3. WEIGH-IN-MOTION SYSTEM DISCUSSION

This section will discuss three types of weigh-in-motion (WIM) systems: bending plate, piezoelectric sensors, and load cell. Information will be presented for each of the WIM technologies. This information comes from either the states that use the systems or the vendors that provide the systems. Table 3.1 shows the WIM system principles that should be considered when selecting a system.

Table 3.1
WIM System Principles Checklist

	WIM System Principle
3.1	**Clearly define the required site design life and accuracy performance level.**
3.2	**Devote the necessary financial and technical resources to reaching the chosen site design life and performance level.**
3.3	**Consider the following aspects of WIM systems when making the selection.**
3.3.1	Sensor type
3.3.2	Site processor
3.3.3	Remote Communication Modem
3.3.4	Operating Software
3.3.5	Data Output format

The American Society for Testing and Materials (ASTM) "Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Method" (ASTM Designation: E 1318-94) classifies WIM systems as Type I, II, III, or IV according to their application and gives related performance and user requirements for each type of system (*1*). The Standard lists user requirements that should be met to ensure that the WIM system functions properly. The four systems have different speed ranges, data gathering capabilities, and intended applications. Table 3.2 shows the information for the four types of systems. Table 3.3 shows functional performance requirements for WIM systems.

Table 3.2
ASTM WIM System Classification

	CLASSIFICATION			
	TYPE I	**TYPE II**	**TYPE III**	**TYPE IV**
Speed Range	16 - 113 km/h (10 - 70 mph)	16 - 113 km/h (10 - 70 mph)	24 - 80 km/h (15 - 50 mph)	24 - 80 km/h (15 - 50 mph)
Application	traffic data collection	traffic data collection	weight enforcement station	weight enforcement station
Number of Lanes	up to four	up to four	up to two	up to two
Bending Plate	X	X	X	X
Piezoelectric Sensor	X	X		
Load Cell	X	X	X	X
Wheel Load	X		X	X
Axle Load	X	X	X	X
Axle-Group Load	X	X	X	X
Gross Vehicle Weight	X	X	X	X
Speed	X	X	X	X
Center-to-Center Axle Spacing	X	X	X	X
Vehicle Class	X	X		
Site Identification Code	X	X	X	X
Lane and Direction of Travel	X	X	X	
Date and Time of Passage	X	X	X	X
Sequential Vehicle Record Number	X	X	X	X
Wheelbase (front to rear axle)	X	X		
Equivalent Single-Axle Load	X	X		
Violation Code	X	X	X	X

Table 3.3
Functional Performance Requirements for WIM Systems

Function	Tolerance for 95% Probability of Conformity				
	Type I	Type II	Type III	Type IV	
				value ≥ kg (lb)*	± kg (lb)
Wheel Load	± 25%	n.a.	± 20%	2,300 (5,000)	100 (250)
Axle Load	± 20%	± 30%	± 15%	5,400 (12,000)	200 (500)
Axle-Group Load	± 15%	± 20%	± 10%	11,300 (25,000)	500 (1,200)
Gross Vehicle Weight	± 10%	± 15%	± 6%	27,200 (60,000)	1,100 (2,500)
Speed	± 2 km/h (1 mph)				
Axle Spacing	± 150 mm (0.5 ft)				

*Lower values are not normally a concern in enforcement

3.1 ESTABLISH SYSTEM REQUIREMENTS

The first step in choosing a WIM system is to clearly define the requirements expected from the system and the staff resources necessary to monitor and maintain the system. The "site design life" and the accuracy level are important requirements to consider when selecting WIM equipment. The cost of the system has been shown to directly relate to the overall performance obtained using that system, as shown in the following section.

3.2 ECONOMIC ANALYSIS

According to research by Taylor and Bergan, each WIM system provides a different level of accuracy at different system and maintenance costs (*2*). Table 3.4 shows the economic analysis produced by Taylor. The cost of the system includes the Estimated Initial Cost per Lane and Maintenance. The Performance of the systems is given as a percent error on gross vehicle weigh (GVW) estimation at highway speeds under ideal, ASTM site conditions. The Estimated Initial Cost per Lane includes the equipment and installation costs. The Estimated Average Cost per Lane is based on a 12-year life span and includes maintenance. The report did not specify the interest rate that was used in the calculations. According to Caltrans, maintenance can be subdivided into three areas: (1) power and communication, (2) structural, and (3) WIM system. The power and communication area includes the WIM power and phone lines. The structural area includes the roadway pavement and scale frames. A service contract with the vendor covers the maintenance for the WIM system.

Table 3.4
Cost Comparison of WIM Systems

WIM System	Performance (Percent error on GVW at highway speeds)	Estimated Initial Cost per Lane (Equipment and Installation)	Estimated Average Cost per Lane (12-year life span including maintenance)
Piezoelectric Sensor	+/- 10%	$ 9,500	$ 4,224
Bending Plate Scale	+/- 5%	$ 18,900	$ 4,990
Double Bending Plate Scale	+/- 3-5%	$ 35,700	$ 7,709
Deep Pit Load Cell	+/- 3%	$ 52,500	$ 7,296

Tables 3.5 and 3.6 show an example of a spreadsheet developed for LTPP to estimate the cost of purchasing, installing, operating, and maintaining WIM equipment (*3*). This example shows the cost of monitoring 100 established sites using both piezoelectric sensors and bending plate scales. The scales are installed on roadways made of both asphalt concrete pavement (ACP) and portland concrete cement (PCC) pavement. The spreadsheet allows for scale replacement, electronics replacement, pavement rehabilitation, calibration, and the necessary office and maintenance staff. The initial cost for this example is $612,000 which includes pavement rehabilitation and initial equipment purchases. The annual cost for this example $2,100,500 which includes pavement rehabilitation and other site maintenance, sensor replacement, electronics replacement, calibration costs, office costs, and travel and perdiem costs. The directions for use of this spreadsheet are given in Appendix 2. Table 3.6 is a summary of the example shown in Table 3.5.

Table 3.5
Example of Weigh-in-Motion Costs

ITEM	VALUE	ITEM	VALUE
Number of Sites			
Number of sites monitored	100		
Number needing new scales	12		
Number needing pavement rehab	10	Number of piezo	50
Percent of initial rehabs that are ACP	50%	Number of bending plate	50
Percent of sites that are ACP	50%		
Percent Bending Plates at existing sites	50%		
Pavement Rehabilitation Cost		**Initial Rehabilitation**	$300,000
ACP rehabilitation	$30,000		
PCC rehabilitation	$30,000		
Equipment Costs		**Initial Equipment Cost**	$312,000
Piezo WIM scale	$10,000	**Annual Sensor Replacement Cost**	$82,500
Piezo WIM scale installation	$10,000	**Annual Electromics Replacement**	$75,000
Piezo sensor cost	$1,500		
Number of piezo sensors per site	2		
Bending plate cost	$12,000		
Bending plate installation	$20,000		
Cost of replacement plates	$3,500		
Number of plates per site	2		
Office computer	$8,000		
Computers needed per site	0.12		
Cost of office software	$15,000		
Percent of new sites using bending plates	50%		

Table 3.5 (Continued)
Example of Weigh-in-Motion Costs

ITEM	VALUE	ITEM	VALUE
Site Maintenance		**Equipment Cost Rehab Sections**	$3,000
Percent of bending plates failing per year	15%	**Annual Pavement Rehab**	$225,000
Percent of piezos failing per year	20%	**Annual non-rehab Maintenance**	$250,000
Percent of ACP sites needing rehab per year	10%		
Percent of PCC sites needing rehab per year	5%		
Percent field electronics needing replacement	15%		
Cost of field electronics replacement	$5,000	**Annual Electronics Replacement**	$75,000
Calibration		**Annual Calibration Costs**	$1,100,000
Calibration trips per year	4		
Percent next to static scales	50%		
Cost per calibration (static scales)	$3,800	$475,000	
Cost per alt. calibration session	$5,000	$625,000	
Type of alternative method	two vehicles of known weight		
Percent with max. calibration trips per year	50%		
Staffing		**Office Costs**	$115,000
Office FTE needed per site	0.02	$2	
Telephones dollars per site	$350	$35,000	
Dollar cost of FTE per year	$40,000	$80,000	
Field FTE per year	4.63		
Dollar cost of field FTE	$50,000	$250,000	
Travel and per diem Costs		**Total Travel and per diem**	$250,000
Dollars per year	$500		

Table 3.6
Summary of Example Weigh-in-Motion Costs

Initial Costs		**Annual Costs**	
Pavement Rehabilitation	$300,000	Pavement Rehabilitation	$228,000
Initial Equipment Costs	$312,000	Other Site Maintenance	$250,000
Total Initial Cost	**$612,000**	Sensor Replacement	$82,500
		Electronics Replacement	$75,000
		Calibration Costs	$1,100,000
		Office Costs	$115,000
		Travel and Per Diem	$250,000
		Total Annual Costs	**$2,100,500**

3.3 BENDING PLATE

Bending Plate WIM systems utilize plates with strain gauges bonded to the underside. As a vehicle passes over the bending plate, the system records the strain measured by the strain gauge and calculates the dynamic load. The static load is estimated using the measured dynamic load and calibration parameters. The calibration parameters account for the influences factors, such as vehicle speed and pavement/suspension dynamics, have on estimating the static weight. This system is classified as an ASTM Type I, II, III, or IV system depending on the intended use of the device and the number of scales placed in the lane. Several vendors provide bending plate WIM systems.

3.3.1 Sensor

Bending Plate WIM systems consist of either one or two scales. The scale or pair of scales is placed in the travel lane perpendicular to the direction of travel. When two scales are used in a lane, one scale is placed in each wheelpath of the traffic lane so that the left and right wheels can be weighed individually. The pair of scales is placed in the lane either side-by-side or staggered by five meters (16 feet) Bending plate systems with one scale placed in either the left or right wheelpath are usually used in low volume lanes.

There are two types of bending plate systems, permanent and portable. The permanent system is discussed in the following section, including a diagram of a typical system layout. The portable system is not high-speed WIM, and therefore will not be discussed in this report.

Bending Plate WIM systems consist of at least one scale and two inductive loops. The scales are placed in the travel lane perpendicular to the direction of travel. The inductive loops are placed upstream and downstream from the scales. The upstream loop is used to detect vehicles and alert the system of an approaching vehicle. The vehicle speed, which is used to determine the axle spacing, can be determined by three methods: weighpad to inductive loop, weighpad to axle sensor, and weighpad to weighpad, if the weighpads are staggered. If an axle sensor is used to determine the vehicle speed, it is placed downstream of the weighpad. An example of the layout for a bending plate WIM system is shown in Figure 3.1.

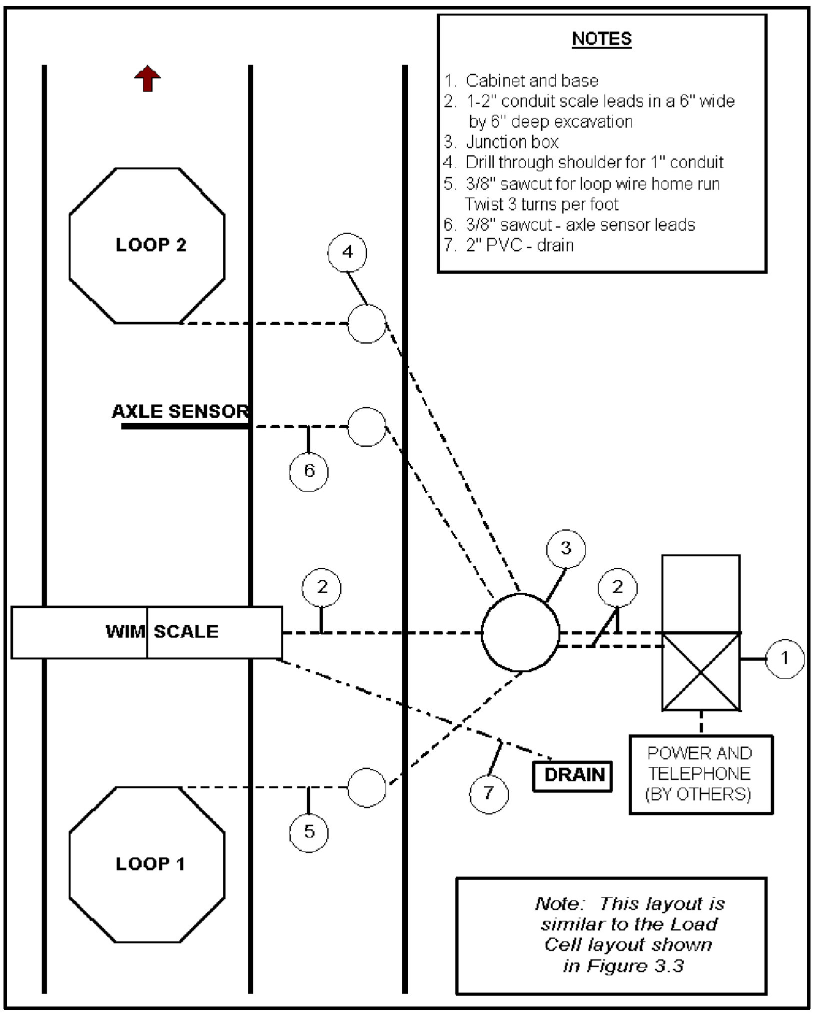

Figure 3.1 Example of Bending Plate System Layout

3.3.2 Site Processor

Processing units are used to sort and analyze the information obtained by the roadway sensors. A typical WIM system can process over 15,000 trucks a day and collect at least 30 days of continuous raw data for a four lane installation. The on-site processor can be provided by either the state or the vendor. Caltrans evaluated both options and determined that the vendor-provided processor is preferable as long as it is compatible with the state-provided in-house computer. The vendor-provided on-site processor eliminates the issue of compatibility between the sensors and the state-provided processor.

3.3.3 Remote Communication Modem

The modem used to collect data to monitor the system needs to be operable on a standard telephone line and capable of at least 1,200 bits per second (bps), but preferably at least 9,600 bps. The amount of data collected at the site and the frequence of downloading should be considered when selecting the telephone line and modem. In general, the download process will be quicker as the quality of the selected phone line and modem increases. The remote communication can be done using either telephone lines or cellular technology.

3.3.4 Operating Software

WIM software includes three separate software packages; on-site software, communications software, and in-house software. The typical on-site software interprets the signals from the WIM scale and generates the on-site files which include information such as:

1. Site Identification
2. Time and Date of Passage
3. Lane Number
4. Vehicle Sequence Number
5. Vehicle Speed and Classification
6. Weight of all Axles or Axle Groups
7. Code for Invalid Measurement
8. Optional Graphic Configuration
9. Equivalent Single Axle Loading (ESAL) value

The typical communications software allows for changes to be made to the on-site software setup including calibration factors from the in-house computer. The typical in-house software generates hard copy reports as well as ASCII files. The software allows reports to be generated on the collected raw vehicle record files. The typical communications and in-house software allow the user to perform the following tasks:

1. Real time vehicle viewing selectable by lane
2. Resetting of the system clock

3. Monitor system memory in terms of storage remaining
4. Setup and initiate the generation of summary reports on data previously collected by the system
5. View generated reports
6. Generate and view error reports including time down, system access, auto-calibration, and improperly completed records
7. Transfer selected raw data files or generated reports from the site system to the office host computer
8. Purge old data files from the system

3.3.5 Data Output Format

The typical in-house software is capable of generating output reports in the FHWA's Traffic Monitoring Guide Card Format. The in-house software is also capable of generating daily, weekly, monthly, or continuous summary reports in hourly increments based on vehicle speed, classification, ESAL, and weight summaries on a lane by lane or directional basis. The typical in-house software can also generate reports on errors, auto-calibration, site history, calibration history, and overweight vehicles.

3.4 PIEZOELECTRIC SENSORS

Piezoelectric WIM systems utilize piezo sensors to detect a change in voltage caused by pressure exerted on the sensor by an axle and measure the axle's weight. As a vehicle passes over the piezo sensor, the system records the electrical charge created by the sensor and calculates the dynamic load. The static load is estimated using the measured dynamic load and calibration parameters.

3.4.1 Sensor

Piezoelectric WIM systems consist of one or more sensors, which are placed across the traffic lane. Piezoelectric WIM systems are piezo sensors that may or may not be encapsulated in an epoxy-filled metal channel, usually aluminum. This system is classified as an ASTM Type I or II system depending on the intended use of the device and the number of sensors placed in the lane.

The typical system consists of at least one sensor and one inductive loop. The sensor(s) is placed in the travel lane perpendicular to the direction of travel. The inductive loops are placed upstream and downstream from the sensor. The upstream loop is used to detect vehicles and alert the system of an approaching vehicle. The downstream loop is used to determine speed and axle spacings based on timing. An example of the layout for a piezoelectric WIM system is shown in Figure 3.2.

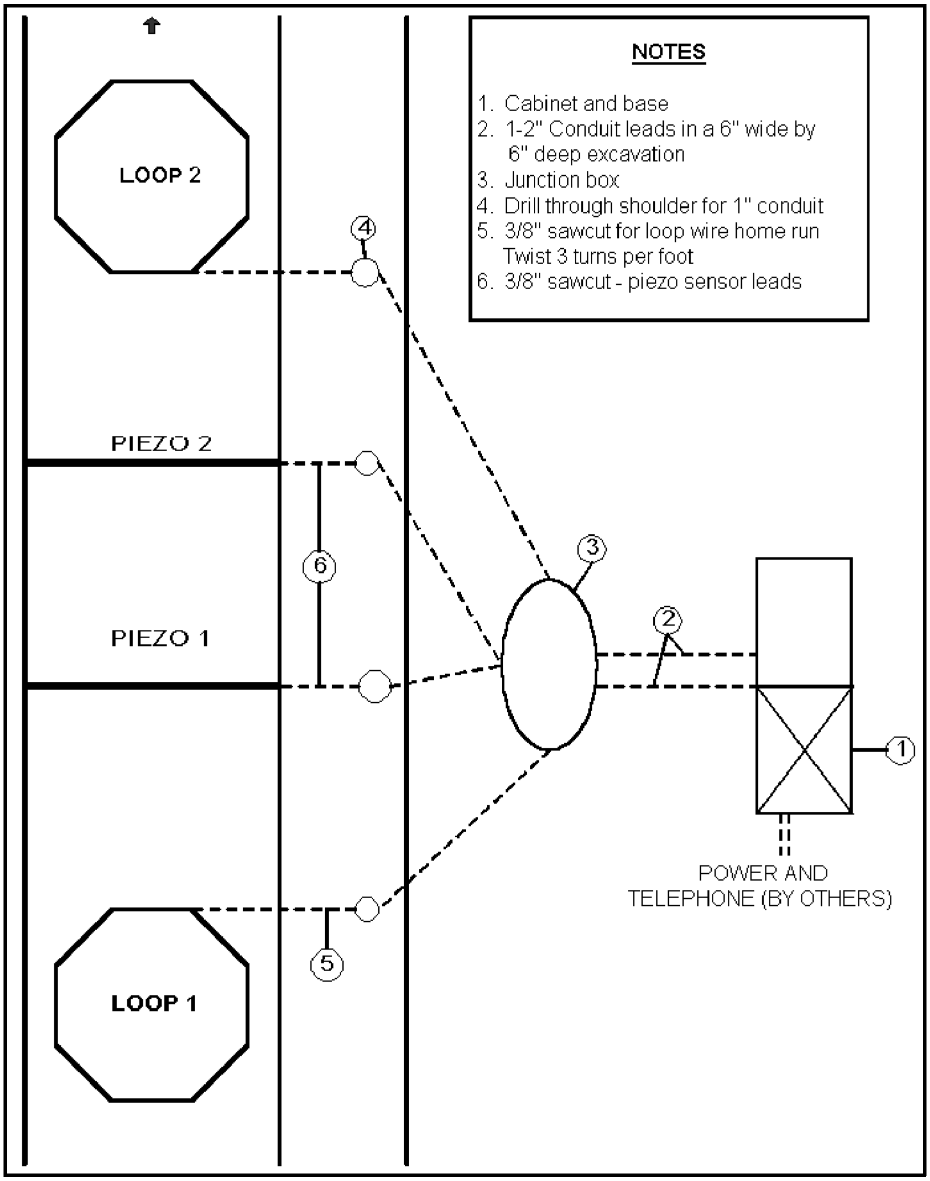

Figure 3.2 Example of Piezoelectric System Layout

3.4.2 Site Processor

Processing units are used to sort and analyze the information obtained by the roadway sensors. The on-site processor can be provided by either the state or the vendor. Caltrans evaluated both options and determined that the vendor-provided processor is preferable as long as it is compatible with the state-provided in-house computer. The vendor-provided on-site processor eliminates the issue of compatibility between the sensors and the state-provided processor.

3.4.3 Remote Communication Modem

The modem used to collect data to monitor the system needs to be operable on a standard telephone line and capable of at least 2,400 bps, but preferably at least 9,600 bps. The amount of data collected at the site and the frequence of downloading should be considered when selecting the telephone line and modem. In general, the download process will be quicker as the quality of the selected phone line and modem increases. The remote communication can be done using either telephone lines or cellular technology.

3.4.4 Operating Software

WIM software includes three separate software packages; on-site software, communications software, and in-house software. The typical on-site software interprets the signals from the WIM scale and generates the on-site files which include information such as:

1. Site Identification
2. Time and Date of Passage
3. Lane Number
4. Vehicle Sequence Number
5. Vehicle Speed and Classification
6. Weight of all Axles or Axle Groups
7. Code for Invalid Measurement
8. Optional Graphic Configuration
9. ESAL value

The typical communications software allows for changes to be made to the on-site software setup including calibration factors from the in-house computer. The typical in-house software generates hard copy reports as well as ASCII files. The software allows reports to be generated on the collected raw vehicle record files. The typical communications and in-house software allow the user to perform the following tasks:

1. Real time vehicle viewing selectable by lane
2. Resetting of the system clock
3. Monitor system memory in terms of storage remaining
4. Setup and initiate the generation of summary reports on data previously collected by the system
5. View generated reports
6. Generate and view error reports including time down, system access, auto-calibration, and improperly completed records
7. Transfer selected raw data files or generated reports from the site system to the office host computer
8. Purge old data files from the system

3.4.5 Data Output Format

The typical in-house software is capable of generating output reports in the FHWA's Traffic Monitoring Guide Card Format. The in-house software is also capable of generating daily, weekly, monthly, or continuous summary reports in hourly increments based on vehicle speed, classification, ESAL, and weight summaries on a lane by lane or directional basis. The typical in-house software can also generate reports on errors, auto-calibration, site history, calibration history, and overweight vehicles. The auto-calibration report is an important report for piezoelectric WIM systems.

3.5 LOAD CELL

Load Cell WIM systems utilize a single load cell with two scales to detect an axle and weigh both the right and left side of the axle simultaneously. As a vehicle passes over the load cell, the system records the weights measured by each scale and sums them to obtain the axle weight.

3.5.1 Sensor

The typical Load Cell WIM systems consist of a single load cell placed across the traffic lane. The single load cell has two in-line scales that operate independently. Off-scale detectors are integrated into the scale assembly to sense any vehicles off the weighing surface. This system is classified as an ASTM Type I, II, III, or IV system depending on the site design.

The typical system consists of the load cell and at least one inductive loop and one axle sensor. The load cell is placed in the travel lane perpendicular to the direction of travel. The inductive loop is placed upstream of the load cell to detect vehicles and alert the system of an approaching vehicle. If a second inductive loop is used, it is placed downstream of the load cell to determine axle spacings, which is used to determine the vehicle speed. The axle sensor is placed downstream of the load cell to determine axle spacings and vehicle speed. An example of the layout for a load cell WIM system is shown in Figure 3.3 on the following page.

3.5.2 Site Processor

Processing units are used to sort and analyze the information obtained by the roadway sensors. The on-site processor can be provided by either the state or the vendor. Caltrans evaluated both options and determined that the vendor-provided processor is preferable as long as it is compatible with the state-provided in-house computer. The vendor-provided on-site processor eliminates the issue of compatibility between the sensors and the state-provided processor.

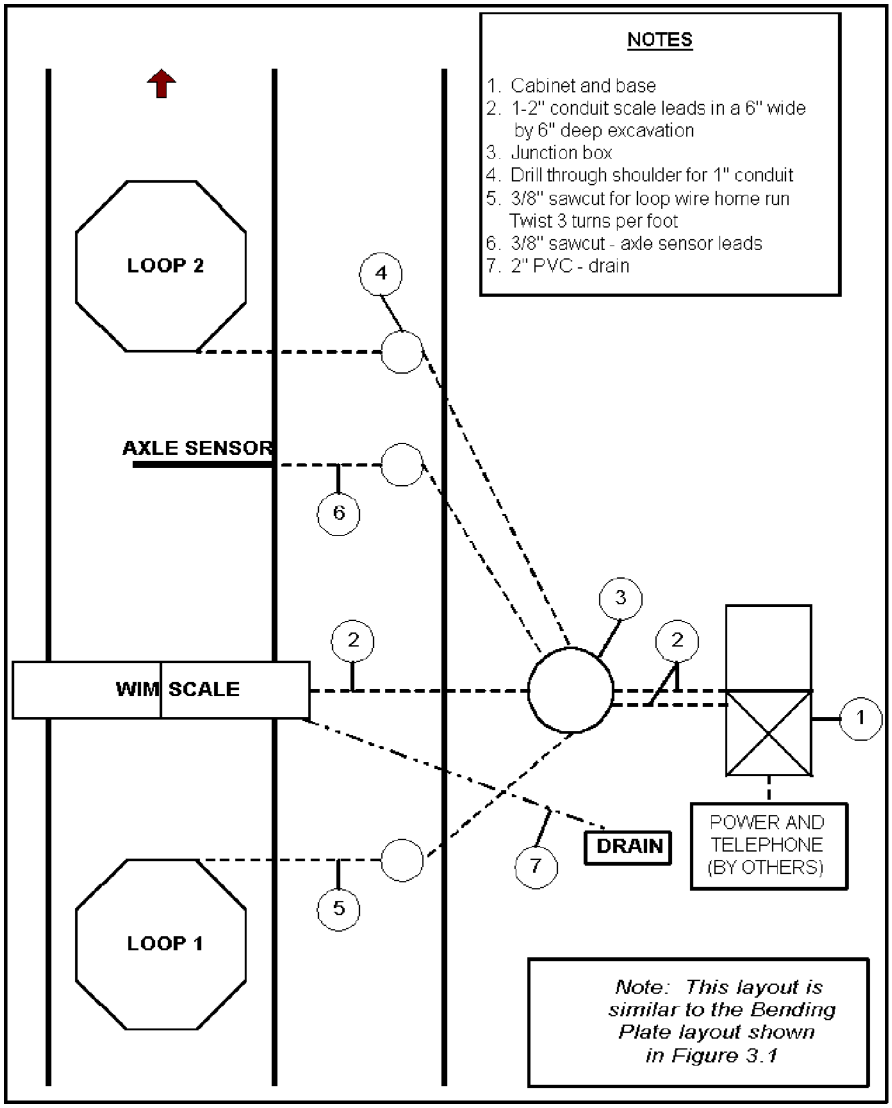

Figure 3.3 Example of Load Cell System Layout

3.5.3 Remote Communication Modem

The modem used to collect data to monitor the system needs to be operable on a standard telephone line and capable of at least 1,200 bps, but preferably at least 9,600 bps. The amount of data collected at the site and the frequence of downloading should be considered when selecting the telephone line and modem. In general, the download process will be quicker as the quality of the selected phone line and modem increases. The remote communication can be done using either telephone lines or cellular technology.

3.5.4 Operating Software

WIM software includes three separate software packages; on-site software, communications software, and in-house software. The typical on-site software interprets the signals from the WIM scale and generates the on-site files which include information such as:

1. Site Identification
2. Time and Date of Passage
3. Lane Number
4. Vehicle Sequence Number
5. Vehicle Speed and Classification
6. Weight of all Axles or Axle Groups
7. Code for Invalid Measurement
8. Optional Graphic Configuration
9. ESAL value

The typical communications software allows for changes to be made to the on-site software setup including calibration factors from the in-house computer. The typical in-house software generates hard copy reports as well as ASCII files. The software allows reports to be generated on the collected raw vehicle record files. The typical communications and in-house software allow the user to perform the following tasks:

1. Real time vehicle viewing selectable by lane
2. Resetting of the system clock
3. Monitor system memory in terms of storage remaining
4. Setup and initiate the generation of summary reports on data previously collected by the system
5. View generated reports
6. Generate and view error reports including time down, system access, auto-calibration, and improperly completed records
7. Transfer selected raw data files or generated reports from the site system to the office host computer
8. Purge old data files from the system

3.5.5 Data Output Format

The typical in-house software is capable of generating output reports in the FHWA's Traffic Monitoring Guide Card Format. The in-house software is also capable of generating daily, weekly, monthly, or continuous summary reports in hourly increments based on vehicle speed, classification, ESAL, and weight summaries on a lane by lane or directional basis. The typical in-house software can also generate reports on errors, auto-calibration, site history, calibration history, and overweight vehicles.