	182	114	21	68	518	458	1	0	1627
15-20	0	1	3	182	21	78	7	78	676	458	3	3	1510
20-25	0	0	4	68	5	60	7	58	609	97	13	9	930
25-30	0	0	5	15	1	12	8	21	515	43	10	18	648
30-35	0	0	0	3	1	1	8	7	575	41	7	30	673
35-40	0	0	0	0	0	0	1	0	369	5	4	36	462
40-45	0	0	0	0	0	0	1	0	143	60	2	23	229
45-50	0	0	0	0	0	0	0	3	53	43	2	1	102
50-55	0	0	0	1	0	0	0	0	20	17	0	3	41
55-60	0	0	0	0	0	0	1	0	8	19	1	1	30
60-65	0	0	0	0	0	0	0	0	3	11	0	0	14
65-70	0	0	0	0	0	0	0	1	1	0	1	1	4
70-75	0	0	0	0	0	0	0	1	1	3	0	0	5
75-80	0	0	0	0	0	0	0	0	1	0	0	0	1
80-85	0	0	0	0	0	0	0	0	0	2	0	0	2
85-90	0	0	0	0	0	0	0	0	0	0	0	1	1

Table A6 GVW Report (continued)

Tonnes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
90-95	0	0	0	0	0	0	0	0	1	1	0	0	2
95+	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTALS	331	83415	31596	720	3680	703	213	802	3528	1327	46	127	126488

Table A7 Errors Report

From: Sat Jul 01 00:00:00 1989, To: Tue Jul 11 23:59:00 1989
Classification: FHWA
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Hour	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-1	1468	0	0	0	0	3	0	0	1	0	0	3	0	1475
1-2	827	0	0	0	1	6	0	0	0	0	1	0	0	835
2-3	529	0	0	0	0	2	0	0	0	0	0	1	0	532
3-4	503	0	0	0	1	2	0	0	0	0	0	2	0	508
4-5	767	0	0	0	0	2	0	0	0	0	0	2	0	771
5-6	1671	0	0	0	1	8	0	3	1	0	1	3	0	1688
6-7	4579	0	0	0	12	20	0	12	4	0	0	12	4	4643
7-8	6324	0	0	0	14	26	0	17	5	0	1	10	7	6404
8-9	4629	0	0	0	14	18	0	8	8	0	1	3	3	684
9-10	4976	0	0	0	15	20	0	12	8	0	1	7	1	5040
10-11	6002	0	0	0	22	18	0	9	6	0	2	12	4	6075
11-12	7069	0	0	0	19	28	0	14	8	0	1	9	6	7154
12-13	7625	0	0	0	18	38	0	14	11	0	1	10	5	7722
13-14	8727	0	0	0	30	37	0	24	7	0	0	12	5	8842
14-15	9053	0	0	0	33	46	0	12	10	0	0	18	5	9177
15-16	9905	1	0	0	31	62	0	21	8	0	1	16	6	10051
16-17	12630	0	0	0	42	62	0	16	10	0	4	15	6	12785
17-18	10907	1	0	0	38	57	0	22	5	0	2	10	6	11048

Table A7 Errors Report (continued)

Hour	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
18-19	8416	0	0	0	20	27	0	12	6	0	3	11	1	5969
19-20	5908	0	0	0	17	26	0	9	4	0	0	5	0	5357
20-21	5303	0	0	0	11	30	0	4	4	0	0	2	3	4692
21-22	4645	0	0	0	11	21	0	6	3	0	1	4	1	3779
23-24	2318	0	0	0	2	5	0	1	0	0	0	3	0	2329
TOTALS	128534	2	0	0	359	572	0	219	112	0	20	174	64	130056

Table A8 Total Esal Report
From: Sat Jul 01 00:00:00 1989, To: Tue Jul 11 23:59:00 1989
Classification: FHWA
Lane 1 Included, Lane 2 Included, Lane 3 Included, Lane 4 Excluded

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
0-1	0	1	2	15	3	0	0	5	63	20	4	18	135
1-2	0	0	1	0	3	0	0	3	110	4	3	18	147
2-3	0	0	0	33	2	0	0	4	86	2	0	34	165
3-4	0	0	0	5	1	0	0	0	86	82	1	14	193
4-5	0	7	2	3	8	0	65	0	117	10	0	13	230
5-6	0	0	3	8	9	18	0	213	192	18	0	4	470
6-7	0	1	10	26	20	22	347	14	317	123	131	216	1233
7-8	0	2	11	68	28	122	11	48	523	538	62	188	1606
8-9	0	1	11	71	42	67	0	31	309	131	31	298	999
9-10	0	1	8	50	23	28	51	18	418	251	8	2	864
10-11	0	1	7	36	23	44	101	238	441	149	2	0	1048
11-12	0	2	9	57	34	34	32	22	449	128	25	2	799
12-13	0	3	7	53	44	41	4	24	520	162	2	0	867
13-14	0	2	17	78	61	42	56	24	536	141	7	0	969
14-15	0	2	10	191	34	27	3	16	490	169	71	8	1027
15-16	0	3	10	32	23	42	1	14	472	127	14	2	744
16-17	0	3	12	60	36	15	1	51	460	107	17	7	775
17-18	0	4	10	45	40	19	21	107	390	118	0	2	762

Table A8 Total Esal Report (continued)

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Total
18-19	0	3	12	53	40	16	13	9	452	132	38	344	1119
19-20	0	2	7	30	88	12	16	27	436	44	0	1	670
20-21	0	2	7	14	12	1	0	13	330	63	0	34	481
22-23	0	1	4	5	5	0	76	4	206	69	0	33	409
TOTALS	0	52	181	2027	605	562	821	899	8023	2714	432	1321	16639

Appendix B

CALIBRATION RESULTS

Table B1
I-205 Northbound Axle Spacings Calibration Results

Axle	1-2		2-3		3-4		4-5		Length[1]	
Static[2]	18.7		4.4		35.1		4.1		67.0	

Lane Northbound Drive **Sensor Configuration: Loop Piezo Piezo Loop[4]**

Rcrd Nbr	1-2	Error[3]	2-3	Error	3-4	Error	4-5	Error	Length	Error
WIM1	18.6	-0.1	4.3	-0.1	35.0	-0.1	4.0	-0.1	67.0	0.0
WIM2	18.6	-0.1	4.3	-0.1	35.1	0.1	4.1	0.0	68.0	1.0
WIM3	18.7	0.0	4.3	-0.1	35.0	-0.1	4.0	-0.1	67.0	0.0
WIM4	18.7	0.0	4.3	-0.1	35.0	-0.1	4.0	-0.1	67.0	0.0
Average		0.0		-0.1		-0.1		-0.1		0.3

Lane Northbound Center **Sensor Configuration: Loop Piezo Piezo Loop**

Rcrd Nbr	1-2	Error	2-3	Error	3-4	Error	4-5	Error	Length	Error
WIM1	18.5	-0.2	4.3	-0.1	34.6	-0.5	4.0	-0.1	66.0	-1.0
WIM2	18.4	-0.3	4.3	-0.1	34.6	-0.5	4.0	-0.1	66.0	-1.0
WIM3	18.4	-0.3	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-1.0
WIM4	18.4	-0.3	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-1.0
WIM5	18.4	-0.3	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-1.0
WIM6	18.4	-0.3	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-1.0
WIM7	18.5	-0.2	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-1.0
WIM8	18.5	-0.2	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-1.0
WIM9	18.4	-0.3	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-2.0
WIM10	18.5	-0.2	4.3	-0.1	34.7	-0.4	4.0	-0.1	66.0	-1.0
Average		-0.3		-0.1		-0.4		-0.1		-1.1

Table B1
I-205 Northbound Axle Spacings Calibration Results (continued)

Lane Northbound Median **Sensor Configuration: Loop Piezo Loop**

Rcrd Nbr	1-2	Error	2-3	Error	3-4	Error	4-5	Error	Length	Error
WIM1	18.6	-0.1	4.3	-0.1	34.9	-0.2	4.1	0.0	67.0	0.0
WIM2	17.9	-0.8	4.1	-0.3	33.7	-1.4	3.9	-0.2	64.0	-3.0
WIM3	17.9	-0.8	4.2	-0.2	33.6	-1.5	3.9	-0.2	63.0	-4.0
WIM4	18.6	-0.1	4.3	-0.1	34.8	-0.3	4.1	0.0	67.0	0.0
WIM5	19.1	-0.4	4.4	0.0	35.8	0.7	4.2	0.1	69.0	2.0
WIM6	18.1	-0.6	4.2	-0.2	34.0	-1.1	4.0	-0.1	65.0	-2.0
WIM7	18.2	-0.5	4.2	-0.2	34.4	-0.7	4.0	-0.1	66.0	-1.0
WIM8	18.4	-0.3	4.2	-0.2	34.6	-0.5	4.0	-0.1	66.0	-1.0
WIM9	18.5	-0.2	4.3	-0.1	34.6	-0.5	4.0	-0.1	66.0	-1.0
WIM10	18.7	0.0	4.3	-0.1	35.1	0.0	4.1	0.0	67.0	0.0
Average		-0.3		-0.2		-0.6		-0.1		-1.0

1 All Measurements in Feet.
2 Single 5-Axle Semi-Truck, Multiple User.
3 Error=WIM, Static Feet.
4 All Sensors Originally Installed in 1988.

Table B2
I-205 Southbound Axle Spacings Calibration Results

Axle	1-2		2-3		3-4		4-5		Length[1]	
Static[2]	18.7		4.4		35.1		4.1		67.0	

Lane Southbound Drive **Sensor Configuration: Loop Piezo Piezo Loop[4]**

Rcrd Nbr	1-2	Error[3]	2-3	Error	3-4	Error	4-5	Error	Length	Error
WIM1	18.7	0.0	4.4	0.0	35.3	0.2	4.1	0.0	68.0	1.0
WIM2	18.6	0.1	4.3	-0.1	35.0	-0.1	4.0	-0.1	67.0	0.0
WIM3	18.6	-0.1	4.3	-0.1	35.0	-0.1	4.1	0.0	68.0	1.0
WIM4	18.6	-0.1	4.3	-0.1	34.9	-0.2	4.1	0.0	67.0	0.0
WIM5	18.6	-0.1	4.3	-0.1	35.0	-0.1	4.0	-0.1	67.0	0.0
Average		0.0		-0.1		-0.1		0.0		0.4

Lane Southbound Center **Sensor Configuration: Loop Piezo Piezo Loop[5]**

Rcrd Nbr	1-2	Error	2-3	Error	3-4	Error	4-5	Error	Length	Error
WIM1	18.5	-0.2	4.3	-0.1	34.7	-0.4	4.0	-0.1	69.0	2.0
WIM2	18.5	-0.2	4.3	-0.1	34.8	-0.3	4.0	-0.1	69.0	2.0
WIM3	18.5	-0.2	4.3	-0.1	34.8	-0.3	4.0	-0.1	69.0	2.0
WIM4	18.5	-0.2	4.3	-0.1	34.7	-0.3	4.0	-0.1	69.0	2.0
WIM5	18.5	-0.2	4.3	-0.1	34.8	-0.3	4.0	-0.1	70.0	3.0
WIM6	18.5	-0.2	4.3	-0.1	34.8	-0.3	4.0	-0.1	69.0	2.0
WIM7	18.5	-0.2	4.3	-0.1	34.8	-0.3	4.0	-0.1	69.0	2.0
WIM8	18.5	-0.2	4.3	-0.1	34.8	-0.3	4.0	-0.1	68.0	1.0
WIM9	18.5	-0.2	4.3	-0.1	34.8	-0.3	4.0	-0.1	69.0	2.0
WIM10	18.5	-0.2	4.3	-0.1	34.9	-0.2	4.0	-0.1	70.0	3.0
Average		-0.2		-0.1		-0.3		-0.1		2.1

Table B2
I-205 Southbound Axle Spacings Calibration Results (continued)

Lane Southbound Median **Sensor Configuration: Loop Piezo Loop**[5]

Rcrd Nbr	1-2	Error	2-3	Error	3-4	Error	4-5	Error	Length	Error
WIM1	18.9	0.2	4.3	-0.1	35.6	0.5	4.1	0.0	69.0	2.0
WIM2	18.3	-0.4	4.2	-0.2	34.4	-0.7	4.0	-0.1	66.0	-1.0
WIM3	18.8	0.1	4.3	-0.1	35.3	0.2	4.1	0.0	69.0	2.0
WIM4	18.4	-0.3	4.3	-0.1	34.6	-0.5	4.0	-0.1	66.0	-1.0
WIM5	18.8	0.1	4.3	-0.1	35.4	0.3	4.1	0.0	68.0	1.0
Average		-0.1		-0.2		0.0		0.0		0.6

1 All Measurements in Feet.
2 Single 5-Axle Semi-Truck, Multiple User.
3 Error=WIM, Static Feet.
4 All Sensors Originally Installed in 1988.
5 New Sensors Were Installed in August of 1993.

Table B3
I-205 Northbound Weight Calibration Results

	Front[2]		Drive[2]		Trailer[2]		GVW[2]	
Static[1]	11.6		27.1		25.6		64.3	

Lane Northbound Drive **Sensor Configuration: Loop Piezo Piezo Loop**[4]

Rcrd Nbr	Front	Error[3]	Drive	Error	Trailer	Error	GVW	Error
WIM1	11.6	0.00%	28.9	6.64%	26.5	3.52%	67.0	4.20%
WIM2	11.8	1.72%	24.9	-8.12%	25.5	-0.39%	62.2	-3.24%
WIM3	11.9	2.59%	28.4	4.80%	26.5	3.52%	66.8	3.93%
WIM4	12.3	6.03%	27.8	2.58%	26.4	3.12%	66.6	3.52%
WIM5	12.1	4.31%	28.6	5.54%	26.4	3.12%	67.1	4.42%
Average		2.93%		2.29%		2.58%		2.57%
Standard Deviation		2.33%		6.00%		1.67%		3.26%

Lane Northbound Median **Sensor Configuration: Loop Piezo Loop**[4]

Rcrd Nbr	Front	Error	Drive	Error	Trailer	Error	GVW	Error
WIM1	11.8	1.72%	26.9	-0.74%	26.5	3.52%	65.2	1.43%
WIM2	11.5	-0.86%	26.4	-2.58%	25.6	0.00%	63.5	-1.26%
WIM3	11.4	-1.72%	24.4	-9.96%	26.6	3.91%	62.4	-2.98%
WIM4	11.4	1.72%	28.2	4.06%	27.7	8.20%	67.3	4.64%
WIM5	11.4	-6.90%	23.4	-13.65%	23.9	-6.64%	58.0	-9.75%
WIM6	10.8	-5.17%	26.8	-1.11%	27.5	7.24%	65.2	1.47%
WIM7	11.0	-1.72%	27.1	0.00%	27.1	5.86%	65.6	1.99%
WIM8	11.4	6.03%	23.6	-12.92%	26.4	3.12%	60.8	-5.38%
Average		-2.80%		-4.61%		3.17%		-1.23%
Standard Deviation		2.94%		6.62%		4.74%		4.66%

Table B3
I-205 Northbound Weight Calibration Results (continued)

Lane Northbound Median **Sensor Configuration: Loop Piezo Loop**[5]

Rcrd Nbr	Front	Error	Drive	Error	Trailer	Error	GVW	Error
WIM1	15.0	29.31%	27.8	2.58%	24.3	-5.08%	67.4	4.81%
WIM2	13.5	16.38%	25.2	-7.01%	22.5	12.11%	61.4	-4.57%
WIM3	14.0	20.69%	29.9	10.33%	24.4	-4.69%	68.5	6.54%
WIM4	13.8	18.97%	29.5	8.86%	23.2	-9.37%	66.7	3.72%
Average		21.34%		3.69%		-7.81%		2.63%
Standard Deviation		5.60%		7.89%		3.57%		4.93%

1 Single Truck, 5-Axle Semi-Multiple Runs
2 Front-Steering Axle; Drive-Driver Tandem Axles; Trailer-Rear Tandem Axles; and GVW-Gross Vehicle Weight.
3 Error=(WIM-Static)/Static*100
4 New Sensors were Installed in August of 1993.

Table B4
I-205 Southbound Weight Calibration Results

	Front[2]		Drive[2]		Trailer[2]		GVW[2]	
Static[1]	11.6		27.1		25.6		64.3	

Lane Southbound Drive **Sensor Configuration: Loop Piezo Piezo Loop[4]**

Rcrd Nbr	Front	Error[3]	Drive	Error	Trailer	Error	GVW	Error
WIM1	11.6	0.00%	22.9	-15.50%	24.2	-5.47%	58.7	-8.71%
WIM2	12.1	4.31%	27.5	1.48%	27.4	7.03%	67.0	4.27%
WIM3	10.3	-11.21%	24.9	-8.12%	27.0	5.47%	62.1	-3.44%
WIM4	11.3	-2.59%	26.4	-2.58%	23.1	-9.77%	60.8	-5.48%
WIM5	12.9	11.21%	29.1	7.38%	25.8	0.78%	67.9	5.62%
WIM6	12.4	6.90%	22.5	-16.97%	26.9	5.08%	61.9	-3.78%
WIM7	12.8	10.34%	29.8	9.96%	25.4	-0.78%	68.1	5.92%
Average		2.71%		-3.48%		0.33%		-0.80%
Standard Deviation		7.95%		10.58%		6.20%		5.95%

Lane Southbound Median **Sensor Configuration: Loop Piezo Loop[4]**

Rcrd Nbr	Front	Error	Drive	Error	Trailer	Error	GVW	Error
WIM1	11.2	-3.45%	28.4	4.80%	24.4	-4.69%	64.0	-0.52%
WIM2	10.9	-6.03%	26.2	-3.32%	24.8	-3.13%	61.8	-3.83%
WIM3	11.4	-1.72%	26.5	-2.21%	23.6	-7.81%	61.5	-4.38%
WIM4	11.6	0.00%	28.4	4.80%	24.4	-4.69%	64.4	0.16%
WIM5	11.4	-1.72%	26.9	-0.74%	24.8	-3.13%	63.1	-1.89%
Average		-2.59%		0.66%		-4.69%		-2.09%
Standard Deviation		0.28%		3.88%		1.91%		1.99%

Table B4
I-205 Southbound Weight Calibration Results (continued)

Lane Southbound Median **Sensor Configuration: Loop Piezo Loop**[5]

Rcrd Nbr	Front	Error	Drive	Error	Trailer	Error	GVW	Error
Data Unavailable								

1 Single Truck, 5-Axle Semi-Multiple Runs
2 Front-Steering Axle; Drive-Driver Tandem Axles; Trailer-Rear Tandem Axles; and GVW-Gross Vehicle Weight.
3 Error=(WIM-Static)/Static*100
4 New Sensors were Installed in August of 1993.

Table B5
I-5 Southbound Ashland
Speed and Axle Spacings Calibration Results[1]

Speed

Lane	1	2	
Average[2]	0.57	0.54	mph
Standard Deviation	1.20	1.5	mph
# of Vehicles	14	11	

Axle Spacings

Lane 1 (28 vehicles)

Axle	1-2	2-3	3-4	4-5	Overall
Average[3]	5.3	2.60	8.6	3.20	4.9 inches
Standard Deviation	1	2.50	2.3	1.60	3.2 inches

Lane 2 (21 vehicles)

Axle	1-2	2-3	3-4	4-5	Overall
Average	6.2	3.10	12	3.50	6.2 inches
Standard Deviation	2.7	0.70	1.6	1.00	3.9 inches

1 Calibration Performed on December 14-15, 1989.
2 Avg=Average Error=Radar-WIM.
3 Avg=Average Error=Tape-WIM.

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Table B6
I-5 Southbound Ashland
Weight Calibration Results[1]

Lane 1 (52 vehicles)[2]

Axle	**Steering**	**Drives**	**Trailer**	**GVW**
Average Error[3]	-9.7	2.9	3.9	0.7%
Standard Deviation	9.9	10.0	12.7	10.7%

Axle	**Singles**	**Tandems[4]**	**GVW**
Average Error[3]	-9.7	3.4	0.7%
Standard Deviation	9.9	11.4	10.7%

Lane 2 (26 vehicles)[2]

Axle	**Steering**	**Drives**	**Trailer**	**GVW**
Average Error[3]	-5.9	11.4	6.3	6.4%
Standard Deviation	1.0	2.5	2.3	5.8%

Axle	**Singles**	**Tandems[4]**	**GVW**
Average Error[3]	-5.9	8.9	6.4%
Standard Deviation	7.7	8.4	5.8%

[1] Calibration Performed on December 14-15, 1989.

[2] 5-Axle Semi-Trailer Vehicles.

[3] Average Error= $\frac{\text{(Static-WIM)}*100\%}{\text{Static}}$

[4] The Average of Driver and Trailer Tandem Axle Sensors.

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Table B7
Errors of Individual Piezoelectric Sensors at Jefferson Multi-Cable Lane
Testing May, June, 1990

Error (%) for Cable

	Cable #	**1**	**2**	**3**	**4**
Steering Axle	*Average Error*[1] *Standard Deviation*	1 12	-2 13	1 17	6 15
Drive Tandem Axle	*Average Error*[1] *Standard Deviation*	-8 11	-13 15	0 17	-7 24
Trailing Tandem Axle	*Average Error* *Standard Deviation*	-8 13	-15 18	-32 21	-8 20
Gross Vehicle Weight	*Average Error* *Standard Deviation*	-7 11	-12 14	-2 14	-5 17

Sample Size=60 Trucks

[1] Average Error = $\frac{\text{(Static-WIM)}}{\text{Static}} * 100\%$

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Table B8
Errors of Piezoelectric Sensor Groups at Jefferson Multi-Cable Lane
Testing May, June, 1990

		Error (%) for Cable			
	Cable #	**1,2,3,4**	**1,2**	**1,3**	**1,4**
Steering Axle	*Average Error*[1]	2	0	1	3
	Standard Deviation	10	10	12	12
Drive Tandem Axle	*Average Error*[1]	-7	-11	-4	-7
	Standard Deviation	11	11	12	14
Trailing Tandem Axle	*Average Error*[1]	-17	-12	-23	-8
	Standard Deviation	13	13	19	14
Gross Vehicle Weight	*Average Error*[1]	-6	-9	-4	-6
	Standard Deviation	-9	10	11	12

Sample Size=60 Trucks

[1] Average Error = $\frac{\text{(Static-WIM)}}{\text{Static}}$*100%