NCHRP
REPORT 509

Equipment for Collecting Traffic Load Data

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Equipment for Collecting Traffic Load Data

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research
Board

This report identifies the key issues that must be considered by state and other highway operating agencies in selecting traffic equipment for collecting the truck volumes and load spectra needed for analysis and design of pavement structures. The report also identifies steps that must be taken to ensure that the equipment performs appropriately and that, as a consequence, the data collected accurately describe the vehicles being monitored. The report is a useful resource for state personnel and others involved in the planning and design of highway pavements and structures.

Traffic information is one of the key data elements required for the design and analysis of pavement structures. In the procedure used in the 1993 AASHTO *Guide for Design of Pavement Structures*, a mixed traffic stream of different axle loads and axle configurations is converted into a design traffic number by converting each expected axle load into an equivalent number of 18-kip, single-axle loads, known as equivalent single-axle loads (ESALs). Equivalency factors are used to determine the number of ESALs for each axle load and axle configuration. These factors are based on the present serviceability index (PSI) concept and depend on the pavement type and structure. Studies have shown that these factors also are influenced by pavement condition, distress type, failure mode, and other parameters.

A more direct and rational approach to the analysis and design of pavement structures involves procedures that use mechanistic-empirical principles to estimate the effects of actual traffic on pavement response and distress. This approach has been used to develop a guide for the mechanistic-empirical design of new and rehabilitated pavement structures as part of NCHRP Project 1-37A. The mechanistic-based distress prediction models used in this guide will require specific data for each axle type and axle load group. Recognizing the constraints on resources available in state and local highway agencies for traffic data collection, the guide will allow for various levels of traffic data collection and analysis.

Because the anticipated guide will use traffic data inputs that differ from those currently used in pavement design and analysis, there was an apparent need for research to provide clear information on traffic data and forecasting and to provide guidance on selection and operation of the equipment needed for collecting these data. This information will facilitate use of the anticipated guide. NCHRP Project 1-39 was conducted to address this need.

Under NCHRP Project 1-39, "Traffic Data Collection, Analysis, and Forecasting for Mechanistic Pavement Design," Cambridge Systematics, Inc., was assigned the objectives of (1) developing guidelines for collecting and forecasting traffic data to formulate load spectra for use in procedures proposed in the guide for mechanistic-empirical design and (2) providing guidance on selecting, installing, and operating traffic data collection equipment and handling traffic data. This report is concerned with

the latter objective; the first objective will be addressed in detail in the agency's final report on the project.

To accomplish the latter objective, the researchers identified the steps required to select the equipment necessary for collecting traffic load data. In these steps, the researchers identified the types of equipment available for collecting classification counts and for weighing vehicles in motion and provided detailed descriptions of various technologies. As part of these descriptions, the researchers reviewed the strengths and weaknesses of each technology. Finally, the researchers provided guidance on selection of equipment by considering (1) data collection needs of users, (2) data handling requirements and capabilities, and (3) characteristics of available technologies. To facilitate implementation and use of equipment, the researchers also provided information on best practices for equipment use.

The information contained in this report should be of interest to those involved in the planning and design of highway pavements and structures. It will be particularly useful to agencies contemplating collection of traffic data for use in conjunction with the guide for the mechanistic-empirical design of new and rehabilitated pavement structures.

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EQUIPMENT FOR COLLECTING TRAFFIC LOAD DATA

SUMMARY   The traffic load data that are key to the design of pavement structures include truck volumes and the load spectra for those volumes. These data are obtained by counting trucks by class and by weighing a sample of trucks to obtain the load spectra associated with each class of truck. Therefore, data collection equipment must allow for collecting both types of data.

Weigh-in-motion (WIM) data collection equipment collects both truck volume and load spectra, but the equipment is more expensive to obtain and more difficult to install and operate than equipment that can only count and classify vehicles. Therefore, highway agencies routinely use a combination of WIM and simpler vehicle classification equipment to collect the data they require for pavement design.

This report summarizes the key issues and information needed by a state or other highway operating agency to select the equipment it needs to perform these tasks. It also summarizes the steps that must be taken to ensure that the equipment selected works as intended and that, as a consequence, the data collected accurately describe the vehicle fleet being measured.

S.1 BASIC EQUIPMENT NEEDS

A combination of permanent and portable data collection is needed to provide the traffic load data required for pavement design. Permanent devices provide more extensive datasets and are generally necessary for collecting the data needed to understand changes in traffic patterns associated with different days of the week and months of the year. Portable devices allow flexibility in collecting data and help ensure that data are collected from specific locations of interest. Portable devices also tend to lower the cost of collecting the geographically diverse and site-specific data needed to develop accurate pavement design loads.

Therefore, a combination of devices—WIM and classification, permanent and portable—are needed to meet their traffic data collection needs for pavement design. Further expanding the need for diversity in the devices that many states will purchase and use is the fact that different technologies have different strengths and weaknesses. Some equipment works nearly flawlessly in rural areas and in moderate environmental

conditions, but that same equipment may work poorly in urban stop-and-go traffic or where snow conditions disrupt driver lane discipline. Other devices work less accurately under the best of conditions but can still operate effectively in harsh data collection conditions such as stop-and-go traffic or adverse weather. Making these tradeoffs is the most difficult part of selecting equipment.

To make these tradeoffs correctly, and then to ensure that the selected equipment operates as intended, requires knowledge. Required areas of knowledge and necessary decisions and/or actions include the following:

- Understanding the equipment's capabilities and limitations;
- Understanding the data collection site's characteristics;
- Choosing data collection locations that provide the best opportunity for collecting accurate data;
- Selecting equipment for each site that can operate effectively in the traffic and environmental conditions present at that site;
- Understanding how data collected from two different devices relate to each other (i.e., are the vehicle classes collected by two different classifiers the same, and if not, how do those classes relate to each other?);
- Installing the equipment correctly;
- Understanding how to test the equipment once it is in place to ensure that it is operating as intended and ensuring that these procedures are followed;
- Properly calibrating the equipment after it has been installed;
- Understanding preventive and corrective "site" maintenance;
- Performing quality control checks on the data produced by those devices; and
- Repairing, re-calibrating, or otherwise adjusting the equipment and site conditions if quality assurance checks indicate that problems are occurring.

While the choice of sensor technology can affect the accuracy of the data collected as well as the cost and longevity of the data collection installation, a wide body of research shows that technology is only one of many factors that affect the reliability of collected data. In fact, recent work done for the Federal Highway Administration (FHWA) concluded that "In general the differences between devices from different manufacturers were more significant than differences between technologies." The report also stated that "It is more important to select a well designed and highly reliable product than to narrow a selection to a particular technology."[1]

This is not to say that technology choice is unimportant. Each technology has specific strengths and weaknesses. Understanding those strengths and weaknesses allows a highway agency to select equipment that is *more likely* to work in a specific situation. While different vendors are often capable of designing around a given technology's weaknesses, the odds of obtaining accurate data are certainly increased by taking advantage of specific technology strengths and avoiding known technology weaknesses. At the same time, as noted in the aforementioned FHWA study, some vendors do a poor job of implementing specific technologies. In addition, even the best technology from the best vendor will not work accurately if the device is poorly installed, maintained, or calibrated.

The rest of this report describes an equipment selection process that guides interested parties toward the technologies that have demonstrated (in the literature published to date) specific strengths and away from technologies that have demonstrated specific weaknesses. Note that (1) this review is not universal (some data collection technolo-

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[1] *Field Test of Monitoring of Urban Vehicle Operations Using Non-Intrusive Technologies,* FHWA, May 1997, FHWA-PL-97-018, by Minnesota DOT and SRF Consulting.

gies have undoubtedly been missed) and (2) data collection technology continues to evolve with time. Specific devices may come to market that are either not part of this review or have different attributes from the technologies reviewed in this report. Therefore, highway agencies are reminded to continually review available sources[2] that describe equipment performance, to communicate frequently with neighboring states to learn about the performance of their data collection equipment and their experiences with vendors, and to monitor the performance of their equipment to ensure that it operates as intended.

S.2 SHORT-DURATION VEHICLE CLASSIFICATION EQUIPMENT

The primary technological attributes that should be considered when short-duration vehicle classification equipment is selected include the following:

- Whether the vehicle (tire) sensors need to be placed on the road surface or will measure from above or beside the pavement,
- The type of vehicle classes that can be collected by the device,
- The number of lanes that each device can observe, and
- The effects that specific environmental conditions will have on equipment performance.

These attributes are summarized in Table S.1 for the technologies commonly found on the market in 2002.

To select equipment, the highway agency must also consider the cost of the equipment (capital, operations, maintenance, and other life-cycle cost considerations), the ability to integrate the data collected by a specific device into the state's traffic data management system (how the vendor's data retrieval software/system works and whether it integrates easily with the state's system), and the various support services and assurances offered by specific vendors, including warranties and other guaranties of performance, proof of previous successful performance (independent testing), the level of technical support offered, and the availability of training. In many cases, these additional factors are the deciding factor in equipment selection, especially when two alternative technologies have similar operating characteristics.

All of the above factors are interrelated. In addition, each can be the deciding factor in an equipment selection decision. Thus, no single piece of equipment is always the best choice, and no single, simple decision process will lead to the correct equipment choice. The state must weigh the relative importance of these attributes each time it selects equipment.

S.2.1 Intrusive or Non-Intrusive Sensors

Perhaps the first question that should be asked when deciding between intrusive and non-intrusive equipment is "Can the portable equipment be safely installed in the roadway section in question?" In most cases, intrusive sensors provide more descriptive vehicle classification data than non-intrusive sensors, especially where the sensors provide axle count and spacing information. They are therefore normally better options for portable classification counts than non-intrusive sensors if they can be safely placed on the road surface.

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[2] On-line resources are provided at the end of this summary, as are references to some conventionally published works.

TABLE S.1   Short-duration classification technology comparisons

Technology	Requires Access to Roadway for Sensor Placement	Types of Vehicle Classifications Collected	Number of Lanes of Data Collected by Each Sensor	Environmental Issues/Concerns	Other Issues/Concerns
Road Tubes – traditional	Yes	Axle Based (FHWA 13+)	1 per pair of sensors (Only lanes bordering shoulders)	Not suited to snowy conditions	Accuracy limitations under very heavy traffic volumes or stop-and-go conditions
Road Tubes – multi-lane design	Yes	Axle Based (FHWA 13+)	1 per pair of sensors	Not suited to snowy conditions	Accuracy limitations under very heavy traffic volumes or stop-and-go conditions
Tape Switches	Yes	Axle Based (FHWA 13+)	1 per pair of sensors	Placement difficulties in wet conditions	Needs protection of lead wires if placed on lanes not adjacent to shoulders
Fiber-Optic Cables	Yes	Axle Based (FHWA 13+)	Can be configured for 1 to 3 lanes per pair of sensors	Placement more difficult in wet or snowy conditions	A relatively new technology, with little history of field use
Magnetometer[1]	Yes	Length Based	1 per sensor	Very cold weather may affect performance	
Piezo sensors (piezo film, piezo cable)	Yes	Axle Based (FHWA 13+)	1 per pair of sensors	Very cold weather may affect performance	Needs protection of lead wires if placed on lanes not adjacent to shoulders
Side-Fired Radar[2]	No	Length Based	Multiple		Use in portable configuration relatively uncommon in 2002
Preformed Inductance Loops	Yes	Length Based	1 per pair of sensors	Placement difficulties in wet conditions	

Notes:

1. Does not include magnetometers placed in conduit under roadway pavements. These are included in Table S.2 (permanent classification technology).

2. Portable versions of side-fired radar are relatively new to the market, and most are based on modifications of equipment designed for permanent installation. Overhead and/or front- or rear-facing radar are considered "permanent" classifiers, as they typically require road closure during equipment placement.

However, if intrusive equipment cannot be safely installed in the roadway, by default, the highway agency must consider non-intrusive[3] vehicle classification equipment, even though that equipment places significant constraints on the types of truck classifications that can be collected and limits the devices that are available for selection.

In some locations, the alternatives to non-intrusive sensors are "no data collection" or "data collection only when full traffic control can be provided."

S.2.2 Vehicle Classes Collected

The mechanistic-empirical pavement design software (which is being developed under NCHRP Project 1-37A) uses the number of axles by axle configuration as an input to the design process. Therefore, in general, data collection equipment that can collect and classify vehicles by using axle count and axle spacing as inputs is preferable over other classification equipment. Ideally, the classification procedure used by a portable counter should match that used by WIM devices in the state. The highway agency can accomplish this by supplying the vendor of a selected device with the classification algorithm used to convert axle count and spacing information into an estimate of vehicle classification. It is strongly recommended that the equipment be able to accept the specific classification algorithm that a state has tested and approved. (A highway agency should also test to ensure that the correct algorithm has in fact been installed and is operating as intended.)

There are cases in which axle-based truck classes cannot be collected (normally because axle sensors cannot be safely placed on the roadway or because traffic flow is unstable, and axle spacings cannot be accurately measured). Where these conditions are expected, it is acceptable to select portable classification equipment that collects truck volume data using other vehicle classes. This usually means classifying vehicles by overall vehicle length. It is important, however, that the state be able to correlate these classes to those used by its WIM system. States are not advised to purchase vehicle classification equipment that produces volume estimates that cannot be correlated effectively with their WIM data.

S.2.3 Lanes of Data Collected: Operational and Geometric Considerations

The next consideration in equipment selection is to understand how many traffic lanes can be monitored by each piece of equipment. For sensors, this normally means determining whether an individual sensor measures one or more lanes, and if more than one lane, whether the data are reported for each lane individually or for all lanes combined. For data collection electronics, this means understanding whether the device can accept sensor inputs from more than one lane of traffic simultaneously.

Many of the older intrusive technologies (e.g., traditional road tubes) only collect data in the outside lane of a facility when they are used as portable detectors. Others (e.g., fiber-optic cable and the new multi-lane road tubes) can collect inside lane data, but only when special precautions are taken to protect the sensor from being dislodged by traffic in the adjacent lanes. When placed, these sensors must be carefully aligned with the existing lane lines to collect accurate truck volume data.

Another concern with axle spaced-based classification counting is that unstable traffic flow speed (stop-and-go traffic in particular) makes the output of many devices

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[3] If the number of these sites is small, the highway agency can also construct "permanent" sensor installations and then rotate data collection electronics among these locations. However, for the purposes of this report, these are considered "permanent" devices and are discussed later in the report.

unreliable. Technologies that can classify correctly without vehicles traveling at a consistent speed are therefore required. These tend to use much broader vehicle classification schemes because these broader schemes are less susceptible to minor errors in length measurement. (Thus, simple length classifiers tend to classify more accurately in congested road sections than do axle sensor-based devices.)

Both operational characteristics and the number of lanes to be counted are determined by the geometric configuration of the roadway. In some instances, more accurate data for pavement design can be obtained by moving upstream or downstream of a desired data collection location. While this makes the data collection site less site specific, it often allows for placement of data collection sensors on a road section with geometric features that are more conducive to accurate classification counting. This is an acceptable practice for use with TrafLoad (which is being developed under NCHRP Project 1-39) and the pavement design software so long as the truck volumes collected provide an accurate measure of the traffic crossing the pavement design section.

S.2.4 Environmental Considerations

Environmental conditions can degrade the performance of specific technologies, especially when those devices are used in a portable mode. For example, snow decreases vehicles' lane discipline and thus badly affects count and classification accuracy for most lane-specific count technologies (although few portable devices are placed during potential snow conditions).

Devices that must be taped to the road surface (tape switches, portable fiber-optic cables, portable piezoelectric film or cable) often do not remain in place very long when the sensors must be placed on wet pavement. Thus, in wet conditions, technologies such as road tubes that can be held in place by pavement nails tend to be better choices. Non-intrusive detection devices that are not affected by wet pavement conditions also tend to perform better than these sensors.

However, non-intrusive detectors can be affected by other environmental factors. For example, video detectors tend to work poorly when visibility is low (e.g., in heavy snow, glare, dust storms, or fog). They make a poor choice for locations subject to these environmental conditions. Infrared sensors have also been shown to perform poorly when visibility is low. Some acoustic sensors have shown performance degradation in cold weather.

S.3 PERMANENT VEHICLE CLASSIFICATION EQUIPMENT

For purposes of this report, "permanent" equipment is differentiated from "short-duration" equipment both because permanent equipment requires more resources to initially place and because its counting session can (but does not necessarily have to) last longer. (That is, permanent equipment cannot be quickly placed at a location that has not been prepared, while the short-duration equipment can.) Thus, devices that can be slid in and out of a conduit placed under the pavement are considered permanent because of the effort required to initially install the conduit, even though once that conduit has been laid, the sensors themselves can be placed or removed quickly.

The attributes of the alternative permanent vehicle classification technologies are summarized in Table S.2. As with short-duration classification counters, these attributes are only part of the information required to choose among alternative devices. In many cases, the other considerations in equipment selection (price, vendor support, and warranties) are even more important than the characteristics of the specific technologies.

TABLE S.2   Permanent classification technology comparisons

Technology	Intrusive or Non-Intrusive	Types of Vehicle Classifications Collected	Number of Lanes of Data Collected by Each Sensor	Environmental Issues/Concerns	Other Issues/Concerns
Piezoelectric Cable	Intrusive	Axle Based (FHWA 13+)	1 per pair of sensors	Susceptible to snowplow damage	Temperature sensitive Doesn't work well in stop-and-go traffic
Piezopolymer Film	Intrusive	Axle Based (FHWA 13+)	1 per pair of sensors	Susceptible to snowplow damage	Temperature sensitive Doesn't work well in stop-and-go traffic
Fiber-Optic Cable	Intrusive	Axle Based (FHWA 13+)	1 per pair of sensors	Susceptible to snowplow damage	New technology, not currently in widespread use Doesn't work well in stop-and-go traffic
Other Pressure Sensors	Intrusive	Axle Based (FHWA 13+)	1 per pair of sensors	Susceptible to snowplow damage	Doesn't work well in stop-and-go traffic
Inductive Loop (conventional)	Intrusive	Length Based	1 per pair of sensors	Freeze/thaw can break loops	
Inductive Loop (undercarriage profile)	Intrusive	Various[1]	1 per pair of sensors	Freeze/thaw can break loops	New technology, not currently in widespread use
Side-Fired Radar	Non-Intrusive	Length Based	Multiple		Not as accurate as overhead-mounted, forward-, or rear-facing radar
Overhead Radar[2]	Non-Intrusive	Length Based	1 per sensor		
Infrared[3]	Non-Intrusive	Length or Height Based	1 per sensor array	Can be affected by heavy fog, snow, glare, dust	New technology, not currently in widespread use

TABLE S.2   (Continued)

Technology	Intrusive or Non-Intrusive	Types of Vehicle Classifications Collected	Number of Lanes of Data Collected by Each Sensor	Environmental Issues/Concerns	Other Issues/Concerns
Magnetometer	Intrusive[4]	Length Based	1 per pair of sensors		
Video (trip wire)[5]	Non-Intrusive	Length Based	Multiple	Can be affected by heavy fog, snow, glare, dust	Requires proper mounting height
Video (object analysis)[5]	Non-Intrusive	Various[6]	Multiple	Can be affected by heavy fog, snow, glare, dust	Requires proper mounting height New technology, not currently in widespread use
Ultrasonic[5]	Non-Intrusive	Length Based	1 per pair of sensors	Temperature variation and air turbulence can affect accuracy	New technology, not currently in widespread use
Acoustic[5]	Non-Intrusive	Length Based	1 per pair of sensors		New technology, not currently in widespread use

Notes:

1. There are two basic undercarriage loop classifier technologies. One uses the "signature" from existing loops to determine classification by matching the shape of that loop to expected profiles. The other uses specific types of loops to detect changes in inductance associated with wheels and then uses that information to detect and measure axles. This device can classify by "axle," while the other defines classes that relate strongly to axle-based classes but are not specifically based on the number and spacing of axles.

2. Overhead-mounted, non-intrusive detectors require a structure (usually a bridge or gantry) upon which to be mounted. Where these detectors do not already exist, the expense of sensor installation increases dramatically.

3. Can be mounted overhead or side-fired. If used in side-fired configuration, vehicle classification is normally based on height, and only one lane of traffic can be detected.

4. Some magnetometers are installed in the pavement, and some are installed in a conduit that is placed underneath the existing pavement by drilling underneath the pavement. This can be done without disrupting the existing traffic stream but does require the appropriate equipment.

5. Overhead-mounted, non-intrusive detectors require a structure (usually a bridge or gantry) upon which to be mounted. Where these do not already exist, the expense of sensor installation increases dramatically.

6. Video image analysis will define classes on the basis of the features the image analysis software can detect. The simplest detection algorithms are based on length. More complex algorithms can detect and classify using axle information, provided that the camera angles are capable of "seeing" different axles.

S.3.1 Choosing Between Intrusive and Non-Intrusive Sensors

As with short-duration classifiers, a key consideration is whether conditions require the use of non-intrusive sensors. As with short-duration counts, the primary drawback of non-intrusive sensors is that very few devices directly measure the number and configuration of axles. This reduces the accuracy of vehicle classification count information for the purpose of pavement design. However, there are conditions when this loss of pavement design accuracy is warranted. These conditions occur where pavement or environmental conditions would result in poor performance of intrusive, axle-based classifiers or where location considerations reduce the cost of non-intrusive sensors significantly relative to the cost of intrusive sensors.

For example, non-intrusive sensors are particularly advantageous for locations where lane geometry will soon change. Because they are non-intrusive, changing the focal point (the exact space at which the sensor points and collects data) for most non-intrusive devices is fairly simple. This is not true for most permanently mounted, intrusive devices. Thus, if a roadway will be restriped as part of an ongoing, long-term construction project, the choice of non-intrusive sensors makes sense. With intrusive sensors, the sensors initially placed are generally useless in the new lane configuration (they often cover parts of two lanes) and must be either dug up or abandoned. (Few sensors can be dug up and then reused.) It makes far better economic sense to place non-intrusive sensors in such a location, even though the data collected are less precise than desired, rather than either not collect data or purchase and install two complete sets of intrusive sensors.

With permanent counter equipment, usually the need for a long-term data collection site makes a highway agency willing to perform the tasks necessary to install sensors in the roadway on all lanes of a facility, regardless of roadway geometry. (For example, the agency will cut slots in the outside lane pavement to protect lead wires leading to sensors that monitor traffic on the inside lanes.) Thus, unlike with short-duration counts, the geometric configuration of a roadway, by itself, is unlikely to cause a state to select non-intrusive sensors over intrusive sensors.

On the other hand, because permanent equipment operates year-round, weather and environmental sensitivity become bigger issues. In locations that experience frequent, heavy snowfall and a resulting decline in driver lane discipline, considerable data can be lost if lane-specific axle sensors are selected. In addition, with sensors that operate year-round, states must determine whether the sensors they select will function in the temperatures expected. For example, piezoceramic cable loses sensitivity in very cold weather. Consequently, states that wish to place sensors in a location that will experience temperatures well below freezing must obtain both documented proof and warranties from their vendors that the selected equipment will operate correctly at the expected temperatures.

S.3.2 Sensor Longevity and Pavement Condition

A second situation in which non-intrusive sensors may be preferable to intrusive sensors is where the pavement condition is poor enough now, or will be in the near future, to raise doubts about the expected life of intrusive sensors and/or where the pavement condition could affect the accuracy of those sensors.

Poor pavement condition can dramatically shorten the life span of intrusive sensors. This is partly because poor pavement conditions increase vehicle dynamics, which in turn increase the impact loads applied to intrusive sensors. But poor pavement condition also commonly leads to premature failure of the pavement/sensor bond, and the

loss of this bond normally results in a non-functional sensor (and often the loss of the sensor itself, because most sensors cannot be reinstalled).

Even if the sensor has not failed, pavement failure around the sensor can lead to the generation of "stray" signals within the sensor. One common form of these signals is "ghost axles" generated in piezoelectric cables when neighboring concrete slabs rock because of failure of the joints between slabs. Stray signals frequently result in mis-classification of vehicles, collection of invalid vehicle records, and ultimately the creation of datasets containing so many invalid data that they become unusable.

If the pavement condition at a proposed permanent data collection site is poor, there are three major options: repave the roadway section that will hold the sensor before installing that sensor; choose a non-intrusive sensor whose performance is not affected by pavement condition; or select a lower-cost intrusive sensor technology recognizing that the life span of that sensor will be fairly short.

The last of these options is often a cost-effective way of collecting a valuable data-set needed for very accurate pavement design, but it requires acknowledgment that the sensor will be lost in a shorter period than most states expect their permanent equipment to last. It also means that great care must to be taken to (1) review data from the device placed at this location to ensure that it works accurately when it is originally placed and then (2) identify when sensor accuracy starts to degrade as the pavement condition continues to deteriorate. Therefore, in these conditions, added quality control and data review are needed both when the sensor is first installed and then as the device continues to operate.

Pavement condition also changes how a highway agency might view the tradeoffs between sensor cost and performance. Poor pavement condition will significantly change the life-cycle of all intrusive technologies. (For example, in some cases sensors will fail before they reach their expected life because of pavement condition.) When pavement condition is poor or even marginal, paying more for a longer lived sensor makes no sense because the sensor failure will not be a function of the sensor itself. Consequently, pavement life should be considered when the life expectancy of a permanent site is computed, and the cost/performance decision should be adjusted accordingly.

S.3.3 Vehicle Classes Collected

As with short-duration counts, the preferred vehicle classification scheme for permanent classifiers is axle based, which means that, all things being equal, intrusive, axle sensor-based classifiers are the preferred technology for meeting the pavement design guide requirements for traffic load data. In fact, use of equipment that provides truck volumes that follow the same classification scheme as the state's WIM devices results in the most accurate traffic load datasets possible and is recommended whenever practical.

However, many of the functions for which permanent classification data are collected (e.g., seasonal adjustment of short-duration counts) require only two or three classes of trucks. Therefore, having permanent classifiers that collect only three or four classes of vehicles is acceptable when axle-based classifiers are not practical or cost-effective.

Selecting a classifier technology that does not use the same classification algorithm as the WIM scales selected requires a careful determination of how the classification schemes of these alternative devices correlate.

S.4 WEIGH-IN-MOTION EQUIPMENT

It is not possible to provide a simple decision process for selecting WIM equipment. In general, each highway agency must determine its own tradeoffs among the cost of

equipment and its installation, the cost of calibration, the expected life span of the WIM sensor, and the expected life span (and structural performance) of the pavement into which the equipment will be placed. These technical considerations must also be examined in light of the compatibility of the data retrieval capabilities offered by specific vendors, how well those capabilities integrate with existing data collection software, the warranties and other guaranties of performance offered with the equipment, the performance history of that equipment and its vendor, and the support services offered by the vendor. Key technology considerations are summarized in Table S.3. An important additional consideration is whether the equipment offered by a vendor has been independently evaluated and found to meet the ASTM E 1318 WIM performance standards.

S.4.1 Technology Choice Versus Location Choice

The primary key to the success of any WIM system's use is the location of the axle weighing sensors. Because vehicle dynamics play such a significant role in the force actually applied by any given axle at any given point on the roadway, the selection of the location used to weigh trucks is often more important than the choice of a specific technology to ensure accurate axle weight data. The placement of a scale in rough, uneven pavement will result in poor quality weight data, regardless of the WIM technology selected. Similarly, if the pavement condition at a WIM site deteriorates after a scale has been installed, the performance of that scale can be expected to deteriorate as well, regardless of the technology selected.

Some scale sensor technologies rely on the structural strength of the pavement in which they are supported. When these sensors are placed in weak pavement (i.e., pavement that flexes), the accuracy of these sensors tends to degrade. Similarly, when the strength of the pavement changes with environmental conditions (usually because of changing moisture content or temperature), sensor performance can be expected to change, and calibration drift frequently occurs. Consequently, where weight data are needed for thinner, flexible pavements subject to changing strength characteristics, selection of a WIM technology that separates the weight sensor from the pavement through the use of some type of frame is a good idea. However, the pavement must be thick enough to hold the frame. Where the pavement cannot support accurate WIM data collection, the highway agency should consider moving the data collection site to a location at which the WIM can function accurately.

Finally, as with permanent vehicle classifiers, the highway agency should consider expected pavement life when determining the life expectancy of a WIM site, as well as the implications of that life span for the WIM technology for that site. That is, the agency should not spend a lot of money on a WIM device and installation where the pavement will not support accurate weighing for more than 1 year. Similarly, more expensive, longer lived WIM scales should be considered for placement in high-quality pavement, where these devices can be expected to operate accurately for many years.

S.4.2 Portable Versus Permanent Scale Deployment

Ideally, as with classifiers, WIM equipment selection would be divided into both permanent and portable devices, because WIM data are also needed both at geographically diverse locations and over long periods at some locations to measure seasonal and day-of-week changes in vehicle characteristics. Because dynamic vehicle motion dramatically affects WIM sensor output, each scale must be calibrated to each of the specific locations where the weighing sensors are placed. Site-specific calibration is the only way

TABLE S.3   Weigh-in-motion technology comparisons

Technology	Installation Requirements	Length of Traffic Disruption During Installation	Environmental Issues/Concerns	Other Issues/Concerns
Bending Plate	Moderate frame installation	Moderate		
Piezoelectric Cable	Narrow slot	Short	Temperature sensitive	Accuracy affected by changes in pavement strength
Piezopolymer Film (BL)	Narrow slot or portable	Short	Temperature sensitive	Accuracy affected by changes in pavement strength
Piezoquartz	Narrow slot	Short – Moderate		Relatively new to the U.S. market Accuracy affected by changes in pavement strength
Hydraulic Load Cell	Deep pit	Long		Most expensive system currently on the U.S. market
Capacitance Mat	Portable or moderate frame installation	Short – Moderate		Only measures one-side of each vehicle Portable operation subject to errors caused by impact loads. When used as portable devices, accuracy is affected by changes in pavement strength
Fiber-Optic Cables	Narrow slot	Short		Not actively marketed in the United States. Still primarily under development Accuracy affected by changes in pavement strength
Bridge WIM	Weight sensors under bridge Either no axle sensors, or narrow slot	Short		Currently out of favor in the United States but not in Europe
Subsurface Strain Gauge	Deep pit	Long		New system design, only in testing in the United States Accuracy affected by changes in pavement strength
Multi-Sensor WIM	Multiple narrow slot	Moderate	Depends on technology used	While excellent potential, not marketed other than as two-sensor systems using the above technologies

that the dynamic effects of the pavement leading to the scale sensor can be accounted for in the WIM scale calibration.

The need for site-specific calibration means that portable scales must be calibrated each time they are placed on the road surface. This roughly doubles the cost of setting up a portable weighing session because calibration often takes as much staff time as (if not more staff time than) portable sensor placement and pick up. When these calibration costs are accounted for, many highway agencies find that portable WIM becomes cost prohibitive relative to the use of "short-term permanent" WIM (placing WIM sensors permanently in the ground, but only collecting data from the sensors periodically for moderately short periods).

S.4.3 Temperature Sensitivity

Some WIM systems are sensitive to temperature. Piezoceramic and piezopolymer sensors are both temperature sensitive (i.e., their signal strength for a given axle force changes with temperature). While some vendors have developed compensation algorithms to account for temperature sensitivity, these technologies are at a disadvantage when placed in environments that include quickly changing temperatures.

Because the strength of asphalt pavements also changes as environmental conditions change, the technologies that rely on direct structural support from the pavement itself will perform less consistently in these pavements than at locations where the pavement's strength characteristics will not change (e.g., thicker asphalt and concrete sections). Also more successful will be WIM technologies whose axle sensor support is not affected by changing environmental conditions.

S.4.4 Scale Sensor Width, Accuracy, and Installation Effects

The larger the size of the scale sensor, the longer a tire is in contact with the sensor and the longer the period during which force is measured. This provides an accuracy advantage to wider sensors in comparison with narrow sensors. (Note, however, that if the scale grows too wide, such as with some bridge WIM installations, multiple vehicles will be on the sensor at the same time, thus degrading weighing accuracy.) Very narrow sensors also permit tires to "bridge" the sensor, meaning that at no point is the entire weight of the tire supported solely by the sensor. This decreases the sensitivity of the sensor and makes weighing accuracy more sensitive to environmental changes in pavement strength.

A significant advantage of narrow strip sensors is that installation is far easier and takes considerably less time than for wider sensors. As a result, these sensors tend to be less expensive to install. They also tend to be less expensive per sensor than wider sensors.

S.4.5 Number and Location of Sensors

The most common means of reducing inaccuracy in weighing caused by vehicle dynamics is to weigh an axle at more than one location as it moves along a road. Increasing the number of weight sensors used by a WIM device (when those sensors are placed in series) allows a more complete analysis of vehicle dynamics and, consequently, provides a better estimate of each axle's static weight. Thus, in general, the larger the number of sensors placed in series on the roadway, the more accurate the system will be. In addition, having multiple sensors allows the failure of at least one sensor without the loss

of all WIM capability. Unfortunately, each extra scale sensor increases the cost of the WIM system. Therefore, multi-sensor WIM systems tend to use less expensive, narrow strip sensors.

Most multi-sensor systems marketed in the United States place two scale sensors in series in the roadway. However, some vendors of wider bending plate sensors achieve a similar weighing-in-series effect by staggering their half-lane sensors (weighing first one side of the truck, and then the other side of the truck), rather than placing them side-by-side. This, too, measures a greater range of the truck's dynamic motion, increasing the scale's ability to account for vehicle dynamics.

Several European WIM tests have shown that further advances in WIM system accuracy can be obtained by using even more sensors. To date, the use of three or more sensors in series has not been adopted in the United States for production weighing.

S.4.6 Location of the Sensor Relative to the Pavement Surface

Field tests to date have shown that the most accurate WIM systems have sensors that are mounted flush with the existing road surface. Sensors that sit on top of the pavement create their own bump (even a very small bump is bad) that increases vehicle dynamics, which in turn decrease sensor accuracy. Sensors that are entirely covered by pavement are affected by changes in pavement strength associated with changes in environmental conditions. Changes in pavement profile (such as rut formation) that decrease the smoothness of the transition from the pavement surface to the WIM sensor surface cause impact loads and increased vehicle dynamics, both of which contribute to loss of WIM system accuracy.

S.5 ADDITIONAL GENERAL GUIDANCE

While it is important to select technologies that can operate in the conditions in which they are installed, a successful data collection program will also incorporate all of the attributes presented below. Some of these attributes have not been mentioned in the preceding sections but are explained more fully in the other chapters.

- Make sure that the equipment selected can collect data that meet the users' requirements.
- For permanently placed equipment, match the design life of the equipment to the (remaining) design life of the location (pavement) where it will be installed.
- Make sure that the equipment selected can operate accurately at the location where data are required.
- Budget the necessary resources to install, calibrate, operate, and maintain the equipment, including site preventive and corrective maintenance. (Under-funded programs often collect poor data because the programs sacrifice quality for quantity, thereby collecting "data" that are mostly noise, not information.)
- Develop, use, and maintain a quality assurance program. This includes making sure that equipment is properly calibrated when first installed, that data produced by that equipment are regularly checked for quality, and that identification of suspect data or equipment performance results in an investigation of the cause and either confirms accurate system performance or results in repairs, replacement, or removal of the malfunctioning equipment.
- Select equipment that has passed an independent performance test (such as ASTM E 1318) and for which vendors are willing to supply warranties of performance.

- Make sure that the staff installing the equipment are fully trained in the installation of that equipment and that they understand the factors that affect its performance.
- Maintain a preventive and corrective maintenance program to ensure that data collection equipment reaches its expected life and that the data provided are accurate.

S.6 RESOURCES

S.6.1 Paper Reports

American Society of Testing Materials, *Annual Book of ASTM Standards 2000*, Section 4, Construction, Volume 04.03, Designation: E 1318—Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Method.

Middleton, D., Jasek, D., and Parker, R., "Evaluation of Some Existing Technologies for Vehicle Detection," *Project Summary Report 1715-S*. Texas Transportation Institute, September 1999.

McCall, B., and Vodrazka Jr., W.C., *States Successful Practices Weigh-In-Motion Handbook*, Center for Transportation Research and Education (CTRE), Iowa State University, December 15, 1997, http://www.ctre.iastate.edu/research/wim_pdf/index.htm.

Skszek, Sherry, *State-of-the-Art Report on Non-Traditional Traffic Counting Methods, Final Report #503,* Arizona Department of Transportation, October 2001.

S.6.2 On-Line Resources (accessible as of June 20, 2003)

The Vehicle Detector Clearinghouse at New Mexico State University http://www.nmsu.edu/~traffic/.

FHWA's Demonstration Project 121 web site on Weigh-in-Motion Technology http://www.ornl.gov/dp121/ maintained by Oak Ridge National Laboratory.

The European Weigh-in-Motion of Axles and Vehicles for Europe (WAVE) project web site, http://wim.zag.si/wave/.

The Minnesota Guidestar Non-Intrusive Traffic Detection Tests http://www.dot.state.mn.us/guidestar/projects/nitd.html.

CHAPTER **1**

INTRODUCTION

This report is designed to serve as a primer on the selection and use of equipment for counting and classifying vehicles and for collecting data on their axle weights. The data collected by this equipment are specifically required by the mechanistic-empirical pavement design procedures being developed under NCHRP Project 1-37A (*Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures*). These data are also required by other procedures that incorporate estimates of expected pavement stresses into the design of pavements.

The most important finding of an extensive review of the available literature on equipment performance is that wide variation exists in the reported error rates for any given technology. In fact, different results are often reported for different tests of a specific device from the same manufacturer. Closer examination of these results almost always leads to the conclusion that the observed variation is a direct result of differences in the environment in which the devices were placed, as well as how well each specific piece of equipment was placed, calibrated, maintained, and operated.

When the Minnesota Guidestar program examined non-intrusive sensors,[1] one of its primary conclusions was that "the differences between devices from different manufacturers were more significant than differences between technologies." The report also stated, "It is more important to select a well designed and highly reliable product than to narrow a selection to a particular technology."

Taken together, these observations make it clear that no single technology is best and that simply purchasing all data collection equipment from a reputable vendor will not ensure accurate data collection. Rather, the following is required:

- A careful examination of equipment capabilities and limitations relative to the data collection environment in which that equipment will be placed and
- The deployment of a comprehensive data collection program that includes, at a minimum,
  – Acceptance testing of purchased equipment;
  – Staff training in that equipment's placement, operation, and maintenance;
  – Quality assurance tests on the data that are collected;
  – The funding necessary to purchase and properly install, inspect, maintain, and operate the equipment; and
  – Sufficient vendor support to quickly resolve problems identified as the equipment is used.

This report provides a basic overview of the steps required to select the equipment necessary to collect traffic load data. The report also discusses all these data collection program attributes.

The report is organized into a summary and five chapters, including this introduction. Chapter 2 provides a brief introduction to the types of equipment available for collecting classification counts and for weighing vehicles in motion, and Chapter 3 contains more detailed descriptions of the various technologies. Chapter 4 provides guidance on the selection of equipment, and the final chapter offers additional guidance on the implementation and use of the equipment.

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[1] *Field Test of Monitoring of Urban Vehicle Operations Using Non-Intrusive Technologies,* FHWA, May 1997, FHWA-PL-97-018, by Minnesota DOT and SRF Consulting.

CHAPTER **2**

TYPES OF EQUIPMENT

This chapter presents an introductory summary of the types of equipment that are available for collecting classification counts and for weighing vehicles in motion. For this purpose, the authors categorize equipment by the type of data collected:

- Short-duration portable vehicle classification counts;
- Continuous (long-duration) vehicle classification counts;
- Short-duration, weigh-in-motion (WIM) data; and
- Continuous (long-duration) WIM data.

In addition, the classification technologies are further differentiated by whether the sensors are placed in or on the roadway surface (intrusive sensors) or whether they are placed above or beside the roadway (non-intrusive). Vehicle classification can be performed using either intrusive or non-intrusive sensors, although the style of sensor used affects the data available for classifying vehicles and thus the definition of vehicle categories into which vehicle counts are placed. On the other hand, current WIM technologies all require on-surface or in-pavement sensors.

2.1 VEHICLE CLASSIFICATION

Vehicles can be classified using any one of several categorization schemes, and alternative schemes often use different characteristics to differentiate between vehicles. The most common classification schemes are based on

- Number and spacing of axles,
- Total vehicle length,
- Body or trailer type,
- Vehicle weight, or
- Engine/fuel type.

Most technologies can collect some but not all of these different characteristics. Thus, if a specific classification scheme is required, it is important to select a data collection technology that can collect the vehicle characteristics that define that scheme. Similarly, if a specific technology must be used because of some other constraint (such as environmental factors or pavement condition), it is important to understand the restrictions that the use of that technology places on the classification scheme. For example, use of two conventional

inductive loops in series (dual loops) allows for classification based on overall vehicle length, but does not allow for classification using the FHWA's 13-category, axle-based scheme.

2.1.1 Short-Duration Classification Counts

Short-duration counts are the most common of all classification counts. Prior to the mid-1980s, classification counts were almost always collected manually by roadside observers. Visual observation allows a wide variety of classification schemes, including those based on body type and those based on vehicle configuration and number of axles. However, because manual observation is expensive, highway agencies have transitioned to automated data collection. Since the mid-1980s, most classification data have been collected using portable sensors placed on top of the roadway surface. This choice of technology means that most classification counts now use axle- or length-based classification schemes. However, further advancements in technology, as well as limitations in the more traditional data collection technologies, have encouraged highway agencies and vendors to experiment with portable versions of non-intrusive sensors.

Short-duration classification counts are collected at a wide variety of locations. In addition to collecting accurate data, the technology used for short-duration counts must be easily moved from location to location, be easy and safe to place, have portable power supplies that can keep the equipment operating for the periods desired, and be relatively inexpensive. Short-duration counts are most commonly collected for periods of 24 or 48 hours, although some highway agencies attempt to collect as many as seven consecutive days of such data.

Portable sensors that are commonly used for collecting vehicle classification data include

- Road tubes,
- Piezoelectric sensors,
- Fiber-optic cable,
- Portable inductance loops, and
- Magnetometers.

The first three of these types of sensor provide information sufficient for use when classifying vehicles into the FHWA's 13-category system, but inductance loops and magnetometers

do not. The primary advantages of these three technologies are that they are relatively inexpensive to purchase, are easy and inexpensive to place, and are capable of providing the information required for most uses. The technologies' biggest drawback is that they are generally designed to operate in low- and moderate-volume rural settings. In congested conditions, where vehicles are accelerating or decelerating while crossing the sensors, or where vehicles are tailgating each other, these sensors often have accuracy problems caused by an inability to measure axle spacings correctly or to distinguish between closely spaced vehicles. (For example, in congested conditions, two closely spaced cars are often reported incorrectly as a single, four-axle, combination truck.) In addition, on higher-volume roadways, even the most quickly installed sensors require the presence of full traffic control in order to protect the staff placing the sensors. The need for traffic control significantly increases the cost of portable data collection and can entirely prevent short-duration classification data collection where staff are not able to safely place sensors.

Research is currently being performed on the development of non-intrusive sensors specifically designed for collecting truck volume information on high-volume urban roadways. The Minnesota Department of Transportation has recently begun testing these devices.

In order to increase staff safety, eliminate the need for traffic control for each count, and allow data collection on high-volume roadways, some highway agencies place sensors permanently in the ground at high-volume locations, but only collect data at these locations periodically. In these cases, the data collection electronics usually "rove" from sensor location to sensor location. This allows short-duration counts to be made quickly and inexpensively by simply connecting the roving electronics to existing permanently mounted sensors. This option reduces the cost and danger of placing sensors whenever counts are required, but it entails a high capital cost for initial purchase and installation of a large number of sensors.

2.1.2 Continuous Classification Counts

Equipment that works well for short-duration classification counting often is a poor choice for continuous data collection over longer periods of time. Technologies that use sensors mounted on the surface of a roadway usually are not able to operate for extended periods of time without having the sensors reinstalled because the traffic has loosened them from their original placements. Continuous counts require a long-lived sensor installation. In addition, continuous count devices require power and communications capabilities that are far different from portable devices. Portable counts normally are collected using battery power, with the counts downloaded manually from the data collection electronics to a laptop computer or data transfer device. Long-duration counts, however, require electrical power, usually from electric power service or from solar cells, as well as telephone communications for downloading data.

As a consequence, data collection efforts at permanently placed, continuous count locations tend to be far more capital intensive than are those of short-duration counts. Continuous counts usually use sensors that require traffic control or heavy equipment (such as a bucket truck and a trenching machine) for placement and are made by counting devices that are stored in installed, locked cabinets rather than chained to nearby utility poles. However, once these devices are placed, they are designed to operate with relatively little staff intervention except for periodic maintenance.

The most common data collection technologies for continuous classification data collection are in-pavement sensors based on dual-inductance loops or piezoelectric (ceramic) cables. Limitations in these two technologies, and the recognition that more classification data are needed, have led to a significant increase in the number of technologies available for conducting continuous vehicle classification counts. In particular, considerable advances have been made in the development of non-intrusive technologies, which use sensors that are not physically placed in the roadway itself but which monitor traffic from above or beside the road. Non-intrusive sensors have the advantage of allowing sensor placement with no lane closure (for roadside sensors) or with a less disruptive closure (for overhead-mounted sensors). They also have the advantage of not being subject to the impact of traffic loads or to the stresses that result from pavement interaction with the environment.

However, non-intrusive sensors have limitations. The foremost limitation is that it is more difficult to detect and count the axles on passing vehicles with non-intrusive sensors than with intrusive sensors such as the piezo cable. Because axle counts by type of axle are generally required for accurately estimating pavement loads, data collected with non-intrusive sensors usually require at least one extra data manipulation step (based on assumptions) when used for pavement load determination. This step involves converting the vehicle classes collected with the non-intrusive technologies into a vehicle classification scheme compatible with the vehicle classes that are collected using available WIM technologies.

Finally, even the newest technologies have difficulty correctly classifying vehicles in stop-and-go traffic and when vehicle separation is small. These conditions make it extremely difficult to separate tailgating cars from multi-unit trucks and make it very difficult to measure vehicle length and axle spacing correctly. These limitations are a primary reason why most states have only modest amounts of classification data for urban roadways.

2.2 WIM DATA

2.2.1 Short-Duration WIM

Two technologies, capacitance mats and BL-style piezo-electric sensors, are commonly used in the United States for high-speed (i.e., on-highway) portable WIM data collection.

Both technologies involve mounting a sensor on top of existing pavement. This action requires a temporary lane closure and often work by more than one person.

While the basic technique of placing sensors on top of the roadway is essential for collecting WIM data in a truly portable mode (i.e., at any site that meets the physical requirements for acceptable sensor operation), there is a system performance problem that limits the accuracy of high-speed portable WIM scales.

Because the sensor is physically on top of the roadway surface, a bump is created as the tire of each axle mounts the weight sensor. This bump causes two physical effects, each of which is detrimental to WIM system accuracy. The first effect is the additional dynamic motion imparted on the vehicle being weighed. This motion makes it much harder for the WIM system to accurately estimate the static weight applied by each axle. The second physical effect is that the need to climb over this bump causes the tire itself to flex, absorbing some of the horizontal force from impact with the bump. This tire flex force is transmitted to the weight sensor, causing additional bias and noise in the measurement process.

The result of these physical phenomena is that portable WIM rarely achieves the same level of accuracy as a correctly placed permanent scale. This does not mean that weights collected using portable scales are not useful in the traffic load estimation process, but it does mean that highway agencies must be particularly careful to calibrate portable scales each time they are placed on the roadway and to monitor the data produced after scales have been calibrated to ensure that the system is producing reliable results.

The need to calibrate every time portable sensors are placed also reduces the difference in the total costs associated with data collection using permanently mounted sensors and using portable sensors. Without calibration, data collected by portable scales will be significantly less accurate than data produced by permanent scales.

Because of the limitations in truly portable WIM systems, some state highway agencies use one of two methods for collecting short-duration WIM data. One method involves the use of low-speed (off-highway) WIM scales or portable static scales. The other method relies on permanently mounted weight sensors and portable data collection electronics.

In the first method, conventional, portable static scales (loadometers) or low-speed portable WIM scales (usually bending plates or capacitance pads) are used for portable weight data collection. These traditional technologies require flat areas (such as a parking area of a rest stop) where the scales can be laid out and trucks diverted over the scales. Trucks are either stopped on these scales or driven at slow speeds over the scales. These data collection techniques tend to be labor intensive (because trucks must be directed over the scales), and they result in fairly small datasets in comparison with high-speed WIM data collection. Also, they disrupt the truck traffic stream (which must be diverted off the roadway and over the scales), and drivers are likely to assume

they are being used for weight enforcement. Hence, these collection locations may be avoided by illegally overloaded trucks, resulting in biased results. However, these technologies are acceptable for truck weight data collection where truck volumes are light, where only a small sample is required, and where truck evasion is difficult because of limited opportunity for trucks to by-pass the scale site.

The second method uses portable electronics with permanently mounted WIM sensors that allow weight sensors to be flush mounted with the roadway. This eliminates the bump that occurs with surface-mounted sensors and results in a better environment for collecting accurate axle weights, but it does not ensure accurate WIM data. Even in this type of portable operation, calibration is required prior to starting data collection, and care should be taken to ensure that pavement deterioration over time has not created bumps at the joint between sensors and roadways. This type of site is less costly to operate than a continuously operated WIM site (because one set of data collection electronics is used for several data collection sites and because permanent power and communications are not needed and therefore do not need to be constructed). However, the initial capital cost is higher than for truly portable WIM—a factor that the highway agency considers when deciding where to collect WIM data.

2.2.2 Continuous WIM

Because of the physics problem noted above for portable equipment, the majority of research and development in WIM has been done for permanently installed weight sensors. Five technologies are currently in common use throughout the United States. Other sensor designs are under active development. The most common permanently mounted weight sensors are

- Bending plates,
- Hydraulic load cells,
- Piezoceramic cables,
- Piezopolymer cables, and
- Piezoquartz sensors.

Other sensor technologies that are either in more limited use or are still under development include

- Permanently mounted capacitance mats,
- Permanently mounted capacitance strips,
- Fiber-optic cables,
- Subsurface strain-gauge frame, and
- Bridge or culvert WIM.

All of the systems are designed to have sensors permanently installed in or under the roadway. This results in less dynamic vehicle motion and less impact force on sensors than for surface-mounted sensors, which in turn results in more accurate weighing conditions and longer sensor life.

The various sensor technologies were developed either to take advantage of particular material properties (to reduce the cost of the sensor and/or installation) or to provide a specific advantage to the signal-processing algorithm that converts sensor output into an estimate of axle weight. Each sensor technology has its own strengths and weaknesses. No one sensor is best for every WIM application.

For example, both the piezoelectric cable and fiber-optic cable sensors are specifically designed to require a relatively small pavement cut for sensor installation. This results in a fast and relatively low-cost sensor installation. However, these sensors are so small that at no time during the weighing process is the entire tire (axle) that is being weighed isolated on the sensor. Thus, both of these technologies suffer from signal noise because of the fact that, during the weighing process, the axle weight is partially supported by the pavement that surrounds the sensor.

Each vendor takes into account the selected sensor's strengths and weaknesses when designing a WIM system. The means for accounting for specific weaknesses has a great deal to do with how well specific sensors work in given installations. Because vendors often take different approaches to sensor installation design and signal processing, the performance of a specific sensor technology can vary widely from vendor to vendor. In some cases, the conditions at a specific WIM site directly (and negatively) coincide with the particular weakness of a given sensor technology. In these cases, even the best vendor responses to handling those weaknesses may not allow sensors to work correctly.

A good example is temperature sensitivity. Temperature-sensitive WIM sensors are not good choices for WIM sites where temperatures change rapidly. Although such sensors are used with temperature compensation algorithms, often based on some type of autocalibration technique, these adjustments cannot be made fast enough to maintain scale accuracy in areas with rapid temperature changes, such as those experienced in mountain passes and in the Southwestern deserts.

Environmental and site conditions (pavement condition, temperature, wind, grades, etc.) play a large role in the performance of any WIM system, regardless of sensor technology. A high-speed WIM system will not work accurately if the site selected for weighing is not conducive to weight data collection. ASTM specification E 1318[1] provides specific guidance on the pavement conditions needed for accurate WIM system performance. This guidance stipulates a pavement that is

- Flat (no horizontal or vertical curves),
- Smooth (no bumps or other surface conditions that create vehicle dynamics),
- Strong (to reduce pavement flex underneath the WIM sensor), and
- In good condition.

WIM sites should also be sites where vehicles are traveling at fairly constant speeds (i.e., not accelerating or decelerating), are not changing lanes frequently, and have good lane discipline. If these conditions are met, then the trucks being weighed are likely to have relatively modest dynamic motion. They will tend to track correctly in their lanes (and will hit the weight sensors as expected), and the speeds measured and used in various signal-processing algorithms will be accurate. All of these factors improve the performance of any WIM system, regardless of sensor technology.

[1] American Society of Testing Materials, *Annual Book of ASTM Standards 2000*, Section 4, Construction, Volume 04.03, Designation: E 1318—Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Method, ASTM, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania, 19428-2959.

CHAPTER **3**

TECHNOLOGY DESCRIPTIONS

Tables 3.1 and 3.2 list the most commonly used technologies for vehicle classification and WIM, respectively, together with their primary strengths and related concerns. Strengths and concerns are summaries of material found in the literature. Opinions of the strengths, weaknesses, or level of expected performance for any given technology or piece of equipment often differ from one expert to another, usually based on the experience that individual has had with a specific piece of equipment. The performance of any specific device may differ from these summaries. This chapter provides further information about

- How these technologies work,
- The types of data they can provide,
- Installation conditions required for accurate performance,
- Specific weaknesses, and
- Typical uses (e.g., portable versus permanent data collection).

As noted earlier, sensor technology is constantly under development. This chapter includes summaries of published research. For more current information, readers should consult resources such as the Vehicle Detector Clearinghouse at New Mexico State University (http://www.nmsu.edu/~traffic/), the FHWA's Demonstration Project 121 web site on WIM Technology (http://www.ornl.gov/dp121/) maintained by Oak Ridge National Laboratories, and the European WIM of Axles and Vehicles for Europe (WAVE) project web site (http://wim.zag.si/wave/).[1] In addition, excellent written documentation exists that should be used when learning about equipment attributes and selection. Useful documents include the FHWA's *States Successful Practices WIM Handbook*,[2] the *Traffic Detector Handbook,*[3] the FHWA's *Traffic Monitoring Guide*,[4] and the ASTM E 1318 WIM[5] standard. This report

should serve primarily as a starting point to the selection and operation of vehicle classification and WIM equipment.

3.1 VEHICLE CLASSIFICATION

The descriptions of technologies for vehicle classification are grouped on the basis of whether they use intrusive or non-intrusive sensors. Technologies using temporary, surface-mounted sensors are considered intrusive technologies, because they involve access to the roadway structure.

3.1.1 Intrusive Technologies

This section covers sensor technologies that are placed either in or on top of the pavement and, at a minimum, provide the ability to classify vehicles into passenger vehicles and trucks.

Portable Operations

Portable sensor technologies used for classification include

- Road tubes,
- Piezoelectric sensors (BL [brass linguini], ceramic cable, and quartz),
- Fiber-optic cable,
- Other pressure sensors,
- Preformed inductance loops,
- Magnetometers, and
- Side-fired radar and other non-intrusive sensors.

Road tubes, piezoelectric sensors, and fiber-optic cable technologies are pressure sensitive. That is, they deflect as vehicle tires pass over them, and the deflection causes a signal that is detected and interpreted. Inductance loop and magnetometer technologies are presence detectors that detect the presence of a vehicle (by changes in the sensor's inductance or the earth's magnetic field) as a result of the presence of metal in the vehicle.

Pressure-sensitive technologies have several strengths and weaknesses. These technologies count vehicle axles and measure axle spacings. Most classification systems that use intrusive sensors base their classification on these variables. Hence, the performance of the equipment is a function of how accurately these measurements are made and how well they assign

[1] All web sites referenced in this report were active as of June 20, 2003.

[2] B. McCall and W.C. Vodrazka Jr., *States Successful Practices WIM Handbook*, Center for Transportation Research and Education (CTRE), Iowa State University, December 15, 1997, http://www.ctre.iastate.edu/research/wim_pdf/index.htm.

[3] J.H. Kell and I.J. Fullerton, *Traffic Detector Handbook*, Second Edition, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1992.

[4] *Traffic Monitoring Guide*, U.S. Department of Transportation, Federal Highway Administration, Office of Highway Policy, January 2001, http://www.fhwa.dot.gov/ohim/tmguide/index.htm.

[5] American Society of Testing Materials, *Annual Book of ASTM Standards 2000*, Section 4, Construction, Volume 04.03, Designation: E 1318-02—Standard Specification for Highway WIM (WIM) Systems with User Requirements and Test Method.

TABLE 3.1   Sensors commonly used for vehicle classification

Type of Sensor	Strengths	Concerns
Portable Vehicle Classification Sensors		
Road Tubes (axle-based classification)	Inexpensive Very common Easy to use	Inaccurate under high volumes Difficult to install on multi-lane facilities Conventional road tubes can only measure classifications in lanes next to shoulders or medians. Multi-lane road tube technology is relatively new to the market
Inductance Loops (preformed) – (total length-based classification)	Inexpensive	More difficult to place than road tubes Difficult to install under high-volume conditions Accuracy degrades with tight headways
Magnetometer (total length-based classification)	Ease of deployment Simple installation	Difficult to deploy in high-volume conditions Little reliability information published Accuracy degrades with tight headways Eight length-based classification bins
Conventional Pressure Sensors includes various piezo technologies and tape switches (axle-based classification)	Well supported by vendor community Ease of deployment in low-volume conditions and when measurement lane is accessible from a shoulder Reliable	Can be difficult to place in high-volume conditions (may require traffic control) Meticulous installation required Easy to break sensor/wiring connection if used for lanes not bordering on shoulders Susceptible to lightning
Fiber-Optic Cable (axle-based classification)	Can monitor multiple lanes Not susceptible to lightning	Relatively new technology with little performance history Often requires traffic control to install if deployed across multiple lanes
Side-Fired Radar (total length-based classification)	Non-intrusive sensor	Use in a portable configuration is relatively uncommon

vehicles to the desired classes. Differentiation between closely spaced vehicles is often improved by using pressure sensors in conjunction with an inductive loop.

Where traffic, geometric, or environmental conditions make it difficult to count axles and measure axle spacings correctly, pressure-sensitive sensors do not work effectively. The three most common problems associated with the use of this type of sensor are

- Very rough pavement (which causes axles to bounce over the sensors);
- Roadway conditions that cause braking or vehicle acceleration while vehicles are crossing sensors (interfering with the estimation of axle spacing); and

- Poor lane discipline, resulting in vehicles changing lanes as they cross sensors or traveling with one tire outside of the established lane lines (and striking sensors in adjacent lanes).

Traffic signals, major interchanges, and congestion can cause the last two conditions. As a result, it is difficult to use these technologies for collecting classification counts at many urban locations or at rural locations immediately adjacent to major interchanges.

Another problem with equipment accuracy is a poor correspondence between the variables measured and the vehicle classes of interest. Pressure-sensitive technologies, by themselves, have difficulty distinguishing between vehicles in the

TABLE 3.1   (Continued)

Type of Sensor	Strengths	Concerns
Permanent Vehicle Classification Sensors		
Intrusive Sensors (General Comments)	*Sensors installed in the pavement tend to be adversely impacted by poor pavement condition* *Poor lane discipline limits accuracy* *Must be reinstalled if channelization changes* *Snow can badly degrade lane discipline and consequently classification count accuracy*	*Axle sensor-based systems allow use of FHWA 13-category system and similar state classification systems* *When traffic flow conditions are unstable, as often occurs in urban areas, simpler, more aggregated, length-based classification schemes often work more accurately than the more complex, axle-based classification systems*
Inductive Loop (conventional) (total length-based classification)	Widely supported technology Inexpensive	Length classification not as detailed as axle-based classifications Loses accuracy in areas with closely spaced vehicles
Inductive Loop (undercarriage profile)	New technology	Relatively new technology with little performance history Higher traffic volumes deteriorate accuracy Requires well-tuned loops
Piezo Cable (ceramic, polymer [film], or quartz)	Widely used and supported Best practices information available Ease of deployment Can work well in areas of high volume, if speeds are stable	Requires regular maintenance Difficult to maintain in areas of high traffic volumes
Fiber-Optic	Promising new technology Immune to lightning Inexpensive if amortized for moderate period of time	Little data available for accuracy and reliability
Other Pressure Sensors	Sensors are generally immune to lighting Technology is generally well understood Used frequently in toll applications along with loops, which allows accuracy in low-speed, unstable (stop-and-go) conditions	Not widely deployed Requires new interfaces from several manufacturers
Magnetometer	Ease of deployment	Limited classification bins based on length Little reliability data available Data retrieval from some models can require wireless communications

FHWA Classes 2 (cars), 3 (light-duty trucks), and 5 (six-tire, two-axle, single-unit trucks). Many of these vehicles have axle spacings that overlap the boundaries that are commonly used to distinguish vehicles in these classes. Various types of recreational vehicles are also difficult to distinguish based on their axle configurations. In some cases, these errors are irrelevant in terms of traffic load estimation (e.g., misclassification of cars as light duty trucks).

A related problem is differentiating between two closely following vehicles (often two cars) and a truck pulling a trailer. Traffic signals tend to create platoons of closely spaced vehicles. These vehicle platoons are often miscounted as multi-unit trucks. These types of errors have more significant impacts on traffic load estimates.

Presence detectors have some of these same problems. In particular, presence detectors rely on constant vehicle speeds

TABLE 3.1   (Continued)

Type of Sensor	Strengths	Concerns
Permanent Vehicle Classification Sensors (Continued)		
Non-Intrusive Sensors (General Comments)	*Easily adjusts to new channelization* *Accuracy normally not affected by deteriorating pavement conditions*	*Normally cannot provide FHWA 13-category classification information* *Requires mounting structure (bridge, sign bridge, pole)* *Accuracy tends to be significantly affected by mounting height and angle of view* *Stability of mounting platform affects accuracy*
Video	Allows multiple lanes of data collection from a single camera Easy to deploy Widely accepted technology Well supported	Affected by visibility problems (snow, fog, heavy mist/rain) Camera lenses must be protected from the elements Less accurate in multi-lane environment Generally, only performs length-based classification accurately
Microwave Radar	Accuracy not affected by weather or poor pavement conditions Allows multiple lanes of data collection from a single device Easy to deploy Widely accepted technology Well supported	Under good conditions is generally less accurate in multi-lane environment than traditional sensors Only performs length-based classification
Infrared	New technology – appears promising Multiple lanes can be measured by one device	Affected by visibility problems (snow, fog, heavy mist/rain) Requires regular maintenance Not as accurate in multi-lane environment Little reliability data available
Ultrasonic	New technology - appears promising	Little reliability data available Requires multiple sensor installation Accuracy deteriorates as traffic volumes increase Some environmental conditions (air turbulence) can decrease system accuracy
Acoustic	New technology	Little reliability data available Accuracy deteriorates with increasing variability in traffic speeds

in order to accurately measure vehicle length (and correctly classify vehicles). Acceleration and deceleration interfere with this measurement. Presence detectors also have difficulty separating closely spaced vehicles and differentiating between tailgating vehicles and vehicles pulling trailers. However, by limiting the number of length classes used, overall accuracy from presence detectors tends to be higher than with axle detectors in areas with only modest changes in vehicle speed.

The other major limitation of most presence detectors is that they are not capable of detecting axles,[6] so they cannot be used to classify vehicles into the axle-configuration cate-

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[6] One new loop-based technology, "Undercarriage Profile Loops," currently under development for use at permanent sites, is designed to detect axles. This technology is discussed in the next subsection.

TABLE 3.2   Sensors commonly used for WIM

Type of Sensor	Strengths	Concerns
Permanent WIM Sensors		
General Comments	*Permanent sensors are placed flush with the road surface, increasing the accuracy of the sensor outputs*	*The accuracy of all WIM sensors decreases with decreasing pavement conditions* *Unstable speeds, which are common in urban areas, result in significant decreases in WIM accuracy, regardless of the technology chosen*
Piezoceramic Cable	Easier, faster installation than most other WIM systems Generally lower cost than most other WIM systems Well supported by industry	Sensitive to temperature changes Accuracy affected by structural response of roadway Susceptible to lightning Meticulous installation required Low cost and ease of installation often result in placement in slightly rutted pavements, resulting in loss of accuracy
Piezopolymer	Easier, faster installation than most other WIM systems Generally lower cost than most other WIM systems Well supported by industry	Sensitive to temperature changes Accuracy affected by structural response of roadway Susceptible to lightning Meticulous installation required Low cost and ease of installation often result in placement in slightly rutted pavements, resulting in loss of accuracy
Piezoquartz	Easier, faster installation than many other WIM systems May be more cost-effective (long term) if sensors prove to be long lived Very accurate sensor Sensor is not temperature sensitive Growing support by industry	More expensive than other piezo technologies Requires multiple sensors per lane Above average maintenance requirement Sensor longevity data not available Accuracy affected by structural response of roadway
Bending Plate	Frame separates sensor from pavement structure Entire tire fits onto sensor Moderate sensor cost Sensor is not temperature sensitive Extensive industry experience with the technology	Longer installation time required than piezo systems Some systems have experienced premature failure, while others have been very long lived

gories used by most WIM systems. Instead, length-based classes are used, producing somewhat less accurate estimates of axle loads experienced by pavements.

Additional details about these technologies follow.

Road tubes. Road tubes are by far the most frequently used portable classification sensors. Like most pressure sensors, the most common configuration is two road tubes placed in parallel, a measured distance apart, perpendicular to and within a single lane of traffic. The time differential between these two known sensor positions allows the computation of vehicle speed and, consequently, the spacing between axles.

Road tubes are air switches. As an axle crosses each tube, the tube collapses and pushes air through a switch at the counter. The air switch generates an electrical signal that is used to record the time each axle crosses the sensor.

TABLE 3.2 (Continued)

Type of Sensor	Strengths	Concerns
Permanent WIM Sensors (Continued)		
Load Cell	Entire tire fits onto sensor	Most expensive WIM system
	Frequently considered the "most accurate" of conventional WIM technologies	Requires significant construction effort to install
	Some systems have demonstrated very long life spans	Becomes cost effective if constructed and maintained for a long life span
Fiber-Optic	Promising technology	New technology, no longevity history
	Not susceptible to lightning	Not well supported yet by industry
		Accuracy affected by structural response of roadway
Subsurface Frame Strain-Gauge System	System designed to eliminate impact loads on sensor, increasing expected design life	Very new technology, currently undergoing testing in the United States
	Buried design increases "time on sensor" for an axle	No data on longevity of system, or accuracy of output using current software design
		Unclear if variation in structural response of pavement will affect system accuracy
		Expensive, long-duration installation
Multiple Sensor Systems (piezo, bending plate)	Increasing the number of sensors used increases accuracy, everything else held constant	Increase in the number of sensors increases the chance that at least one sensor will fail
	System performance only somewhat degraded if one sensor fails, thus increasing system reliability	Higher number of sensors increases installation time and maintenance costs
Bridge WIM (includes CULWAY)	Bridge platform limits the effect of vehicle dynamics	Only proven to work consistently on a limited set of bridge designs (mostly short-span girder bridges)
	Recent European advances offer significant improvements over previous U.S. versions	Needs truck isolated on bridge to weigh accurately
		Not actively marketed in the United States
Capacitance Mats	Modest sensor cost	Most common configuration only measures one wheel path
	Frame separates sensor from pavement structure	

Tubes used for classification purposes must be placed parallel to each other and perpendicular to the direction of travel. (If the tube is not placed perpendicular to the direction of travel, a single axle may generate more than one air pulse, resulting in an inaccurate count of axles.) Both tubes must be the same length, or the timing of the air pulse at the air switches will not be equal, and the time differential between the first and second sensors will be inaccurate, resulting in inaccurate estimation of speed and, consequently, axle spacing.

Traditional road tubes were limited to outside travel lanes for classification purposes. This is because placing a single tube across more than one lane of travel generates signals from each lane. Several tube makers have solved this problem by making road tubes that have only a limited section of tubing that produces air pulses. These tubes are lane sensitive and can be used in multi-lane applications. Also, it is possible to use a multi-tube configuration with certain detector products to obtain classification and lane volumes across

TABLE 3.2   (Continued)

Type of Sensor	Strengths	Concerns
Portable WIM Sensors		
General Comments		*Sensors placed on top of the pavement create a "bump" that decreases the accuracy of static weight estimates*
		Placement of portable sensors without performing new, "in place" calibration effort is likely to lead to unreliable weight estimates
Bridge WIM (includes CULWAY)	In most "portable" configurations, only axle counting sensors must be placed on the roadway, leading to easy, short-duration equipment set up	Only proven to work consistently on a limited subset of bridge designs (mostly short-span girder bridges)
	Recent European advances offer significant improvements over previous U.S. versions	Generally needs truck isolated on bridge to weigh accurately
		Not actively marketed in the United States
Piezo (ceramic cable, BL-polymer film)	Ease of deployment	Susceptible to variations in temperature
	Inexpensive sensor cost	More accurate if used in permanent installation
Capacitance Mats	Ease of deployment	Only measures one wheel path
	Modest sensor cost	Creates the largest "bump" of the portable technologies

multiple lanes in the same direction. However, multi-lane installations are prone to error because it is difficult to anchor them tightly enough to keep them from bowing in the middle, violating the requirement that they remain perpendicular to traffic.

The primary advantages of road tubes are that they are very inexpensive to purchase and are easy to install. They also are frequently used for traditional volume counting.

Piezoelectric sensors (BL and ceramic). Piezoelectric sensors come in a variety of shapes and materials. For classification purposes, each of the most common sensor styles has fairly similar properties. When a mechanical force is applied to a piezoelectric device, it generates a voltage by causing electrical charges of opposite polarity to appear at the parallel faces of the piezoelectric material. An electronic component of the counter detects this signal and uses it to indicate the passage of an axle. The measured voltage from the sensor is proportional to the force or weight of the wheel or axle as it is applied to the sensor. This allows the piezo sensor to be used as a scale. Sophisticated vehicle classifiers use this measure of axle weight to improve the accuracy of the vehicle classification algorithm; however, many classifiers use the strength of the sensor output signal only to separate signal noise from the passage of an axle.

The piezoelectric effect is dynamic; i.e., charge is generated only when the forces applied to the sensor are changing. Thus, piezoelectric sensor systems can only be used in applications where vehicles are moving at speeds above 10 mph. Piezoelectric sensor systems cannot be used at locations with either slow-moving or stop-and-go traffic.

Some piezoelectric materials (and sensors) are sensitive to temperature and do not perform well in very cold temperatures.

As with road tubes, the most common portable piezo sensor installations consist of two sensors, parallel to each other and perpendicular to the roadway, a measured distance apart.

Unlike conventional road tubes, piezoelectric sensors are lane specific. Thus, they can be used to monitor inner lanes; however, for portable operations, lead wires to the sensors must be placed across the outer lane(s). This increases the potential for damage to sensor connections to lead wires, one of the more common causes of sensor failure.

Fiber-optic cable. Use of fiber-optic sensor technology for axle detection is fairly new and relatively uncommon in comparison with other intrusive technologies. Fiber-optic sensors detect the presence of a load by measuring the decrease in optical transmission caused by constriction of the fibers when tires pass over the sensors. Fiber-optic sensor systems contain a light transmitter (usually a light-emitting diode), a photon

detector, and signal analysis hardware and software in addition to the fiber sensor itself.

Fiber-optic sensors are used in the same way as piezoelectric sensors. The sensor itself is normally the width of a lane. Like road tubes, sensor manufacturers have also designed specific sensors that allow for collection of data on all lanes of a multi-lane facility.

Fiber-optic sensors are more responsive than road tubes, theoretically making them more accurate under both very slow speed conditions and very high volume conditions. The advantage of fiber-optic sensors over piezo sensors is that the former are not temperature sensitive and the sensors themselves do not conduct electricity, thus making devices using these sensors less susceptible to lightning strikes.

Other pressure sensors. A variety of other pressure sensors have been used at one time or another as portable axle sensors. All share the basic functionality of producing an electrical signal when the pressure from a passing axle closes a circuit. The most common of these is probably the tape switch. Most portable pressure sensors, like the tape switch, are laid on top of the travel lane and held in place by asphalt tape.

Preformed inductance loops. Inductance loops are used in traffic signal operations, making them the most common permanent vehicle sensors. When two loops are placed in series, they allow passing vehicles to be classified on the basis of their overall length. This is done by determining the difference in time between activation of the first and second loops. This time difference, and the distance between loops, allows for the computation of vehicle speed. Using vehicle speed and the total time one of the loops stays active allows overall vehicle length to be derived.

It is possible to use preformed inductance loops (most commonly, wire loops attached to a thin solid frame) as portable sensors. Preformed loops are taped to the road surface a predetermined distance apart in order to create the required sensor configuration. Lead wires can also be taped to the road surface, allowing preformed loops to be placed on multi-lane facilities.

Loops have the advantage of being placed in the center of the lane and so are not subject to the same level of impact loading as pressure-sensitive portable sensors. Thus, they are less likely to be knocked loose by passing traffic, and they can frequently be used for longer counting periods than pressure-sensitive detectors.

Dual-loop installations, however, are limited in the accuracy of the data they can provide. Because inductance loops actually measure the presence of metal, and signal strength is a function of the amount and proximity of the metal, not all vehicles are detected at the same distance from the loop. Vehicles that contain large amounts of metal tend to be detected for a longer time period than vehicles with little metal. This means that inductance loops tend to overestimate the length of vehicles with a lot of metal and underestimate the length of vehicles with less metal.

Limitations in the accuracy of the overall length measurement restrict how many vehicle categories are normally collected. In addition, considerable error exists in the correlation between overall vehicle length and the FHWA's 13-category classification system (or the state-specific variations of that system) used by most WIM scales. As a result, most dual-loop systems normally classify traffic into only three or four broad length categories. This reduces the number of classification errors, while still providing an excellent measure of the number of large trucks versus the number of smaller trucks and passenger cars. However, it does not provide other potentially useful information, such as distinctions between the number of heavy single-unit trucks with three or more axles and the number of usually less-damaging two-axle trucks.

Magnetometers. Magnetometers measure changes in the magnetic field surrounding sensors to determine the presence of passing vehicles. Like dual-inductance loop technology, magnetometers use estimates of vehicle speed and the duration of the signal to determine the length of vehicles. Vehicle length is then used to classify vehicles into defined length categories.

Portable magnetometers are commonly used throughout the United States for volume counting and, to a lesser extent, vehicle classification. They are placed on top of the pavement in the center of each traffic lane, much like portable inductance loops. However, they are much smaller, making them easier and faster to place. In other respects, their characteristics are similar to those of inductance loops.

Side-fired radar and other non-intrusive sensors. Because intrusive sensors cannot be placed in many locations due to high traffic volumes, a variety of non-intrusive sensors have been developed. These sensor technologies are described in Section 3.1.2. The vast majority of these technologies are currently designed strictly for permanent operation. A number of vendors are currently working on developing portable versions of their existing non-intrusive detectors.

In addition, a number of enterprising efforts have already been undertaken to create portable devices using these sensor technologies. For example, Ohio Department of Transportation (DOT) has developed the ability to use a side-fired microwave radar system as a portable traffic counter. In this case, the radar sensor is mounted on an extendable pole that is mounted on a trailer. The trailer can be parked in a safe location beside a roadway. The pole is then raised, and the radar system aimed and operated. Power for the system is supplied by batteries.

Permanent Operations

Except for road tubes, the portable sensor technologies described above can also be permanently installed in the pavement and used for continuous data collection. For this purpose, the sensors are placed in a pavement cut, which is

then sealed with an epoxy or tar and used for data collection over extended periods of time. Road tubes, by design, must be placed on top of the pavement, where they do not have a long enough fatigue life to be used as permanent sensors.

Sensors placed in the pavement for long-duration counting have particular attributes. The primary advantage of in-pavement sensors is that the impact loads associated with surface-mounted sensors are no longer present. This greatly increases sensor life.

However, placing sensors in the roadway has some disadvantages. A road closure is needed to initially place the sensor, as well as every time the sensor needs to be examined or maintained. Road closures are both expensive and publicly unpopular, particularly on high-volume roads.

Once placed, in-pavement sensors normally cannot be moved. Thus, if channelization changes (i.e., the lane lines are moved), the sensors are no longer correctly located in the lanes and new sensors must be installed. This makes intrusive sensors a poor choice for those locations where lane lines will be moved in the near future.

Permanent sensors can fail because of fatigue or because of environmental effects such as moisture getting into the sensor or a nearby lighting strike that shorts out the sensor or its electronics. Also, failure of the surrounding pavement can destroy a sensor or render its output unusable.

Successful practices designed to limit failures and extend sensor life are discussed in Chapter 5. In summary, initial site selection and installation are the key to achieving long sensor life. Placing an intrusive sensor in pavement that is in poor condition is likely to result in poor sensor performance and short sensor life, regardless of the technology chosen. Similarly, haphazard sensor installation (e.g., poorly cleaned or dried pavement cuts) can also lead to early sensor failure.

Placement of sensors in pavement that is badly deteriorated also leads to inaccurate results. Vehicle axles that are bouncing badly "jump" over pressure sensors. Concrete slabs that rock because of joint failure cause pressure sensors to pick up spurious signals and report "ghost axles." In these cases, the sensors are actually working correctly; they are just functioning in an operating environment that prevents them from counting axles accurately.

Descriptions of intrusive sensor technologies that can be permanently installed follow.

Piezoelectric sensors. The various types of permanent piezoelectric sensors have similar layouts and slightly different operating characteristics but different installation requirements and performance history. The minimum layout is two parallel sensors. An inductance loop can be added to this basic installation (usually placed mid-way between the two parallel sensors), which is used to help separate vehicles. (That is, the loop presence is used to tell the data collection equipment when one vehicle ends and the next begins.) An alternative to this sensor layout is to place two inductance loops (to measure vehicle speed and presence) with a single piezo sensor in between (to count axles and determine the spacing between those axles). Also, a four-sensor layout can be used (two loops and two piezo sensors) in order to allow for loss of one sensor (either a loop or piezo) without loss of classification capability.

The differences in piezo sensor operating characteristics are more important for weighing accuracy than they are for classification capabilities. In general, BL sensors require the smallest pavement cut. Quartz sensors are the least affected by temperature change and forces (stresses) that move horizontally through the pavement. Quartz sensors are also the most expensive and are primarily used as WIM sensors, rather than simply for classification.

Piezo sensors can often be paved over and still function correctly. That is, most piezo sensors are sensitive enough that they can be covered by an asphalt overlay and still be used to detect passing axles (so long as the sensor and its lead wire and connections are not damaged in the process of laying the new pavement).

Other pressure sensors. There are a variety of other pressure sensors available for use as permanent classification sensors. Fiber-optic cable and older pressure switch technologies belong to this category.

Like the piezo sensors, other pressure sensors are typically placed into small saw cuts in existing pavement and held in place by some type of epoxy or other bonding agent. However, unlike piezo sensors, most of these pressure sensors are not sensitive enough to function correctly underneath an asphalt overlay layer.

Other pressure sensors generally are less expensive to purchase than piezo sensors, though installation time and effort tends to be very similar.

Dual-inductance loops. Dual-inductance loops were the first mechanism used to collect long-duration classification data. While the number of these systems in rural areas has been declining in favor of axle sensor-based systems (in order to collect data using the FHWA's 13-category classification scheme), they are still commonly used in urban areas.

Because urban environments often involve congested traffic conditions, many agencies are unwilling to spend the money needed to place the more expensive sensors required to perform axle-based classification. At the same time, in many urban areas, volume, speed, and lane occupancy data are needed to operate modern traffic control systems. By placing dual loops in the roadway, these data can be obtained. Loop systems also offer the potential for collecting length-based classification data.

Loops have an advantage over pressure-sensitive technologies in that they do not involve contact with vehicle axles and so are not subject to the impact loading that leads to sensor failure. Sensor failure for loops is more commonly tied to freeze-thaw conditions that result in pavement movements

sufficient to "cut" the wire placed in the pavement. They also fail as a result of failing roadside amplifiers.

Given the weaknesses inherent in the collection of length-based vehicle classes, the primary drawback to loop systems (other than their susceptibility to freeze-thaw failure) is the fact that classification accuracy degrades significantly under congested conditions. Thus, significant quality assurance efforts are needed before data collected at congested, urban sites are accepted as accurate measurements of truck volumes.

Undercarriage profile loops. A new technology has recently been released by several manufacturers that uses the shape of the inductance signature of passing vehicles to classify the vehicle. While the specific technical approaches used by the different manufacturers appear to be somewhat different, the overriding concepts appear to be similar. In one approach, additional loops are used to help detect axles (by detecting the change in inductance caused by presence of the metal in the axles), while in another approach, the shape of the primary inductance pattern itself is matched against the known shape of specific vehicle types.

This approach shows more promise to allow sophisticated classification capabilities than previously available using loop technology. At this time, however, these systems are relatively new, and little practical experience is available to determine their accuracy and reliability.

Magnetometers. As with undercarriage profile loop classifiers, several different versions of permanent magnetometers are being marketed currently. Some are placed directly in the pavement, and others are inserted into conduits placed underneath the pavement. Both styles of magnetometers measure vehicle presence by monitoring changes in the earth's magnetic field. The sensors are capable of estimating vehicle speed and use that measure along with the duration of vehicle detection to estimate vehicle length. This length estimate is used to classify vehicles.

Note that the conduit style of magnetometer is frequently considered to be "non-intrusive" because the conduit can be placed (by drilling under the pavement from the roadway shoulder) without closing the lane of travel. The sensor can be placed in the conduit without disrupting traffic, and the sensor can be repositioned within the conduit if lane geometry is changed.

3.1.2 Non-Intrusive Technologies for Classification

While the majority of vehicle classification counting is performed with intrusive or surface-mounted sensors, an increasing percentage of classification counting is being performed with non-intrusive sensors. Non-intrusive technologies include sensors that can be mounted overhead or to the side of the roadway.

Non-intrusive technologies have been available for vehicle detection and volume counting for a number of years,[7] and improvements in computer processing power have allowed these technologies to be extended to the more complex task of vehicle classification. In addition, with both the reduction in computer costs and the increased production of non-intrusive sensors resulting in economies of scale for their manufacture, the cost of many of these technologies has declined considerably in the last 10 years.

Non-intrusive technologies have a number of distinct advantages over technologies that must be placed in or on the roadway surface, including the following:

- Increased staff safety (as staff do not need to be in the roadway in order to place the sensors),
- Less traffic disruption during sensor installation (as sensors can be placed with little or no traffic disruption, even on high-volume roadways),
- The ability to reorient the sensor to adjust for changing lane configurations or other geometric changes without having to physically replace sensors,
- The capability of some non-intrusive sensors of collecting data on more than one lane at a time from a single sensor (e.g., camera),
- Ease of maintenance and repair of above-ground sensors in comparison with sensors that are placed in ground, and
- Not being subjected to many types of environmental damage that commonly reduce the sensor life of intrusive sensors (e.g., freeze-thaw damage, tire impacts on exposed sensors, and pavement failure around sensors).

Non-intrusive sensors also have weaknesses. The biggest drawback is the difficulty for non-intrusive sensors to count vehicle axles accurately, which is a key aspect of traffic load estimation for pavement design. Some non-intrusive sensors do count vehicle axles, but these systems are limited in their application and have either installation problems similar to intrusive sensors (i.e., they can only measure one lane of traffic without being placed at roadway level on the lane lines) or suffer from occlusion that occurs when a system cannot "see" one vehicle or axle because the sensor's "view" of that vehicle is blocked by an intervening vehicle.

As a result of their inability to easily count axles, most non-intrusive sensors classify vehicles by overall vehicle length, similar to dual-inductance loop technology. While this does not correlate directly with the vehicle classes commonly collected by WIM systems, it does provide useful data for pavement design purposes. Use of vehicle classifications based on overall vehicle length does require an additional data manipulation step for correlating these classes to those used by an agency's WIM equipment. The staff time and the

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[7] *Field Test of Monitoring of Urban Vehicle Operations Using Non-Intrusive Technologies,* FHWA, May 1997.

potential for error associated with this extra data processing step must be traded off against the benefits obtained from use of non-intrusive technologies.

Currently, most non-intrusive classification counting is done with permanently mounted sensors. Some vendors and several highway agencies have been exploring the development of portable versions of non-intrusive devices. These devices usually consist of one of two designs. In one design, sensor arrays are mounted to poles, which are in turn mounted onto trailers fitted with a power source.[8] The trailer is then towed to the desired roadside location, and the pole is lifted into position. This allows side-fired detection systems to operate. The second style of system is designed to be temporarily mounted on existing highway infrastructure, usually light standards or highway signs.[9] These portable systems are not actively marketed in the United States.

As with intrusive sensors, the accuracy of non-intrusive classification systems is a function of the quality of the classifier's sensing system, the proper installation of the sensor, the placement of the sensor in an environment that is conducive to the proper operation of that specific technology, and the vendor's algorithm used to process the raw sensor data.

The placement of the sensor in a location where it will work correctly is the most important variable that is within the control of the data collection agency. The starting point for this process is the ability to place the sensors where they can properly sense the vehicles they are intended to classify. When sensors are mounted on the side of the road, it usually means that they must be placed high enough to sense over vehicles in nearby lanes in order to count and classify vehicles in lanes that are farther away. Sensor height and angle of view are also important for overhead-mounted sensors that collect data on more than one lane of travel. The specific sensor mounting locations required by each device will vary with the device and are not discussed in this report. Specific guidance on these details should be obtained from the vendor of each device. (However, it will be noted that overhead-mounted sensors tend to perform somewhat more accurately than the same sensor mounted at the roadside, all other things being equal. This is most likely a result of the overhead position generally having a better "field of view" than the roadside position.)

The specific technologies presented in this section include

- Video,
- Radar,
- Doppler microwave radar,
- Passive infrared,
- Active infrared,
- Passive acoustic, and
- Ultrasonic.

The accuracy of specific implementations of these technologies was recently studied by a project jointly sponsored by the U.S. DOT and the Minnesota DOT.[10] The first round of field tests was completed in 2001, and the second round was completed in September 2002. While the study focused on the collection of volume data using non-intrusive devices, the results of these tests can be of considerable use to agencies interested in using non-intrusive data collection equipment. A pooled fund study specifically looking at portable use of non-intrusive devices has been proposed and is actively being pursued. Information on the completed and ongoing non-intrusive detector tests can be obtained from http://www.dot.state.mn.us/guidestar/projects/nitd.html.

Video

Video detection is the most widely used of the non-intrusive detection technologies. Video devices convert camera images into digital representations (pixel images) and then use microprocessors to analyze those representations. There are two primary video image analysis techniques, trip line and image tracking, with the trip line approach being the oldest and most commonly used.

In the trip line technique, a specific portion of the video image is defined as a "zone." Pixels within this zone are monitored for change, and changes in pixels are used to determine when vehicles are entering or leaving the zone. (Zones in video images can be considered "virtual inductance loops.") Activations of virtual zones can be used to determine volume and lane occupancy. Two or more consecutive zones (set at a known distance apart) can be used, just as dual-inductance loops are used, to measure vehicle speed and consequently overall vehicle length. This allows for vehicle classification based on total vehicle length.

Image tracking relies on pattern recognition algorithms to detect, recognize, and track specific kinds of vehicles. These systems allow for more detailed data collection. (For example, they examine pixel images to detect axles, not just the presence of a vehicle, in order to provide axle-based classifications.) However, the complexity of the algorithms and shortcomings of video image quality place additional constraints on their operation.

Video detectors of both types are sold by a number of different vendors, and these systems can have very different capabilities. These differences are caused primarily by the use of a variety of different data processing algorithms, each of which has different strengths and weaknesses. While considerable experience has been gained as a result of the current use of these devices, the differences in specific vendor implementations make it difficult to identify the differences of those experiences.

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[8] This style of system has been used or tested in Ohio and New York among other states.
[9] This style of system has been used or tested in Virginia and Minnesota among other states.

[10] The Minnesota Guidestar Non-Intrusive Traffic Detection Tests http://www.dot.state.mn.us/guidestar/projects/nitd.html.

Factors that have been shown to affect video system performance adversely include

- Shadows (both stationary and moving shadows cast by vehicles);
- Direct sunlight;
- Reflections caused by wet pavement and headlights;
- Transition from light to dark or dark to light;
- Wind-induced pole movement;
- Environmental degradation of the video image caused by (1) water on the camera lens, (2) icicles hanging in front of the camera lens, (3) salt grime on the camera lens, or (4) cobwebs on the camera lens; and
- Limited visibility caused by such phenomena as heavy snow, heavy mist, or dust storms.

Each of these factors creates artificial changes in pixels within the camera image (i.e., a change not caused by a vehicle passing through the image). Some of these causes are transient environmental conditions, while others are more permanent and require corrective maintenance action. (Note: camera-based systems may require more frequent maintenance activity than conventional loop-based systems.) The accuracy of counts obtained from these systems is largely dependent upon how effectively each system can deal with these situations.

It is also apparent that the design and construction of sensor installations must take into account performance limitations. Camera lenses need to be protected as much as possible from the elements. Similarly, placement of the cameras to minimize the effects of changing lighting conditions is also important for maximizing the performance of video-based systems.

The two primary strengths of video image detection are (1) the ability to easily move "virtual sensors" to adapt to changing lane configurations or to the need for new sensor locations and (2) the ability of field staff to use a video monitor to observe what the sensor is actually observing and to consequently (and easily) make adjustments to the operation of the sensor.

Video detection has also the advantage of ability to collect, from a single video image, data on more than one lane of traffic at a time. The keys to collecting multiple lanes of data from a single camera are (1) the ability to obtain a clear video image of the lanes with sufficient pixel resolution to accurately monitor vehicle presence and (2) sufficient computing power to monitor all "virtual detectors" in the image.

Radar

Conventional radar-based detection uses pulsed, frequency-modulated, or phase-modulated signals to detect vehicles. This technology is currently the only other non-intrusive technology that is designed to collect data from more than

one lane at a time with a single sensor. Radar technology has been in use in the United States for a number of years.

Radar sensors can be either side-fired (mounted beside the roadway) or overhead mounted. A single, side-fired radar unit can collect data on more than one lane, but a unit is required for each lane if overhead mounting is selected. (Overhead mounting is more accurate, according to the manufacturer.)

Because radar technology is relatively immune to weather conditions (snow, fog, etc.), it is used in a number of locations where poor visibility conditions make video impractical. Radar is easy to place, because side-fired systems can be pole mounted at a height of only 5 meters (15 feet), which is considerably lower than for video systems that must often be mounted as high as 10.7 meters (35 feet).

Finally, conventional radar has the ability to detect slow-moving and non-moving vehicles. This means that system count accuracy does not degrade significantly in stop-and-go traffic conditions.

In some system tests, radar has slightly undercounted vehicles relative to counts made using conventional loop detectors.[11]

Doppler Microwave Radar

Doppler microwave radar is a variation on conventional radar systems. Doppler technology employs a continuous wave signal and measures the wave's Doppler shift as it is reflected by passing vehicles. These detectors provide vehicle counts and speeds, but are not capable of detecting stopped vehicles and may be less applicable for the classification of vehicles other than non-intrusive detectors.

Passive Infrared

Passive infrared devices detect the presence of vehicles by comparing the infrared energy naturally emanating from the road surface with the change in energy caused by the presence of the vehicle. Because the roadway may generate either more or less radiation than a vehicle depending on the season, the contrast in heat energy is detected.

As with radar detectors, passive infrared detectors can be mounted either on the side or overhead for data collection. These sensors provide the same detector output as conventional loops: vehicle volumes and presence. Monitoring these from two consecutive sensor locations allows the computation of vehicle speed and consequently overall vehicle length.

Sensor output from passive infrared appear to be unaffected by changes in weather conditions. While several vendors sell these devices on the U.S. market, there are a relatively small number of current installations.

[11] Lawrence Klein, Michael Kelley, and Milton Mills, "Traffic Detection Technologies for a Modern Transportation Infrastructure," SPIE Conference 2592, *Collision Avoidance and Automated Traffic Management Sensors,* October 25–26, 1995, Philadelphia, Pennsylvania.

Active Infrared

Active infrared sensors differ from passive sensors in that a low-power laser beam is directed from the data collection device to the road surface. Measurement of the time lapsed until the reflected signal returns to the device is used to determine the presence of a vehicle. By splitting the laser beam into two separate signals from a single sensor, it is possible to compute vehicle speed and overall length. This allows length-based classification from a single active infrared sensor.

Active infrared systems are also capable of measuring vehicle height and can thus create two- and three-dimensional images of passing vehicles. This allows even more comprehensive vehicle classification capability.

Infrared sensors do have signal degradation during weather conditions that reduce visibility. A good rule of thumb recommended by the Vehicle Detector Clearinghouse[12] is that if visibility drops to the point where the human eye does not see an object clearly, then infrared sensors are also likely to experience difficulties.

Passive Acoustic

Passive acoustic devices consist of an array of microphones aimed at the traffic stream. The devices are passive in that they are listening for the sound energy of passing vehicles. The primary source of sound is the noise generated by the contact between tires and road surface. At slower vehicle speeds, the sound of the vehicle's engine is more prominent. Passive acoustic devices are best used in a side-fired position, pointed at the tire track in a lane of traffic.

Acoustic detectors physically measure the changes in sound energy radiating from the roadway. Increases in energy indicate the arrival of a vehicle, and decreases in energy indicate its departure. From these data, it is possible to determine lane occupancy. By using multiple detection zones, it is possible to estimate vehicle speed and length, thus allowing vehicle classification by length.

Some models of acoustic sensors have been shown to be sensitive to undercounting in cold temperatures. In addition, some acoustic sensors have a loss of accuracy when vehicles are stopped or moving very slowly. These sensors are not commonly used for classification purposes in the United States at this time.

Ultrasonic

Pulse ultrasonic devices emit pulses of ultrasonic sound energy and measure the time lapsed until the signal returns to the device. When the sound energy returns more quickly

than the normal road surface energy returns, a vehicle is present. Signal analysis allows determination of vehicle presence and occupancy. Using two closely spaced beams aimed a known distance apart allows for computation of vehicle speed and consequently vehicle length. Pulse ultrasonic devices are capable of high count accuracy when optimally mounted. An overhead mounting location provides a perpendicular reflective surface, offering the best signal return.

Tests indicate that great changes in temperature and extreme air turbulence may inhibit accuracy of ultrasonic devices. Such devices are not commonly used in the United States at this time.

3.2 WIM

This section discusses sensor technologies that provide the ability to weigh vehicles. The systems must be capable of supplying axle weights and classifying vehicles into at least the 13 FHWA vehicle classification categories.

All WIM sensors currently used in the United States measure transient forces applied by tires to sensors as vehicles pass over. They use the measured force to predict the weight applied by the tire (axle) when the vehicle is at rest. The sensors used to perform this measurement include very thin, narrow sensors placed directly in the pavement (fiber-optics, piezo cables); large plates resting in frames that are in turn imbedded in the pavement (bending plates, hydraulic load cells); instrumented roadway structures (bridge and culvert WIM); and flat sensors placed on top of the road surface (capacitance pads). Selecting a specific technology requires considering the following factors:

- Cost of the sensors and their installation,
- Locations where a given technology can be successfully installed,
- Sensitivity of sensors to various factors (temperature, vehicle dynamics, traffic volume, and speed),
- Expected life span of sensors, and
- Robustness of sensor installation (e.g., the ability to continue to collect data if one or more sensors fail or to compare output of one sensor against another).

The WIM task is heavily complicated by the dynamic motion of trucks being weighed. As trucks move, they bounce. The degree to which each truck bounces is a function of pavement roughness, vehicle load, environmental conditions such as wind, and each vehicle's design and suspension systems. The greater the amount of vertical motion exhibited by trucks, the more difficult the task for WIM systems to accurately estimate static axle loads.

Thus, for all WIM technologies, a key issue for collecting accurate weight data is to select locations for data collection that minimize the dynamic motion of trucks being weighed. The lower the vertical dynamic motion of passing trucks, the

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[12] Mimbela and Klein, *A Summary of Vehicle Detection and Surveillance Technologies Used in Intelligent Transportation Systems*, prepared by the Vehicle Detector Clearinghouse, for FHWA, Fall 2000.

more accurate the WIM scale, regardless of the technology selected.

The other step required to account for truck dynamics is to calibrate the WIM scale to the unique traffic characteristics of each data collection site. While it is possible to calibrate each sensor in the laboratory, it is not possible to account for the dynamic motion of trucks at a specific roadway site without measuring those forces in the field at the location where the sensor is being placed. Only direct comparison of WIM system output against known axle weights for specific vehicles allows the calibration needed to enable a WIM system to accurately predict static axle weights. While many vendors supply autocalibration features with their WIM systems, autocalibration depends on one or more key assumptions that also must be calibrated to each specific site.

3.2.1 Portable WIM Operations

There are only two technologies commonly used for portable WIM data collection in the United States: capacitance mats and piezoelectric (BL-style) sensors, although a number of states used bridge WIM systems in a portable fashion in the late 1980s and early 1990s. These three technologies are discussed in this section. Finally, some states perform portable operations by moving electronics from one set of permanently mounted sensors to another. This style of "portable" data collection will be treated as permanent operations simply because the sensors themselves are permanently placed in the roadway.

Capacitance Mats

A capacitance mat consists of two metal sheets separated by dielectric material. An outer surface layer surrounds the sensor, protects the steel plates, and allows the sensor to be placed on the pavement. A voltage is applied across the two metal plates. When a vehicle crosses over the plate system, it causes the distance between the two plates to decrease, which increases the capacitance of the system. Measurements of the resonance frequency of the circuit allow the estimation of axle weight as it is applied to the sensor system.

A typical portable capacitance mat system covers one-half of a lane and measures one side of each passing axle. It is usually secured to the roadway surface using a combination of asphalt nails and tape. Portable loops are usually also placed as part of the system installation in order to provide measures of vehicle presence and vehicle speed.

Capacitance mats are moderately priced (each pad is about $10,000, not counting data collection electronics) and lightweight. Installation requires several people, however, both to help place the sensors and to provide traffic control and calibration assistance. Use of portable capacitance mats allows WIM data collection to take place on the outside lane of almost any level roadway that has a reasonable shoulder.

(Capacitance mats are difficult to use on inside lanes because the lead wires and sensor connections must be exposed to traffic in those positions.)

Portable capacitance mats have significant shortcomings in terms of overall system accuracy. The primary ones are that (1) the system only weighs one side of passing axles and (2) the sensor itself is fairly thick, creating a "bump" in the road that both increases vehicle dynamics and causes an impact load on the sensor that degrades system accuracy. These shortcomings cause accuracy from portable systems to fall below that of flush-mounted, full-lane width, permanent WIM systems.

Accuracy limitations are also inherent in the placement of mats on the roadway. While mats can be initially calibrated at a control location, the effects of vehicle dynamics at each given data collection location can only be determined by site-specific calibration efforts. The cost of these efforts often far exceeds the cost of placing and retrieving the data collection sensors and greatly increases the cost of collecting accurate weight data with these systems. While many states limit the amount of site-specific calibration done with their portable mat systems, the lack of site-specific calibration significantly affects the mat's ability to accurately estimate the static axle weights needed for the pavement design process.

Piezoelectric Sensors (BL and Ceramic Cable)

The primary alternative to capacitance mats currently used by state highway agencies for high-speed portable WIM data collection is thin-strip piezo sensors. There are two basic styles of thin-strip piezo sensors: a flat plate configuration (the BL sensor) and unmounted piezoceramic coaxial cable.

Both systems operate on the same basic principle. When a mechanical force is applied to a piezoelectric device, it generates a voltage by causing electrical charges of opposite polarity to appear at the parallel faces of the piezoelectric crystalline material. The measured voltage is proportional to the force or weight of the wheel or axle. The piezoelectric effect is dynamic (i.e., charge is generated only when the forces are changing); piezoelectric sensor systems can only be used in applications where vehicles are moving at speeds not less than 10 mph. Piezoelectric sensor systems cannot be used in applications having either slow-moving traffic or stop-and-go traffic.

For portable weighing operations, sensors (each sensor is roughly one lane width in length) are taped to the roadway, perpendicular to traffic. Normally, two sensors are placed a measured distance apart. The time difference between axle contact on the two cables is used to determine vehicle speed, which is then used to determine the axle spacings needed for vehicle classification.

These systems are relatively easy to set up, although, like capacitance mats, they are routinely placed only in the outside lane of traffic in order to allow the lead wires to be placed

on the roadway shoulder. The sensors themselves are less expensive than individual capacitance mats.

However, like the capacitance mat systems, piezo cables used in portable operations suffer from significant limitations in accuracy for the following reasons:

- Sensors are temperature sensitive, making it difficult to keep them in calibration when temperature changes during the day.
- The sensors' narrowness allows tires being weighed to "fold" over them, meaning that at no time during the axle weighing process is an entire tire isolated on the sensor. Therefore, changes in tire pressure or tire-tread patterns affect the force measured by this type of sensor more significantly than many other WIM technologies.
- The same site-specific calibration problems that affect all portable WIM systems also affect these systems (calibration of the sensors to site-specific vehicle dynamics is necessary to obtain the level of accuracy needed for direct inclusion of these data into the pavement design process).
- Sensors have a relatively high signal-to-noise ratio.

Bridge WIM

In the 1980s and early 1990s, a number of states instrumented bridges for use as WIM platforms. The technology works by measuring the response to traffic loads as measured by strain gauges attached to girders under the bridge. A number of European countries are still strong supporters of bridge WIM, and Australia extensively uses a similar system based on the deflection of culverts.

Portable operations were achieved by attaching the strain gauges, either with C-clamps or permanently, and then connecting portable roadside electronics to those gauges when data collection was desired.

Bridge WIM has the advantage of having a very large weighing platform: the bridge deck itself. This helps limit the effects of vehicle dynamics. Unfortunately, various other factors degrade the signal from the strain gauges and limit the accuracy of data from bridge WIM. The most significant of these factors are the presence of other traffic on the bridge at the same time a truck is being weighed (which significantly increases the noise in the weight signal) and the fact that states could not adequately define the expected response of many bridges to given loading conditions (which limits the accuracy of the computation of loads based on bridge response).

Currently, without extensive site-specific set-up, calibration, and testing, bridge WIM is considered reliable only on short-span, simply supported, steel girder bridges where trucks can be isolated on the span during the weighing process. However, the Australians use a similar WIM technology called "CULWAY" that works on a similar principle (measuring the strain of the underside of a structure), but is attached to the underside of large culverts rather than to bridge girders. Use of

this technology may increase the number of structures suitable for use as weight sensors.

Conventional Static (Loadometer) Scales

For low-volume roadways, it is also possible to collect truck weight data with portable static scales used for truck weight law enforcement. Any scale that meets Handbook 44 standards[13] is acceptable for truck weight data collection.

Collecting data with static scales requires either a permanent scale facility or a level, paved surface where trucks can be pulled off the road safely. This requirement significantly limits the locations at which data can be collected.

Significant numbers of workers are needed to perform this task. Weighing vehicles statically is a slow process and results in a dataset of limited size. On high-volume roads, this small dataset can easily represent a biased estimate of actual traffic loads, especially if by-pass routes exist, that might bias the weights of trucks being sampled. However, on low-volume roads with little bypass opportunity, this approach to weight data collection can provide an accurate and complete measure of truck traffic for the periods for which the highway agency can afford to collect data.

A number of low-speed WIM systems can be used to speed up this process, while maintaining good data quality. Information on such systems can be found on the FHWA Demonstration Project 121 web site http://www.ornl.gov/dp121/.

3.2.2 Permanent WIM Operations

The majority of WIM data collection is now done with permanently installed weight sensors, although many states do not collect data continuously at these sites. Instead, they attach data collection electronics to previously mounted sensors when data collection is desired. The scale sensors are then calibrated (or should be calibrated), and data are collected for the desired time period.

Permanently mounting WIM sensors allows them to be installed flush with the roadway surface. When done properly, this eliminates the bump that vehicles experience when crossing surface-mounted sensors. The removal of impact loads on sensors and the elimination of extra vertical motion caused by bumps result in improved system accuracy.

Permanently mounting sensors flush with the pavement surface also decreases the impact loads on sensors themselves, which in turn increases sensor life. One common cause of sensor failure is when sensors become directly exposed to horizontal forces from tire contact. This exposure often leads to early fatigue failure for both sensors and the bonds between

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[13] Tina G. Butcher et al., Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices: As Adopted by the 83rd National Conference on Weights and Measures, 1998, ISBN #0-16-049825-2.

sensors and pavement. Exposed sensors are also highly susceptible to damage from contact with snowplow blades.

As noted in Section 2.2.1, a variety of other factors play important roles in both the output accuracy and the life of permanently mounted sensors. Pavement at permanent sensor locations should be

- Flat (no horizontal or vertical curves),
- Smooth (no bumps or other surface conditions that increase dynamic vehicle motion),
- Strong (to reduce pavement flex underneath the WIM sensor), and
- In good condition.

Flat, smooth pavement reduces vehicle dynamic motion and increases the accuracy of all WIM sensors. Strong pavement results in longer lived pavement, which in turn increases sensor life. Strong pavement is especially important for strip sensors that are embedded directly into the pavement. The output from these sensors depends on the performance of the pavement itself. If pavement strength varies significantly over time (e.g., with environmental conditions), sensor output will also vary, and this greatly decreases the likelihood of accurate sensor calibration. Some researchers have suggested criteria for the pavement strength required for installing WIM equipment based on falling weight deflectometer (FWD) measurements. These criteria stipulate a maximum deflection under the center of the applied load and a minimum deflection basin area.

Good condition pavement reduces vehicle dynamics and makes the bond between sensors and pavement more likely to last. A common cause of sensor failure is the failure of sensor/pavement bonds, which is often traced to poor pavement condition. Poor installation is another common cause of this failure. Poor cleaning or drying of pavement cuts results in a weak bond that allows moisture intrusion and further deterioration of the bond.

Moisture is also a common cause of equipment failure because of intrusion into either the sensor itself or the communication lines connecting the sensor to the data collection electronics.

Each vendor and each state highway agency has its own procedures for fighting moisture intrusion. Similarly, agencies and vendors have equipment and procedures for protecting permanent equipment from lightning strikes, other environmental effects (extreme temperatures, humidity, dust), insects, power surges, and various other causes of equipment or communications failure. No single document exists that lists best practices for protecting equipment from these common problems. The U.S. Department of Transportation has recently started promoting information exchanges between state highway agencies in order to increase the sharing of knowledge in these areas.

Specific WIM system technologies that can be used for permanent, continuous weight data collection are

- Piezoceramic sensors,
- Piezopolymer sensors,
- Piezoquartz sensors,
- Bending plates,
- Hydraulic load cells,
- Bridge and culvert WIM systems,
- Capacitance mats, and
- Other WIM technologies (fiber-optic, subsurface strain gauge, multi-sensor).

Each of these technologies is introduced briefly below.

Piezoceramic Sensors

As noted above, piezoelectric WIM sensors come in various forms, but all systems operate on the same basic principle. When a mechanical force is applied to a piezoelectric device, it generates a voltage by causing electrical charges of opposite polarity to appear at the parallel faces of the piezoelectric material. The measured voltage is proportional to the force or weight of the wheel or axle and is transmitted by the sensor to electronics that measure and interpret the voltage signal.

The first piezo traffic sensor marketed in the United States uses a ceramic powder compressed between a solid core and an outer sheath of copper. The cable is about the size of conventional coaxial cable. When used as permanent WIM scale sensors, the cable is most commonly placed in aluminum channels filled with epoxy resin or another substance. The channel is then placed so that the top of the sensor is flush with the road surface, in a slot cut into the pavement, less than 2 inches wide. (Different vendors use slightly different sensor mounting techniques.) Routine site installations can consist of two piezoceramic sensors, two sensors plus an inductance loop, or one piezo sensor and two inductance loops.

Each of these configurations allows for the computation of vehicle speed and, consequently, axle spacing, which in turn permits vehicle classification as well as axle weighing. The installations using two piezo sensors tend to provide better estimates of static axle weights because each sensor provides an independent measure of axle weight during a different time period associated with the vertical motion of the vehicle being weighed. Combining the two independent weight estimates generally improves the accuracy of the static weight estimate.

The piezoelectric effect generated by the sensor is dynamic. That is, the charge is generated only when the forces applied to the sensor are changing. As a result, piezoelectric sensor systems can only be used in applications where vehicles are moving at speeds not less than 10 mph; they are not reliable in slow-moving or stop-and-go traffic.

In addition, it is difficult to construct a cable for these sensors that has uniform response across its entire length. Strict laboratory testing is done to ensure that cables used for weighing meet uniformity standards. Cables that successfully pass

uniformity tests are called "Class 1" sensors. Sensors that function correctly but do not meet the highest signal uniformity standards are designated as "Class 2" sensors and can be used for vehicle classification purposes, but not for weighing.

Piezoceramic sensors produce weight estimates of average quality. They suffer from three significant limitations in system accuracy: temperature sensitivity, reliance on the pavement itself for structural support, and narrow sensor design.

Because the piezoceramic sensor is temperature sensitive, piezoceramic WIM systems must include various algorithms and/or additional sensor inputs that allow the WIM system to account for temperature changes when estimating weights. Each equipment vendor tends to approach this problem differently, and different levels of success are achieved. The technical process is further complicated by the fact that sensors are placed directly in the pavement structure and, because many pavement structures have structural responses that are also temperature dependent, this also affects the piezo's signal strength for a given load. Consequently, the sensor response is affected by two independent (but related) sources of variation in signal strength, and these lead to errors in estimated axle weights.

The narrow-sensor design is an advantage when it comes to the time and cost required for installation. However, the narrow sensor also means that tires being weighed are never isolated on the sensor. That is, during all points in the weighing process, at least part of the tire is being supported by the pavement surrounding the sensor and not the sensor itself. Thus, the sensor never senses the entire force applied by a tire. This effect is exacerbated by some tire tread designs that can concentrate forces on small surface areas, and those surfaces may or may not be directly on the sensor itself. The combination of these effects is that the sensor can sense a variety of different forces, and this results in a larger error when estimating static weights than with some other WIM technologies.

Piezopolymer Sensors

The second common piezo technology uses a piezoelectric polymer surrounded by a flat brass casing. This sensor, commonly called the BL sensor, is placed directly on the road for portable weighing but, like the piezoceramic cable, is commonly placed into an aluminum channel filled with epoxy resin when being used as a permanent WIM sensor.

This sensor is used exactly as the piezoceramic cable is used and has essentially the same benefits and drawbacks. The BL sensor is also temperature sensitive, and the piezoelectric effect it generates is dynamic. It is not a reliable sensor in slow or stop-and-go conditions, and additional steps are needed when processing sensor output to account for changes in sensitivity because of changing temperatures. Finally, like the piezoceramic cable, it comes in Class 1 and Class 2 configurations, which indicates the degree of sensor uniformity.

Piezoquartz Sensors

The piezoquartz sensor was recently introduced in the United States. It differs from the other piezoelectric sensors both in the piezoelectric material used and in the design of the sensor itself, although it still fits into a pavement cut generally less than 2 inches wide.

While it is more expensive per sensor than the other piezo-style sensors, the quartz sensor has the distinct advantage of being insensitive to changes in temperature. It is therefore generally more accurate than other piezo sensors. However, because the sensor still relies on structural support from the pavement, if the pavement structure is sensitive to temperature, the sensor will show some change in response to a given axle load simply as a result of the change in pavement strength with changing environmental conditions. This sensor is not sensitive to changes in temperature or soil moisture if placed in a thick portland cement concrete pavement. However, output from this sensor is likely to be sensitive to changes in temperature, although not as much as other piezo sensors would be, if placed in a moderately thin asphalt pavement.

Like other piezo sensors, this sensor is placed into a relatively small slot cut into the pavement. Each sensor is roughly 1 meter (3 feet) long, so four sensors are placed in an end-to-end arrangement to instrument an entire 12-foot traffic lane. The site installation can consist of two lines (eight sensors) of piezoquartz sensors, two lines plus an inductance loop, or one line of piezo sensors and two inductance loops.

As with other piezo installations, each of these configurations allows for the computation of vehicle speed and, consequently, axle spacing, which in turn allows vehicle classification. The installations using two piezo lines tend to provide better estimates of static axle weights, because each line provides an independent measure of axle weight, and the averaged weight estimate can be used to account for the dynamic motion of the vehicle more effectively than a single line of sensors.

Real-world experience with piezoquartz sensors is still being gained in the United States, but the sensor appears to offer accuracy on a par with bending-plate systems when installed in structurally strong pavements.

Bending Plates

Bending-plate WIM systems use plates with strain gauges bonded to the underside. As axles pass over the bending plate, the system measures the strain on the plate and calculates the load required to induce that level of strain.

Individual bending plates are generally 6 feet long and roughly 2 feet wide. One bending plate is generally installed in each wheel path. In some cases they are installed aligned, while in other cases the right and left wheel path plates are staggered in order to measure tire loads at two different points in the vehicle's dynamic path. A typical bending-plate site also includes two inductance loops used to detect approaching

vehicles, to differentiate between closely spaced vehicles, and to measure speed.

Bending plates are mounted flush with the roadway into steel frames placed in the pavement. The use of steel frames separates the plate sensor from the roadway structure and increases the accuracy of the weight measurement in comparison with strip sensors. In addition, the weighing platform is large enough to isolate each tire as it is weighed. This also negates the bridging effect from which strip sensors suffer, as well as limiting the effect that different tire pressures and tread designs have on the forces exerted on the scale platform.

Tests of system performance generally indicate that bending plates are more accurate than traditional piezo cable and capacitance mat WIM systems and are roughly equivalent in accuracy to piezoquartz sensors, but are less accurate than hydraulic load cells. However, differences in weighing accuracy that result from technological differences between WIM systems are often overshadowed by problems inherent with specific weighing installations. (For example, a load cell placed in rough pavement will provide less accurate data than a bending-plate system placed in smooth pavement.)

The cost and installation time required to place bending-plate systems also falls between that of piezo and load-cell systems. Because placement of the steel frame involves a more substantial pavement cut than is required for the strip sensor installation, the duration of the lane closure required for system installation is far longer than for piezo systems. However, the time required for bending-plate installation is considerably less than that required for load-cell installation.

Hydraulic Load Cells

As with most of the WIM technologies, there is more than one high-speed hydraulic load-cell WIM system design in the United States. The most common versions operate by transferring wheel weights applied to the weighing platform to one or more hydraulic cylinders containing oil. Changes in the hydraulic pressure are correlated with axle weights. The most common load cell design uses two in-line scale platforms that operate independently and provides weight estimates for the right and left tires of each axle. The system records the weights measured by each scale and sums them to obtain the axle weight. Off-scale detectors are frequently integrated into the scale design to detect any vehicles off the weighing surface. In addition, at least one inductive loop and one axle sensor are usually included as part of the system design. The inductive loop is placed upstream of the load cell to detect vehicles and alert the system of an approaching vehicle. The axle sensor is usually placed downstream of the load cell to determine axle spacings and vehicle speed. If a second inductive loop is used in place of the second axle sensor, it is placed downstream of the load cell to determine vehicle speed, which is needed to determine axle spacings.

The deep-pit load-cell system is generally considered the most accurate of the available conventional high-speed WIM systems. It is generally insensitive to changes in temperature and can weigh vehicles at both low and high speeds. It is, however, the most expensive WIM system to purchase and install. The term "deep-pit scale" comes from the fact that this load cell itself requires a significant excavation in the roadway for installation. This means long lane closures are required for sensor installation. Heavy construction equipment is needed to dig installation pits and place sensors and associated electronics. However, the fact that considerable construction is involved normally means that sensors are only placed at locations with smooth pavements (or pavements are made smooth at the time of sensor installation). Thus, hydraulic load cells tend to be correlated with "expensive" installations, which in turn result in better system performance.

Load cells are contained in a steel frame that is independent of the pavement. This makes the load cell's response to axle weights insensitive to changes in pavement strength caused by changes in environmental conditions (i.e., temperature and moisture content). In addition, the weighing platform is large enough to isolate each tire as it is weighed. This again eliminates the negative effect pavement strength has on strip sensors, as well as limiting the effect different tire pressures and tread designs have on the forces exerted on the scale platform.

Bridge and Culvert WIM Systems

In bridge WIM systems, strain gauges are placed on the underside of bridges or on the girders of bridges. Strain-gauge output is analyzed to determine the loads on specific vehicle axles. While the number of bridge WIM installations has declined in the United States since the late 1990s, considerable research on this subject is still being performed in Europe. Information on this research is available at http://wim.zag.si/wave/download/wp12_report.html.

Culvert WIM is a variation of bridge WIM and is extensively used in Australia. In this system, strain gauges are attached to the underside of large culverts, and the strain measurements obtained are used to estimate truck axle loads. The short span of the concrete culvert and the relatively simplistic design of the culvert make the analysis of the strain signal straightforward, thus eliminating several of the problems experienced by bridge WIM systems used in the United States.

While the culvert-based system has been marketed in the United States, it is not widely used at this time.

Capacitance Mats

Capacitance mats consist of two metal sheets separated by a dielectric material. An outer surface layer surrounds the sensor, protects the steel plates, and allows the sensor to be placed on the pavement or in a mounting frame. A voltage is applied across the two metal plates. When a vehicle crosses

over the plate system, it causes the distance between the two plates to decrease, which increases the capacitance of the system. Measurement of the resonance frequency of this circuit allows the estimation of the weight of each tire as it is applied to the sensor system.

Permanently mounted capacitance mats differ from portable mats in that the former mats are placed in steel frames that are installed in the pavement surface. This allows the surface of the mats to be flush with the roadway and improves the accuracy of the system. It also reduces the impact load on the sensor itself, both increasing sensor life and decreasing the potential for the sensor to be dislodged from the roadway.

Most capacitance mat systems rely on weighing only one wheel path. This limitation makes them slightly less accurate than other potential WIM system alternatives. However, vendors do sell permanent capacitance mat systems that use mats in both wheel paths.

Other WIM Technologies

New WIM technologies continue to be developed and brought to the market. Many of the new technologies have been developed specifically to address limitations in the cost, performance, and flexibility of current technologies. The systems discussed below are either in active use elsewhere in the world or in active development in the United States:

- *Fiber-optic* sensors detect the presence of a load by measuring the decrease in optical transmission caused by constriction of the fibers when vehicles pass over sensors. Fiber-optic sensor systems contain light transmitters (usually a light-emitting diode), photon detectors, and signal analysis hardware and software in addition to the fiber sensor itself. The potential advantages of fiber-optic sensors are relative insensitivity to road temperature and low cost. Fiber-optic sensor systems are not fully developed and are not in field operational use. System accuracy and life have not been established.
- *Capacitance strip* sensors have been used in the United Kingdom for a number of years. These sensors use the same basic principle as capacitance mats (described above), but use a thin sensor (instead of the larger mat) designed for in-pavement installation similar to piezo-sensor deployment. The capacitance sensor material was selected to avoid the temperature sensitivity problems associated with piezoceramic and piezopolymer sensors. However, only limited testing of this sensor has been done in the United States, and the sensor is not actively marketed in the United States.
- *Subsurface strain-gauge frame* technology is currently being tested at Virginia Polytechnic Institute and State University. This technology places a steel frame fitted with a large number of strain gauges underneath the pavement. (The 2-ton frame is installed at least 2 inches under the pavement surface and can be completely below the roadbed.) The scale sensor is placed by removing the existing pavement at the site and repaving once the scale is correctly positioned. The sensor's strain gauges register the strain transmitted through the pavement to the steel frame. A neural network computing algorithm then converts these signals to estimates of vehicle and axle weights. The system uses the pavement structure to dampen the effect of vehicle dynamics and to increase sensor life by limiting the fatigue problems associated with repetitive tire contact and pavement maintenance activities. The manufacturer claims that the sensor system is maintenance free. The testing being performed will determine whether the neural network processing algorithm is able to accurately estimate weights given the mitigating effects of the overlying pavement structure.
- *Multi-sensor WIM* is one of the bigger research issues in Europe's WAVE ("WIM of Axles and Vehicles for Europe") program. The concept is to use a larger number of moderately priced sensors to weigh a given vehicle multiple times during a single pass. By stretching these sensors over many meters, it is possible to determine a vehicle's dynamic motion and thus significantly improve the estimate of vehicle weight. The use of multiple sensors also provides multiple independent measures of the same basic quantity. While this technique shows considerable promise, it is unclear if it is economically feasible or if the improvements in accuracy achieved warrant the cost of additional sensors and their placement.

A number of states and vendors have moved to take advantage of the concept of multi-sensor WIM without taking the approach the European WAVE program tested. In Europe, multi-sensor WIM systems deployed a large number of sensors (10 or more). In the United States, vendors and states have both increased the number of sensors deployed and changed the location of sensors in order to improve the measurement of vehicle dynamics. However, they have not increased the number of sensors to the extent examined in the European tests. The increase in sensors allows a more accurate measurement of (and accounting for) the variation in axle weight caused by vehicle motion. However, by limiting the number of sensors added, the increase in capital cost and installation time required to build the WIM site is moderated.

One fairly common approach to multi-sensor WIM in the United States has been to use three half-lane bending plate scales (rather than the traditional two sensors) and to stagger the left wheel path and right wheel path sensors (rather than placing them side by side). This allows measurement of both sides of the vehicle and provides measurements at three different points in the dynamic spectrum while only increasing the sensor cost by 50 percent.

Another common approach is to place four staggered sets of half-lane piezo sensors. The concept is the same for this system as for the bending plate system, in that staggering the

sensors yields more information on the dynamic variation of axles, while, in this case, there is no actual increase in the number of sensors required when compared with a conventional piezo-based layout (i.e., two full lanes' worth of sensors).

Both of these designs also have the advantage of providing an extra layer of site reliability. This is because the extra sensors allow "graceful degradation" of the WIM system. That is, the loss of one sensor does not make the WIM data unusable; it simply degrades the accuracy of the system somewhat.

In the case of the bending-plate system described above, the loss of one of the two right bending plates actually leaves the site as being equivalent to a conventional bending-plate WIM site in terms of sensor accuracy.

Note that before such an approach is adopted, the highway agency must make sure that the vendor's data collection electronics can both handle any additional sensor inputs and correctly interpret the signals coming from sensors placed in a staggered position.

CHAPTER **4**

A PROCESS FOR SELECTING EQUIPMENT

Each of the technologies discussed in Chapters 2 and 3 has strengths and weaknesses for collecting classification and weight data. Under the right conditions, most of the technologies can collect data of the quality needed for estimating traffic loads for the pavement design software. However, each of these technologies can perform very poorly when placed in environments that are not conducive to the technology being used or when used incorrectly.

As a consequence, the state highway agencies most successful at data collection own and operate more than one type of vehicle classification and/or WIM equipment. Different types of equipment are used in different operating environments. This helps ensure the quality of data that are collected, but also forces understanding of and accounting for minor differences in data supplied by different devices. (For example, some agencies use dual-inductance loops to collect length-based truck classification data on urban freeways but axle sensor-based counters to collect classification data on rural roads. Special studies are needed to correlate these two data collection schemes. But through the use of detectors placed to collect traffic operations data, these simple correlation studies provide access to large amounts of important truck count information that could not be collected otherwise.)

Selecting technologies (and vendors) requires careful analysis of three different types of information:

- Data collection needs of users,
- Data handling requirements and capabilities of the highway agency, and
- Characteristics of available makes or models of equipment (e.g., cost, reliability, and data provided).

Within each of these general subject areas are a variety of important issues. It is each agency's responsibility to explore these issues and to balance the advantages and disadvantages of each technology when selecting equipment both in general and for specific data collection implementations.

The material presented below briefly describes the issues that need to be considered when agencies select equipment for vehicle classification and/or truck weight data collection. In addition, Chapter 5 presents a series of best practices recommendations that describe tasks needed to ensure the collection of reliable, accurate traffic data. Adoption of these practices, or of variations in these practices, is likely to improve the quality of the data collected and reduce the overall cost of the data collection effort.

4.1 DATA COLLECTION NEEDS

The traffic data needs for the pavement design software are being addressed in detail under other tasks of NCHRP Project 1-39. These needs require capability to collect the following:

- Short-duration (48-hour) classification counts on roads and road segments where traffic loads will be needed,
- Long-term classification counts (i.e., data collected for more than 1 year) at a limited number of locations around the state, and
- WIM data collection at a limited number of locations.

These capabilities are consistent with the general agency counting needs identified in the FHWA's *Traffic Monitoring Guide* as meeting the needs of a wide variety of users.

The specifics of the required data collection efforts are divided into vehicle classification issues, location issues, and count duration issues.

4.1.1 Classification Issues

A good starting point when examining data collection equipment is the type of classification scheme the equipment is capable of providing. Axle-based classifications are preferred for pavement design purposes, but length classification is acceptable when axle classes cannot be reliably collected.

Truck characteristics (overall length, axle spacing, etc.) tend to differ from state to state. Each state highway agency should have an algorithm they have tested and certified that can correctly convert axle count and spacing information into accurate vehicle classification. Can this algorithm be implemented with the proposed equipment? If not, what flexibility is offered by the vendor in the classifications supported, and how do those classes correlate with the FHWA's 13 classes or the classification system used by the state highway agency? Finally, if a classification algorithm other than the one tested and approved by the highway agency must be used, the agency must thoroughly test the new algorithm. Acceptance of the new data collection equipment should be contingent on the

satisfactory performance of the equipment in that test, and the highway agency should use those results to understand how data collected with the new device correlate with the data collected using the agency's WIM scales.

4.1.2 Location Issues

Often the classifications collected are not driven by the preferences of the user, but by the constraints of the location at which data must be collected. A number of location-specific constraints can affect the choice of data collection technology. Key location-specific constraints and their effects include the following:

- Is the data collection site urban or rural oriented? (That is, is congestion likely to be present? Are vehicles often formed into closely space platoons?) Devices that work effectively in uncongested rural areas often do not work effectively in more congested urban conditions. (Tests performed by Minnesota Guidestar in 2001/2002 should provide guidance on which non-intrusive devices can accurately collect data in urban conditions. See http://www.dot.state.mn.us/guidestar/projects/nitd.html.)
- Are there traffic signals or other control devices nearby that may affect vehicle speeds and/or spacings? (Classification and WIM equipment should not be located near signals because vehicles frequently accelerate and decelerate near intersections, causing problems in the performance of most classification and weight data collection devices.)
- At what speeds are vehicles traveling? (Some devices do not operate at very low traveling speeds, while others are not effective at very high traveling speeds.)
- On how many lanes do data need to be collected, and what is the layout of those lanes? (Some devices can only collect data in one lane, and that lane must be on the outside of the roadway, next to a shoulder or median.)
- Can detectors be placed safely in (or above) the travel lanes? Is formal traffic control needed for this purpose? (Inability to place sensors in the lanes of travel would indicate the use of non-intrusive detectors, and inability to work above the lanes of travel would further restrict the technology choice to one that can function from beside the roadway.)
- Are there specific site constraints that need to be accounted for in the selection of equipment? (Will the road's channelization be changing in the near future, so that permanent intrusive sensors are not cost-effective and non-intrusive sensors should be selected?)
- Are there other features to the site that constrain or enhance the use of certain data collection technologies? (What is the availability of power or communications, and does that availability indicate the need to select a low-power consumption data collection technology? Does the presence of an existing sign, bridge, or other overhead

structure reduce the cost of non-intrusive sensor placement to the point where they have a cost advantage over intrusive sensors?)
- Are there site conditions that prevent accurate data collection from taking place? (Is the pavement in too bad of a condition for WIM or classification equipment to operate correctly? Does the poor pavement condition warrant the use of non-intrusive data collection technologies either because intrusive sensors will not survive long or because the poor pavement will cause axles to jump the intrusive sensors?)
- Is the pavement depth deep enough to allow sensor installation? (If not, choose a different location, use a non-intrusive sensor, or build a special pavement slab deep enough to hold the sensor.)
- Are there environmental conditions that restrict the use of specific technologies? (Do temperatures drop below levels at which some technologies work? Are temperature variations sufficient to cause calibration errors in some sensor technologies? Are there visibility constraints that limit the accuracy of specific non-intrusive data collection technologies?)
- Are there environmental conditions that are likely to badly impact the duration of data collection? (For example, are freeze-thaw conditions likely to reduce the expected sensor life?)

In some cases, shortcomings of the site should warrant selection of another data collection location. For example, poor pavement condition affects the performance of all WIM sensors. Rather than accepting poor WIM performance (and perhaps choosing an inexpensive, inaccurate sensor because "bad data will be collected no matter what sensor is chosen"), consideration should be given to either (1) moving the data collection site upstream or downstream to a site more conducive to WIM data collection but with essentially the same traffic stream as at the original site or (2) improving the pavement condition prior to the installation of data collection sensors. The goal is to meet two criteria: (1) that the traffic data being collected correlate very closely with the traffic at the site for which the data are being collected and (2) that the new site has conditions that allow the equipment to perform accurately.

4.1.3 Count Duration Issues

The intended duration of a count has a considerable impact on the type of data collection technology selected. The longer the desired count duration, the more likely a permanently mounted sensor is needed.

For long-duration data collection sites, it is also important to determine the expected life span of the site itself. For example, because vehicle weight data are scarce on most roads in most states, it seems prudent to collect no more than 2 years' worth of weight data at a specific site and then move

the data collection electronics to a new road in a different part of the state.

With this type of scenario, the highest quality (and most expensive) WIM systems are not good investments. Instead, a more modestly priced sensor should be installed, with the intent of abandoning the site after 2 years. However, if data on the proposed site will be gathered for many years in order to track trends on key routes, it is often cost-effective to spend additional resources up front in order to reduce the cost of future maintenance and increase the life span of sensors placed at a given location.

A similar type of situation can also affect the selection of classification technology. If the proposed data collection site is due to be repaved in 2 years, it may not be appropriate to place sensors in the pavement. Or it may be less expensive to install non-intrusive sensors that can be used even after the pavement replacement takes place.

4.2 DATA HANDLING AND OTHER AGENCY CONSIDERATIONS

The next series of basic considerations when selecting equipment pertain to how effectively new equipment can be integrated into the existing (or planned) data handling system of the state highway agency.

Perhaps the most important issues are what vehicle classification categories can be collected (see Section 4.1) and how those classifications relate to the classes currently collected. However, there are a number of equally important factors to examine that relate to what other data are collected and how those data are handled within the highway agency's data collection, storage, and reporting system:

- How are the data retrieved from the data collection site? (Can the equipment be polled automatically using telecommunications? Does a staff person need to visit the site? Are the data extracted directly to a computer or must they be transferred to a data storage unit and then downloaded to a computer in a second step?)
- How large are the files being transferred? (How much communications bandwidth is needed for the site?)
- If remote communications capabilities exist, what communications options are supported? (For example, what telephone baud rates can be used? Does the system support direct Internet connections? Are digital, wireless modems supported? Are other communications mechanisms supported that are already used by the highway agency?)
- What computer formats are used as part of this data transfer, and are they proprietary to the vendor or can the state highway agency communicate to these devices using an existing standard (e.g., the National Transportation Communications for ITS [intelligent transportation systems] Protocol, or NTCIP)? (Are these formats compatible with existing central database software used by the state?)

- Does central system software provided by the vendor allow for the conversion of formats?
- What levels of data aggregation are available when collecting data from the field (individual vehicle records, 5-minute summaries, or hourly summaries)?
- How much data processing takes place at the site, and how much takes place at the central office? Can this distribution of data processing be changed when setting up the data collection system?
- Are the data available by individual lane or for all lanes at a site?
- What error detection and reporting mechanisms are built into the vendor's data collection equipment and software? Are error flags included in the data stream sent back from the field equipment?

Another area of concern for a highway agency is the staffing resources needed to install, operate, and maintain the data collection equipment. Staffing issues relate to the number of staff needed to place, operate, and maintain data collection equipment, as well as the skill sets those staff need. Do the equipment maintenance staff need specific tool sets (oscilloscopes, video monitors, specialized circuit boards or tools, etc.) in order to maintain the equipment (i.e., diagnose and repair problems)?

In many data collection locations, an even bigger issue is the inability to gain physical access to the roadway when desired. (Many high-volume roadways allow sensor installation only for a limited time during the night when traffic volumes are low and/or when other construction or maintenance activities are being performed. Can the technology selected be installed under these time constraints?)

How long does it take to install the sensors, and what impact does that installation process have on the use of the existing roadway? Are those timeframes politically acceptable?

4.3 UNDERSTANDING EQUIPMENT CHARACTERISTICS

Chapter 2 presented an introduction to the technologies available for collecting the classification and weight data required to meet the user needs determined from the effort described in Section 4.1. Additional information on equipment accuracy, reliability, and cost is available through the following:

- References provided as part of this report, as well as those published in a variety of technical sources;
- Experience gained by the highway agency as it uses specific equipment;
- Communication with other highway agencies about their experiences with specific types and models of data collection equipment;

- Specific tests done to measure the performance of equipment; and
- Vendor responses to requests for proposals or requests for information published by the highway agency.

It is important to collect device-specific information from these sources. Because a specific technology appears to be a good fit for a specific application does not mean that all devices using that technology will work equally well. Specific implementations of a given technology from two different vendors can result in data of very different quality. Similarly, the cost for specific technologies can vary considerably from vendor to vendor, along with the features supplied with the proposed equipment. Only by looking at the specifics of vendors' proposals can these details be determined and compared.

It is important to obtain information about the performance of specific models offered by vendors. Similarly, it is important to determine what warranties and/or guaranties vendors supply with the equipment as these provide both assurances that equipment will perform as claimed and remedies if the equipment does not. Lastly, it is important to test the equipment when it is first placed in order to determine if the equipment meets the standards warranted by the vendor.

Table 4.1 presents a summary sheet that can be used to highlight the specific data collection issues important to selecting the appropriate equipment for a specific project or set of data collection efforts. (Additional factors can also be added to reflect needs not discussed in this document.) It is up to each highway agency to weigh the relative importance of each of these issues.

TABLE 4.1   Sample equipment selection analysis summary sheet

Technology/Vendor/Model: _____

Subject Area	Issues/Concerns	Technology/Vendor Review Comments
Equipment Capability		
Type of Data Collected • WIM • Classification		
Types of Vehicle Classes Measured • 13 FHWA axle-based classes • Vehicle lengths only • Other (total number allowed)		
Desired/Required Sensor Location • In pavement • On pavement • Non-intrusive	Can sensor be placed? • Condition of pavement, planned pavement maintenance and repair? • Traffic volumes • Availability of overhead structures or poles	
Count Duration • Portable (several days) • Permanent	• Seasonal changes? (in traffic generators?) • Correlation with permanent sites, reliability of measurements?	
Output from Device • Level of aggregation • Specific • Quality-control metrics available for analysis of device output	• Can be polled from central source, or only from the site? • Flexibility of output formats • Availability of standardized formats (NTCIP? Other?)	
Site Conditions		
Operating Environment • Temperature range and daily variation • Visibility constraints (fog, mist, dust) • Snow (loss of lane lines) • Free-flow or congested traffic (including other acceleration/deceleration conditions)		
Number of Lanes • Are all lanes next to a shoulder?	• Number of sensors required • Number of sets of electronics required	
Is Power Available?	Can device run off of solar panels?	
Are Communications Available? • Telephone, DSL, wireless • Other	Bandwidth required from device • Frequency of communications	
General		
Technology Price	Total Cost = Sensor Cost x Number of Sensors + Cost of Electronics	
Staff Training to Install, Operate, and Maintain the Devices		
Equipment Needed to Install, Operate, and Maintain the Device		
Published Accuracy Achieved with the Technology	Has the technology been used previously?	
Previous Experience with this Technology/Vendor	Vendor support offered/available	

CHAPTER **5**

BEST PRACTICES FOR EQUIPMENT USE

The collection of traffic load data required by the pavement design software is just one of a variety of traffic data collection tasks that highway agencies must perform. The traffic load data collection effort cannot be done as an independent activity. It must be performed within the context of the entire traffic data collection effort undertaken by a highway agency.

Determination of what equipment to purchase and how to install, calibrate, and maintain it, as well as what data to collect, how equipment and staffing resources are efficiently used to collect it, and how the collected data are manipulated, stored, and reported once they are available, must be done within the context of the entire agency's traffic data needs. Separation of the pavement design needs from the other traffic data needs leads to considerable inefficiency in traffic data collection. Therefore, a need for good data practices applies throughout the agency's traffic data collection program.

In general, good data collection practice can be summarized as nine basic steps:

1. Identify user requirements and develop an implementation plan.
2. Determine location and system requirements.
3. Determine site design life and accuracy necessary to support the end user.
4. Budget the resources necessary to support the selected site design life and accuracy requirements.
5. Develop and maintain a thorough quality assurance and performance measurement program.
6. Purchase the WIM or classification equipment with a warranty.
7. Manage the equipment installation.
8. Calibrate and maintain calibration of equipment.
9. Conduct preventive and corrective maintenance at the data collection sites.

It is important to remember that good traffic data collection practice requires the agency to also consider the impact on data collection of other traffic data needs. This section expands on the traffic data collection and equipment needs discussed elsewhere in the report by explaining how pavement design data needs fit together with other agency needs.

5.1 IDENTIFY USER REQUIREMENTS

The pavement design process requires an accurate estimate of the number of heavy vehicles projected to use the roadway lane being designed and the number, type, and weight distribution of the axles on those trucks. These data will come from a combination of project-specific counts and the summary tables developed from the general truck counting and weighing program performed by the state highway agency.

The level of reliability desired by pavement design engineers (and the budget available to them for data collection) will result in their selection of the level of data collection performed for pavement design projects. The level will define the amount of truck volume and weight data collected specifically to meet the needs of pavement design efforts. These needs will become requests to collect specific data that are sent to the traffic data collection section of an agency.

Traffic data collection units will need to develop mechanisms that allow them to efficiently respond to both these specific requests (which will vary from request to request) and the need to collect the more general data that are used to create the summary statistics and tables used when project-specific data are not required or cannot be affordably collected.

To create a cost-effective data collection program, both of the above needs must be efficiently coordinated with the other truck volume and weight data needs of the highway agency. Collecting the data needed for general summary tables is part of routine data collection programs, and directions for this are included in the FHWA's *Traffic Monitoring Guide*, Sections 4 and 5. Responding efficiently to the need for project-specific counts is a more difficult undertaking. Often it can most effectively be accomplished by setting up one or more meetings during each year between traffic data collection staff and pavement design staff to discuss roadway sections that will most likely be the subject of new pavement designs in the next year or two. These sections will require truck traffic data collection, and a 1- to 2-year timeframe should allow efficient scheduling of the data collection effort.

Scheduling this meeting (or meetings) to take place prior to the development of each year's traffic data collection program allows data collection staff to efficiently schedule their data collection resources. This significantly decreases the cost of data collection efforts, and this scheduling efficiency more

than makes up for any "extra" counts that are taken but not actually used because expected pavement projects are delayed.

Data collection staff have the responsibility of coordinating the needs of different users. A key to this function is knowing where flexibility exists in the collection and reporting of data. In a simple example, if two users request the same data for the same road but for road segments one-half mile apart, the data collection staff need to be able to determine if those two data collection requests can be met by a single count, halving the number of counts that need to be taken.

Where flexibility exists is a function of the roadway characteristics and the uses of the data. If the road is a rural highway with limited activity, the two requests can likely be met with one count. If a major freeway interchange occurs between the two locations, it is unlikely that the two counts can be combined. Still, the same data collection crew will probably collect both counts, and by collecting both counts in the same trip at least the travel time and cost associated with the data collection can be halved.

Traditionally, this type of coordination has been difficult to perform because pavement project selection processes were not done early enough to fit into traffic data collection schedules. However, most states now operate pavement management systems that identify roadway sections in need of repair or rehabilitation in the near future. These program outputs can be used to create a short list of projects that are likely to occur in the next 2 years. The state's transportation improvement plan (TIP) may also provide such a list. If the actual pavement design list is not available when the traffic data collection program needs to be developed, this slightly larger list can be used as a surrogate for the actual list. It may require a minor increase in the number of pavement design counts that need to be collected, but the slight increase in counts is more than offset by the decrease in cost per count due not only to the coordination efforts, but also to the more timely manner in which data can be made available to the pavement design team.

Implementation of the recommendation to enhance the communication and coordination of pavement design engineers and traffic data collectors is more of an administrative and institutional problem than a technical problem. If an agency succeeds, four positive changes should take place:

- The availability of traffic load data for pavement design purposes should improve.
- The cost of collecting traffic load data for pavement design should decline.
- Data quality should improve as more staff review and use the data collected.
- Internal support for traffic data collection activities should improve as the users of the data improve their understanding of the value and limitations of the traffic data they are receiving.

The keys to all of these improvements are (1) achieving a high level of communication between pavement design engi-

neers and traffic data collectors and (2) combining that communication with strong advance planning. Both pavement design engineers and traffic data collectors obtain considerable benefits from improving communications. Well-run traffic counting programs invariably have strong connections to their users, and the pavement design section is a very important user group.

5.2 DETERMINE SITE LOCATION AND SYSTEM REQUIREMENTS

As noted in the example in the previous section, a key component of the data collection process is understanding what, where, and why data are being collected. Understanding these factors is necessary for determining exactly what, when, and how data need to be collected and for selecting the equipment to be used.

Traffic data are collected from a given location either because data from that point are important to a specific design or project, or because data from that location are needed to help develop a default or average value that can be used at many sites where site-specific information cannot be affordably collected. The first of these count efforts is generally referred to as "project counts." These generally are data collected (1) to describe the current traffic stream crossing the design lane for a project and (2) to serve as a baseline upon which to forecast the future traffic stream. The second data collection effort is often thought of as planning counts, which are performed as part of general agency data collection efforts. While also meeting general agency needs, these data are used to compute the Level 2 and Level 3 load-spectra defaults[1] used by the pavement design software. These counts include WIM efforts used to compute truck weight road group (TWRG[2]) axle-load distributions, and continuous classification counts are used to determine seasonal truck volume and other truck traffic patterns. Some flexibility exists in the collection of both of these types of data.

Ideally, project-specific counts are taken at the project site, as this provides the most reliable estimate of current traffic crossing the design pavement. However, the actual data collection effort can be moved upstream or downstream from the project location if the project location is not conducive to accurate traffic data collection or if other circumstances warrant such a move. One good reason to move a project-specific count is that the pavement at the project site is in such poor condition that the available traffic sensors will not work accurately. In general, having accurate, representative data is more important than having data from the exact site of the pavement project.

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[1] Level 2 load-spectra defaults are those axle weight distributions used when site-specific data for a project site are not available, but when the site can be identified with a regional average. (Level 2 is the regional average.) Level 3 represents the statewide average and is used only when no better information is available for a pavement design.

[2] TWRGs are groups of roads that have trucks with similar loading conditions. A sample of vehicle weights is collected and used to represent the axle load distribution for all roads that belong to that group when site-specific load information is not available.

If the count is moved, it should be placed so that truck traffic being measured is as closely related to the actual project traffic as possible. If the project location, for example, is on I-80 in Wyoming, a valid data collection location could be several miles away. However, if the project location is on I-95 in New Jersey, the count most likely needs to be taken within the same set of interchanges as the pavement project.

Selecting data collection locations for pavement design purposes can also be affected by the need to coordinate with other data collection needs. A highway agency may be willing to accept some minor error in the traffic loading estimate in order to reduce the total counting burden of the state, and the agency thus may choose to use an existing count that is slightly removed from the project location rather than go to the expense of collecting newer, more precise information.

Even broader flexibility is available to highway agencies as they select those locations where data are collected to compute the TWRGs. The primary goal of the TWRG is to provide an accurate measure of average conditions for a given set of roads. Given the lack of weight data available to most highway agencies and the cost and difficulty of collecting accurate weight data, most agencies know relatively little about the vehicle weights present on specific roads. Thus, considerable latitude is available in the selection of data collection sites that are included in the TWRG computations because most agencies have little information upon which to judge alternative locations and any valid data are better than no data.

The first criterion of TWRG formation is that the sites be similar in characteristics to the other roads they represent. (For example, the shape of the axle load distribution associated with FHWA Class 9 trucks should be similar at all sites within the TWRG.) The second criterion for data collection is that the sites selected be conducive to accurate weight data collection. This means that the pavement should be in good condition. It should be flat, with no ruts. The pavement should be strong enough to support weight sensors effectively under whatever environmental conditions are present when weight data are being collected.

It is recommended that, at least initially, data collection for TWRG development be oriented toward sites at which accurate data can most confidently be collected. As budgets permit, the weight data collection program should then be expanded or moved to other locations around the state (where WIM equipment can be accurately operated) in order to gain a more complete picture of truck weights around the state.

5.3 DETERMINE DESIGN LIFE AND ACCURACY REQUIREMENTS

Another key to efficient expenditure of data collection resources is to match the design life of equipment to the life of pavement and select the equipment accordingly. It is rarely a wise decision to select a WIM sensor that is expected to outlive the pavement in which it is placed. Few WIM installa-

tions can be removed intact from the roadway and reused. (This does not include technologies such as bending plates, where the sensor itself can be removed, but the frames into which the plates are set are not removable.) Thus, it makes little sense to design a 5-year WIM site for a pavement that will be repaved in 3 years.

For WIM data collection, site failure is often the result of failure of the pavement condition around the site, not just the failure of sensors themselves. Thus, site design life is a function of the fatigue life of the sensor itself, the installation quality of the sensor, the initial site condition and design, and the expected wear on the pavement.

Sensor fatigue life is usually a function of the sensor design and the traffic loadings. Vendors normally warranty their sensors for a specified period, and obtaining a warranty is itself a recommended best practice. Sensors with longer fatigue lives are usually more expensive than shorter-lived sensors.

However, many WIM systems become inoperable not because of sensor failure, but because of the failure of pavement around them. This includes both when the pavement/sensor bond fails and when pavement deterioration such as rutting exposes the sensor to impact loads (e.g., snowplow blades) that cause catastrophic failure. A primary cause of premature pavement/sensor bond failure is poor initial installation quality. This includes such errors as poor mixing of adhesives, poorly cleaned or dried pavement cuts, incompatibility of sealants and pavement, and inappropriate temperature conditions.

Site condition and site design are key areas that successful programs examine as part of WIM site design and implementation. Where remaining pavement life is only modest, strong consideration should be given to rehabilitating the pavement prior to WIM sensor installation if an extended design life for the site is desired. Unfortunately, pavement rehabilitation is a costly addition to WIM installation. However, if a scale site is expected to have a long life, life-cycle costs are far lower if the pavement at the site is rehabilitated prior to initial sensor installation.

In many cases, highway agencies have found it to be a wise investment to build 300-foot concrete pavement sections into which WIM scales are placed. This gives agencies smooth, strong, maintainable platforms in which to place sensors. Strong concrete pavements generally do not change structural strength with changing temperatures and tend to deteriorate slowly. Thus, strong concrete pavements are generally considered to be good locations for scale sensors. A pavement with high-durability characteristics provides for a long design life and low maintenance costs for the scale system. (However, it is important to note that the pavement must be smooth as well as durable to be good for vehicle weighing.)

Not all WIM installations are intended to last many years. In many cases, an agency only wishes to collect data for a year or two at a location before moving the agency's scarce WIM resources to another location. In such a situation, the design

life of the system can be fairly short and pavement rehabilitation may not be warranted, so long as the pavement condition is adequate for collecting accurate weight data. In such cases, it may be unwarranted to construct a new 300-foot pavement slab for a WIM installation that is needed only to provide an accurate week-long sample during a particular commodity movement (for example, during a harvest season) and where the existing pavement is reasonably smooth.

5.4 BUDGET NECESSARY RESOURCES

Initial site and equipment costs are not the only budgetary requirements of truck volume and weight data collection. While a large portion of the data collection budget is associated with initial system purchase and installation, these funds are poorly spent if the other tasks associated with data collection are not also adequately funded. Staffing and other resources are needed to collect, review, and summarize the

data being collected. They are also needed for calibration, routine scale calibration verification, site maintenance, and site repair in order to obtain the maximum value from the funds spent on initial site implementation.

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

Similarly, the cost of poor data collection is most likely to be made apparent in costs incurred as a result of poor pavement design. (That is, poor design resulting from bad input data is ultimately more expensive than collecting the data needed to create a good design.)

Table 5.1 (based on vendor- and state-supplied data) provides general equipment costs. (Note that these costs will

TABLE 5.1 WIM equipment estimated initial and recurring costs[1]

Site Cost Considerations	Piezo	Piezo Quartz	Bending Plate	Deep Pit Load Cell
Initial Costs				
Pavement Rehabilitation[2]	??	??	??	??
Sensor Costs, Per Lane[3]	$2,500	$17,000	$10,000	$39,000
Roadside Electronics	7,500	8,500	8,000	8,000
Roadside Cabinet	3,500	3,500	3,500	3,500
Installation Costs/Lane				
Labor and Materials	6,500	12,000	13,500	20,800
Traffic Control	0.5 days	1 day	2 days	3+ days
Calibration	2,600	2,600	2,600	2,600
Annual Recurring Costs/Lane				
Site Maintenance	4,750	7,500	5,300	6,200
Recalibration	2,600	2,600	2,600	2,600

Notes:

1. These cost estimates have been developed based on a variety of published sources. However, costs vary over time and especially from vendor bid to vendor bid. Thus, actual costs can vary considerably from what is presented here.

2. Pavement rehabilitation costs are a function of current pavement condition, desired smoothness, desired site life, and desired WIM system accuracy. Consequently, they differ dramatically from site to site. At a given site, however, they will be similar for all technologies.

3. These costs can vary considerably based on the exact sensor configuration chosen for a given site, as well as the specific bid prices provided by vendors.

change from vendor to vendor and from site to site.) However, when budgeting for new sites, initial costs should also include any necessary pavement rehabilitation costs (although those costs are often paid out of other funding sources). Pavement rehabilitation to achieve necessary smoothness levels is not a function of the equipment technology selected. Accuracy degrades for all types of WIM equipment when they are placed in rough pavement. Other initial costs include vehicle presence and weight sensors, roadside electronics, roadside cabinets, and installation. Annual recurring costs include site maintenance, system maintenance, calibration, and performance evaluation.

Site design life and expected sensor life can be combined to predict the estimated initial cost per lane and the estimated average cost per lane over the selected site design life. For example, Table 5.2 provides an estimate of system performance, initial cost per lane, and average annual cost per lane (not including pavement rehabilitation costs). This comparison of performance and cost is based on the information initially provided in the *States' Successful Practices Weigh-in-Motion Handbook,* dated December 1997. The performance of the systems is given as a percent error on gross vehicle weight (GVW) at highway speed and is contingent on the site's meeting ASTM E 1318 standards. The estimated initial cost per lane includes the equipment and installation costs, calibration, and initial performance checks. It does not include the cost of traffic control. The estimated average cost per lane is based on a 12-year site design life and includes expected maintenance and the cost of periodic calibration and validation checks. The system maintenance is based on a service contract with the system provider.

A more detailed method (including a simple cost-calculation spreadsheet) that includes all the site cost considerations listed in Table 5.2 has been developed for LTPP. A brief discussion of the method was presented in Appendix 2 of the *States' Successful Practices Weigh-in-Motion Handbook.* The LTPP calculation allows inclusion of specified pavement rehabilitation and maintenance. The spreadsheet used by LTPP to compute WIM cost estimates is available through the LTPP web site at http://www.tfhrc.gov/pavement/ltpp/spstraffic/index.htm. While now several years old, the spreadsheet allows input of up-to-date cost components (including pavement rehabilitation costs), as well as the costs and characteristics of new WIM equipment.

5.5 DEVELOP, USE, AND MAINTAIN A QUALITY ASSURANCE PROGRAM

No matter how much money is budgeted and spent for the initial purchase and installation of a WIM site, all WIM equipment requires continual care and attention. Without ongoing attention to equipment performance and data collection site conditions, equipment performance will degrade over time. While vehicle classification equipment tends to be more robust (it is less sensitive to calibration drift), it requires periodic attention and continuous monitoring.

Consequently, another key practice is for highway agencies to implement and use a quality assurance program that monitors data being collected and reported.

It is poor practice to simply place equipment and hope that an autocalibration function will soon bring the system into calibration. While autocalibration has some important uses, all autocalibration functions have significant shortcomings. Each relies on the concept that some particular traffic value will remain constant over time, and that constant value can be used to tune the calibration of the data collection device.

TABLE 5.2   WIM system accuracy and cost comparison

WIM System	Performance (Percent Error on GVW at Highway Speed)	Estimated Initial Cost Per Lane (Equipment and Installation Only)[1]	Estimated Average Cost Per Lane Per Year[1] (12-Year Life Span[2] Including Maintenance)
Piezoelectric Sensor	± 10%	$22,600	$7,350
Bending-Plate Scale	± 5%	$37,600	$7,900
Piezoquartz Sensor	± 5%	$43,600	$10,100
Single Load Cell	± 3%	$73,900	$8,800

Notes:

1.   Pavement rehabilitation costs are not incorporated in this estimate or the average annual cost.

2.   Some of these systems are unlikely to reach a 12-year life span due to early sensor failure, failure of the pavement/sensor bond, or deterioration of the pavement condition itself.

(The most common value used is the mean front-axle weight of FHWA Class 9 trucks.) Unfortunately, these values often are not constant. Even more importantly, there often are site-specific variations in the values of these variables. Thus, unless the autocalibration function is first independently measured and tracked at a site, the equipment controlled entirely by an automatic self-calibration function will be miscalibrated, producing biases in the data collected.

Calibration problems identified by a quality assurance program may also not be solved through simple adjustment of the calibration factor for the scale. In many cases, calibration drift is a symptom of a larger problem (pavement deterioration, sensor degradation, etc.) that requires a site visit and equipment or site maintenance action.

Quality assurance programs are designed to review collected data and report unusual or unexpected results. In many ways, this is similar to how many autocalibration systems work. Where they differ is that quality assurance programs should not result in automatic changes to the data collection equipment or collected data. Instead, problems identified by the quality assurance process should result in an independent review of the operation of the equipment. Only after this independent check takes place should data and equipment be discarded or adjusted.

For permanently installed sensors, unusual data flagged by the quality assurance process normally means that a site visit should occur to check the performance of sensors and their connected electronics. Such a site visit should include a visual review of pavement and sensor condition and a short, manual classification count that can be compared with reported traffic counts. For WIM equipment, it is often necessary to validate the calibration setting for the site.

The following types of data checks are often used in the quality assurance process:

- Has the location of either the loaded or unloaded peak in the GVW distribution for the FHWA Class 9 trucks changed since calibrated data were last collected at this site? (See Figure 5.1.) Other vehicle classes that exhibit a common loading characteristic at the site in question can also be used in this data review.
- Has the mean front-axle weight for loaded FHWA Class 9 trucks changed since calibrated data were last collected at this site?
- Has the percentage of all weekday trucks that are classified as FHWA Class 9 changed significantly from previous counts at this site? Did percentages increase in classifications that indicate malfunctioning classification equipment (e.g., an increase in FHWA Class 8 would indicate a missed axle)?
- Did the number of unclassified vehicles increase to unexpected levels?
- Did the number of counting errors reported by the equipment increase to unexpected levels?
- Are the left and right wheel path sensors (for those scales with multiple sensors) reporting similar axle weights?
- Has the measured distance between axles for tractor drive tandem axles changed?
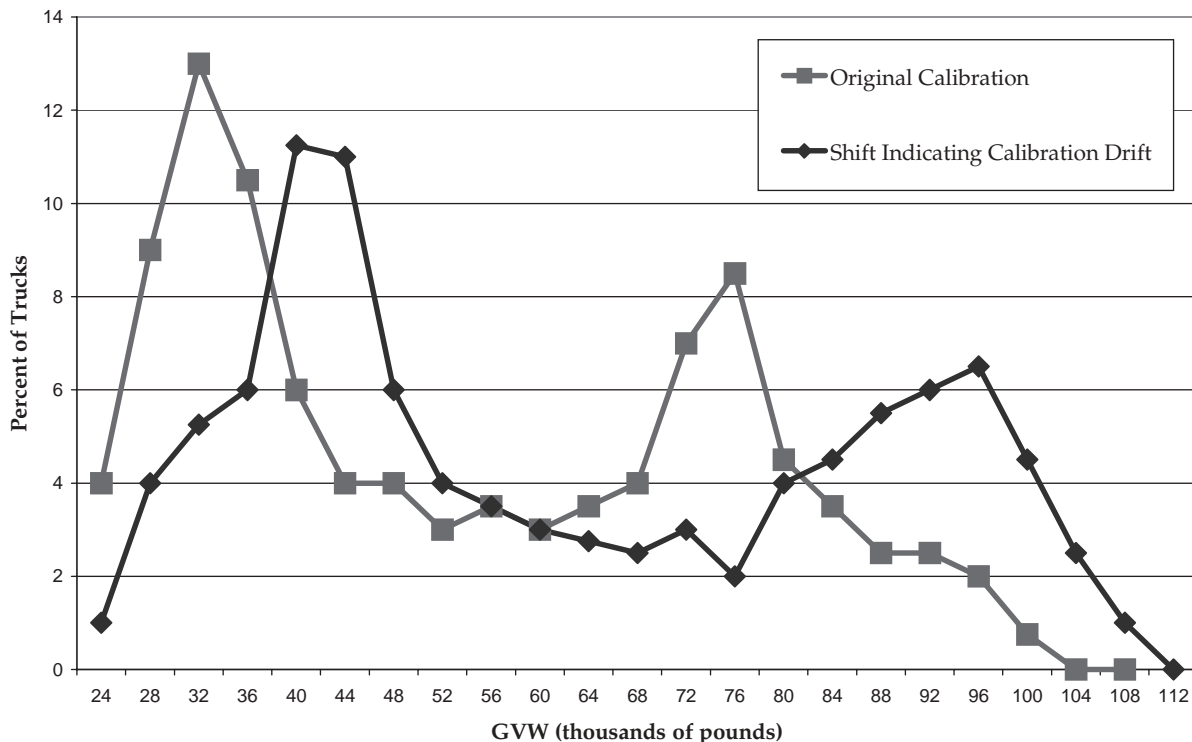

Figure 5.1.   Use of GVW of FHWA Class 9 trucks to detect scale calibration drift.

- Is the total number of vehicles counted within expected ranges? (Note that the range used should be fairly large because truck volumes in particular can vary significantly from day to day.)
- Are there any unusual time-of-day traffic patterns that would indicate the potential for some type of counter failure or inappropriate counter setting? (For example, does the volume at 1:00 a.m. exceed the volume present at 1:00 p.m.?)
- Are hours of data missing from the dataset?
- Have the scale's diagnostics reported any problems?

Most of these checks assume that a trusted dataset exists against which new data can be compared in order to determine the presence of unusual data. For permanent data collection sites, the best place to get these trusted datasets is immediately after the site is first installed and calibrated. The initial calibration effort should ensure that the site is working correctly, that the vehicles crossing the sensors are being correctly counted and classified, and that the weights are accurate. Data collected immediately after calibration should then serve as the initial trusted dataset.

If traffic patterns change over time (and the validity of these changes is independently confirmed), additional trusted data patterns can be developed, stored, and used as part of the quality assurance process.

For short-duration counts, it is important that data collection crews that set equipment confirm the equipment's proper operation at the outset before leaving the site and then reconfirm the equipment's proper operation prior to picking up the sensors at the end of the count. (That is, the crews should perform a consistent, routine check to ensure that the counter is correctly counting and classifying vehicles each time it is placed.) Office-based reviews can then compare the collected data against the short-duration counts made to confirm equipment operation, as well as against earlier (historical) counts made at that site or at nearby sites on that roadway.

In addition to these basic data checks, a number of additional routines are often provided by equipment vendors or developed by individual agencies. These should be reviewed, tested, and used whenever they offer cost-effective improvements to available procedures.

The key to any quality assurance program is that the routines available are tested and used. This requires resources and effort, but results in substantial improvement in the quality of data collected and supplied to users. Over time, quality assurance practices will help identify poor equipment and poor data collection practices, which can then be discarded or modified as appropriate. These practices also will help agencies improve their knowledge of traffic patterns in the state, which is a major benefit to an agency.

Wherever possible, quality assurance tests should be automated. However, the automated tests should primarily be limited to

- Creating easy-to-use data summaries,
- Flagging questionable data, and
- Removing poor data after their quality has been confirmed to be poor by qualified staff review.

Staff review of these summaries and the performance of independent reviews of irregular data collection results should still be done for all collected data. As noted earlier, traffic can vary considerably from location to location, and knowledge of site-specific traffic patterns and independent review of questionable data are keys to successful quality assurance programs.

5.6 PURCHASE EQUIPMENT WITH A WARRANTY

When purchasing equipment, it is good practice to obtain a warranty on the life of that equipment. The warranty should specify the expected life of the sensor given specific uses of that sensor. For example, a 5-year warranty on bending-plate weigh pads might be specified given a lane volume of less than 5,000 trucks per day.

Warranties provide agencies insurance against poor manufacturing quality control and also provide incentives to vendors and manufacturers to improve the quality of their equipment. Warranties are not free, but limit the cost of equipment replacement. For a vendor, the added revenue obtained in return for a warranty becomes profit, so long as the equipment performs as specified. However, if equipment fails prematurely, a significant loss to the vendor occurs. This approach provides a significant incentive to correctly predict the life span of sensors and other equipment.

Warranties of overall system performance have been successfully used by some states. These warranties extend protection beyond the sensor and accompanying electronics to the quality of the data produced by the data collection systems. These warranties are only effective when the highway agency can supply appropriate site conditions (e.g., smooth enough pavement) to make the warranty valid and when a mechanism to monitor compliance with the warranty is in place.

For example, with WIM equipment, it is likely that the equipment vendor subject to this type of warranty requirement will require the site to meet the site specifications defined in ASTM E 1318 specifications. While these conditions may be met immediately after sensor installation, it may be nearly impossible to meet these conditions after two additional years of pavement deterioration. Such difficulties can make performance warranties unenforceable.

This example points out that if a highway agency chooses to require data quality warranties from outside vendors, it is necessary to set up a quality assurance program that can be used both to detect equipment that needs repair and to determine when the site conditions no longer meet warranty specifications. The specifications developed for LTPP SPS

WIM data collection are a good first step toward this type of program.[3]

5.7 MANAGE EQUIPMENT INSTALLATION

Proper installation of sensors is key to both performance and life span, regardless of the technology involved.

To ensure the quality of any given installation, it is good practice to have at least one agency representative and one vendor representative oversee the sensor installation process at permanent sites. This ensures that both the state's and the vendor's requirements are met during the installation process. This is particularly important when warranties are used to ensure system performance, in that it ensures that both parties are satisfied with the initial site conditions and installation. (For WIM performance warranties, site conditions must usually match ASTM E 1318 site condition specifications. These site conditions should be verified by both parties when the site is first selected, well *prior* to the beginning of the installation process.)

Installation of sensors does not just involve placement. For permanently mounted sensors, installation also involves (among other items) placement of conduit for lead wires, placement and design of junction boxes, design and placement of cabinets that hold data collection electronics, and provision of environmental protection (lighting and electrical surge protection, moisture protection, temperature controls, defenses against insect and rodent infestation) for the entire system.

Poor installation of any features can lead to early system failure and significant increases in both sensor downtime and maintenance and repair costs.

Good practice for equipment installation includes choosing good equipment and sensor locations in the first place. For intrusive sensors, this means placing them in or on pavement that is in good condition and likely to last well past the design life of the sensors being installed. For both intrusive and non-intrusive sensors, it means understanding the environmental conditions that occur at a site and designing sensor installations so that sensors are protected as much as possible from environmental effects on system performance. (For example, video cameras need to be placed so that glare and other lighting problems are minimized and so that the cameras are protected from rain, snow, and spray generated by vehicles. Similarly, intrusive sensors need to be protected from moisture intrusion, with particular attention paid to in-pavement wiring when freeze-thaw conditions exist.)

A variety of techniques exist for protection of sensors from environmental conditions. Good management practice is to document those practices that are successful (for future use by new staff within the agency) and to share those successes with other agencies.

5.8 CALIBRATE AND MAINTAIN CALIBRATION OF EQUIPMENT

Installation of equipment should not be considered complete until that equipment has been calibrated and acceptance testing of the device in that location has been completed. Both WIM and vehicle classification devices require calibration, although WIM calibration is far more complex and difficult than vehicle classification.

5.8.1 Initial Calibration

A number of procedures for calibrating WIM scales exist. Appendix 5-A in the 2001 FHWA *Traffic Monitoring Guide*[4] provides a reasonably complete description of the current state-of-the-art in WIM system calibration. Some material from this appendix is reprinted below. In addition, ASTM[5] and the FHWA's Long Term Pavement Performance Project[6] have recommended the use of two test trucks of known weight but different vehicle characteristics (different classifications and/or suspension types) for performing WIM scale calibration.

The two-test-truck calibration technique consists of obtaining static weights for two distinctly different vehicles and then repeatedly driving those vehicles over the WIM scale. Scale calibration factors are then adjusted to minimize the mean error obtained when comparing static and dynamic weights. (Both the ASTM and LTPP documents provide step-by-step directions for calibrating scales using this technique.) Ideally, during the calibration effort, the two test trucks should be driven over the WIM scale at a variety of speeds and under varied pavement temperature conditions in order to ensure that the scale operates correctly under all expected operating conditions.

The use of two calibration vehicles is specifically designed to limit calibration biases that can be caused by the use of a single test vehicle. Biased calibration when using a single test truck comes from the fact that every truck has its own unique dynamic interaction with a given road profile given a specific load. Calibration of a scale to a single vehicle's dynamic performance (motion) is acceptable when the motion of that vehicle is representative of the traffic stream. Unfortunately, it is extremely difficult to determine if a given test truck is representative of the traffic stream, and consequently use of a single vehicle can cause a calibration bias that forces the scale to weigh most vehicles inaccurately.

The source of this calibration bias can be explained with two figures. Figure 5.2 illustrates how the force applied by a

[3] http://www.tfhrc.gov/pavement/ltpp/spstraffic/index.htm (active as of June 20, 2003).

[4] http://www.fhwa.dot.gov/ohim/tmguide/index.htm (active as of June 20, 2003).

[5] American Society of Testing Materials, *Annual Book of ASTM Standards 2000*, Section 4, Construction, Volume 04.03, Designation: E 1318-02—Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Method, ASTM.

[6] *Long Term Pavement Performance Program Protocol for Calibrating Traffic Data Collection Equipment*, April 1998 (with 5/10/98 revisions). http://www.tfhrc.gov/pavement/ltpp/pdf/trfcal.pdf (active as of June 20, 2003).

Greater force than
static weight

Bias caused
by measuring
this axle at
Point A

Axle force as the
truck moves down
the road

Actual force
(axle weight)
at Point A

Static

Weight

Lesser force than
static weight

Scale
Location

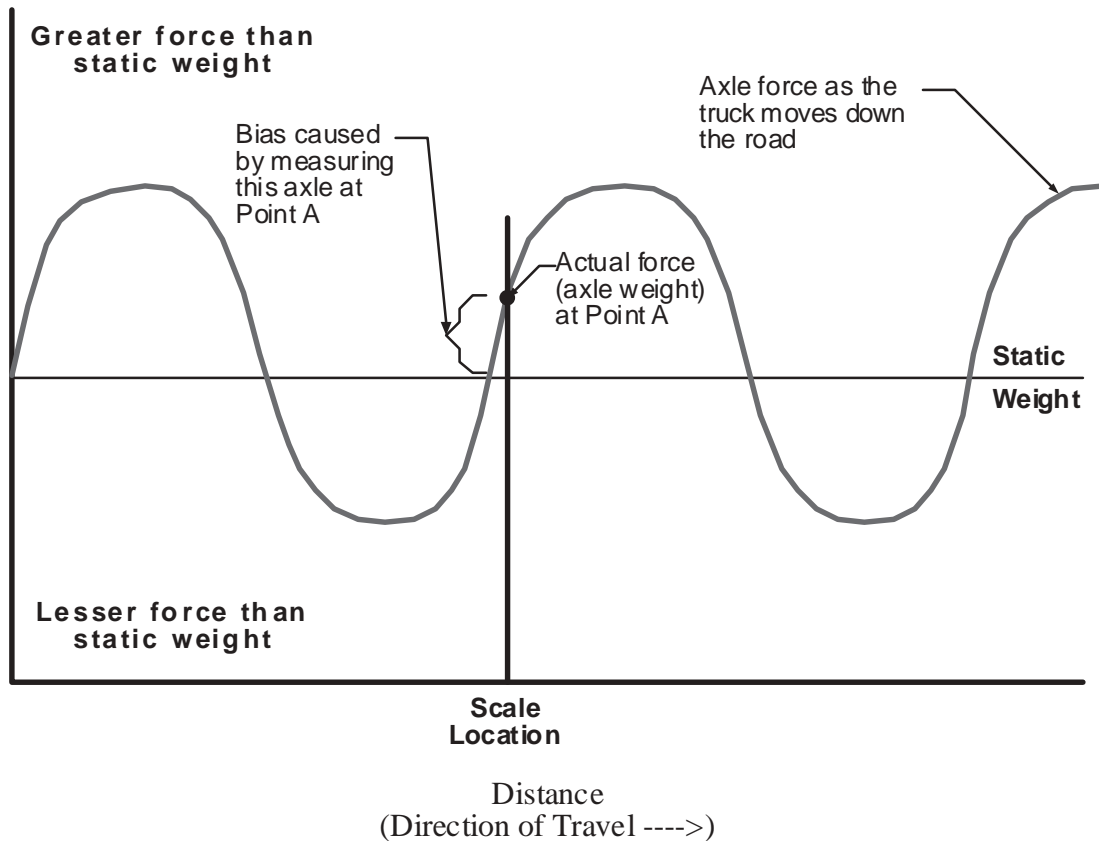Distance
(Direction of Travel ---->)

Figure 5.2.   Variation of axle forces with distance and the resulting effect on WIM scale calibration.

truck (or any given truck axle) varies as it moves down the road. This sinusoidal oscillation (bouncing) results from the interaction between the vehicle's suspension system(s) and the road's roughness. The vehicle's dynamic motion causes the weight felt by the road (or the scale sensor) to change from one pavement location to the next as the vehicle moves down the road. The goal of the WIM calibration effort is to measure this varying force at a specific location (Point A in Figure 5.2) and relate it to the truck's actual static weight. To do this, the scale sensor must be able to measure the weight actually being applied at Point A and also to correct for the bias resulting from the fact that, at Point A, the test truck is actually producing more force than it does when the truck is at rest (because it is in the process of landing as it bounces down the road).

By using a test truck, it is possible to directly relate the actual weight sensor measurement to the actual static weight in one simple calculation. If the test truck is driven over the WIM scale several times and the weights estimated by the scale are compared with the known static values, it is possible to determine whether the scale is operating consistently and, if it is, to calculate a statistically valid measure of the scale's ability to estimate that truck's axle and gross vehicle weights. The scale's sensitivity is adjusted (the "calibration factor") until the weights estimated by the scale equal the known static weights of the truck and its axles.

The problem with the single test truck technique occurs because each truck has a different dynamic motion. When the test truck has a different set of dynamics than other trucks using that road, the scale is calibrated to the wrong portion of the dynamic curve. In the example illustrated in Figure 5.3, if the scale is calibrated to the dynamic motion of the test truck, it will cause the scale to overestimate the weights associated with the majority of trucks on that road (Point B).

A change in a given vehicle's speed affects the force applied by that vehicle's axles at any given point in the road. This is because the oscillation of the suspension and load are primarily based on time, not distance. Thus, the load always lands at the same time after a bump in the road is crossed, but if the truck is going slowly, that landing is located closer to the bump than if the truck is moving quickly. Thus, on roads where truck dynamics are high (and the trucks are bouncing a lot), a change in average vehicle speed (e.g., caused by congestion or some other factor) can result in a shift in the appropriate calibration factor for a scale.

To solve the calibration problem caused by dynamic vehicles, five basic approaches have been proposed in the literature:

- A scale sensor can be used that physically measures the truck weight for a long enough period to be able to account for the truck's dynamic motion (this is true of
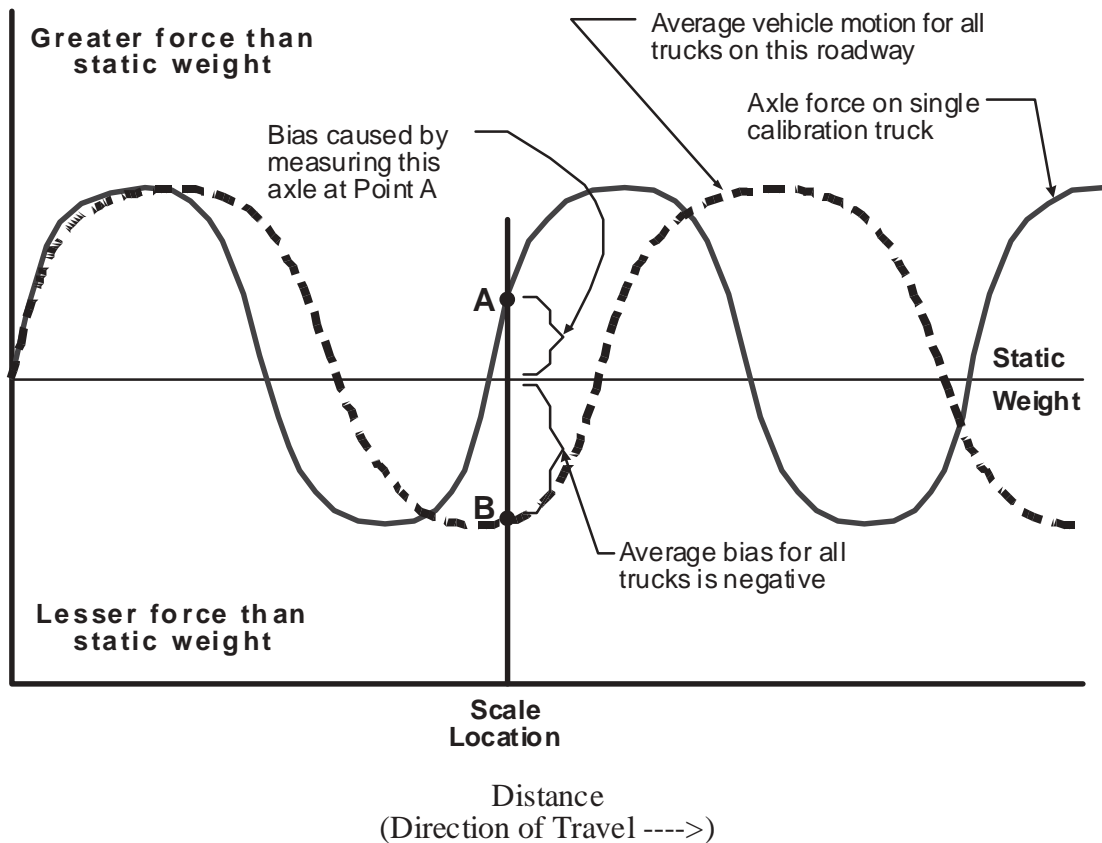
Greater force than static weight

Average vehicle motion for all trucks on this roadway

Axle force on single calibration truck

Bias caused by measuring this axle at Point A

A

B

Static Weight

Average bias for all trucks is negative

Lesser force than static weight

Scale Location

Distance
(Direction of Travel ---->)

Figure 5.3.   Variation of axle forces with distance and the resulting effect on WIM scale calibration.

the bridge WIM system approach where the truck is on the scale the entire time it is on the bridge deck).

- Multiple sensors can be used to weigh the truck at different points in its dynamic motion either to average out the dynamic motion or to provide enough data to predict the dynamic motion (so that the true mean can be estimated accurately).
- The relationship of the test truck to all other trucks can be determined. This is often done by mathematically modeling the dynamic motion of the truck being weighed in order to predict where in the dynamic cycle the truck is when it reaches the scale.
- More than one type of test truck can be used in the calibration effort (where each test truck has a different type of dynamic response) in order to get a sample of the vehicle dynamic effects at that point in the roadway.
- Independent measurements can be used to ensure that the data being collected are not biased as a result of the test truck being used.

As noted earlier, the current best practice relies on the use of multiple test vehicles (a minimum of two) for initial calibration of WIM scales. This technique was chosen over the other methods because of its simplicity and its relatively low costs compared with the other alternatives, though there is appreciable interest in the multi-sensor approach in Europe.

5.8.2 Maintaining Calibration

Once a scale is initially calibrated, best practices maintain calibration over time by a combination of periodic on-site calibration verification field tests and an ongoing review of the scale output against known quantities (e.g., have the locations of the loaded and unloaded peaks for Class 9 trucks moved since the scale was calibrated?). When changes are observed in the reported values for these known quantities, scale performance is investigated (i.e., the measured changes trigger one of the periodic field calibration tests) to determine if a change in vehicle characteristics is occurring or if changes in pavement profile or sensor sensitivity have affected the scale's calibration.

5.8.3 Autocalibration

While many WIM systems feature autocalibration functions, these are not an acceptable substitute for the initial site calibration, and, even when used for maintaining the calibration of a previously calibrated WIM, they should only be used with caution.

Many autocalibration techniques were originally designed to adjust scale calibration factors to account for known sensitivities in sensor performance to changing environmental

conditions. Others were software adjustments developed to take into account equipment limitations. Common techniques include

- Using the average front-axle weight of FHWA Class 9 trucks and
- Using the average weight of specific types of vehicles (often loaded five-axle tractor semi-trailers or passenger cars).

Although these techniques can have considerable value, they are only useful after the conditions they are monitoring at the study site have been confirmed. In fact, tests performed by LTPP[7] showed that autocalibration functions were not always successful at maintaining calibration of environmentally sensitive sensors when environmental conditions were changing rapidly. Autocalibration functions cannot be expected to calibrate a scale accurately if key autocalibration values have not been independently confirmed at that site.

Site-specific confirmation of autocalibration variables is important because research has shown that those key variables are not as constant as thought when autocalibration for WIM was first developed. For example, while the average front axle weight for Class 9 vehicles at most sites stays fairly constant (and can be measured accurately if a large enough sample is taken), the average front axle weight often varies significantly from site to site across the country or even within a state. Part of this variation is due to different weight laws and truck characteristics, part is due to different truck loading conditions at each site, and part is due to vehicle characteristics that are controlled by vehicle drivers.

Most drivers of modern tractors can change the location of the "king pin" (i.e., the point at which the semi-trailer connects to the tractor). Setting the king pin close to the cab pulls in the trailer, reducing air resistance and improving fuel efficiency. However, this setting also magnifies the roughness of the ride in the cab and increases driver discomfort. Setting the king pin farther away from the cab smoothes the ride in the cab but results in higher fuel consumption. When operating on rough roads, drivers tend to set the king pin farther back than when they operate on smooth roads.

If no other changes are made, simply moving the king pin setting from its foremost position to its rearmost position can shift as much as 2,000 pounds onto or away from the front axle of a fully loaded heavy truck. This is a change of 10 to 15 percent. By not accounting for these fairly common fleet changes at a specific WIM scale location, similar errors can be autocalibrated into the WIM system. In fact, LTPP has confirmed several cases in which autocalibration settings forced scales to adopt biased calibration factors simply because the autocalibration setting was incorrect for a particular site.

Autocalibration is not a bad idea. However, before it can be used even to maintain a scale's calibration, several factors must be understood:

- What autocalibration procedure the scale is using,
- Whether that procedure is based on assumptions that are true for a particular site,
- How that procedure complements the limitations in the axle sensor (and sensor installation) being used, and
- Whether enough vehicles being monitored as part of the autocalibration function are crossing the sensor during a given period to allow the calibration technique to function as intended.

The highway agency should also thoroughly test the actual performance of an autocalibration system before assuming that a vendor's claims about its accuracy are valid. Only after testing has been satisfactorily completed should a state routinely use autocalibration. Even then, autocalibration does not eliminate the need for a state to monitor scale output or periodically perform calibration verification tests in the field.

5.8.4 Calibration of Vehicle Classification Equipment

In theory, calibration of vehicle classification equipment is not as difficult as WIM system calibration. In reality, some specific installation problems can cause problems with classifier output. Compared with WIM equipment, axle-based vehicle classification equipment is generally less sensitive to minor variations in signal strength. However, some non-intrusive sensors can be very sensitive to input parameters and may require careful tuning of sensor performance to work correctly.

There are basically three issues related to the performance of classifiers that need to be reviewed as part of the installation calibration:

- Sensor configuration and layout information,
- Conversion of the outputs into estimates of each passing vehicle's characteristics (vehicle speed, vehicle length, and distance between axles), and
- The conversion of the vehicle characteristic information into estimates of that vehicle's classification.

Automated vehicle classifiers generally require input of information related to the specific layout of the sensors used. For axle classifiers, this generally means the distance between the two axle sensors (or two loops used for vehicle speed computation). For non-intrusive detectors, it may include measurements such as the height of the camera and angle of view or the distance of a sensor from the roadway.

These measurements are used as input to the sensor systems to convert the sensor outputs into the estimates of vehicle speed, length, and axle spacing, which are in turn used to

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[7] *SPS Traffic Site Evaluation—Pilots Summary and Lessons Learned*, May 2, 2002, http://www.tfhrc.gov/pavement/ltpp/reports/lessons/Lessons.pdf (active as of June 20, 2003).

compute vehicle classification. While these outputs are the key calibration measure, problems with the estimation of these values are often a function of poor measurement of the sensor layout. Adjustment of these parameters may be needed to make the classifier correctly report vehicle speed and consequently axle spacing or vehicle length. (Note that, depending on the classifier technology used, other device parameters may also require adjusting to produce correct device output.)

The accuracy of vehicle speeds should be determined by comparing device output against independent measures of vehicle speed collected using a calibrated radar gun or similar device. Vehicle length and axle spacing computations should be compared by comparing these outputs against independently collected axle spacing and vehicle length data.

Correctly classifying a vehicle requires more than an accurate measurement of vehicle speed and the distance between axles (or overall vehicle length). The conversion of these vehicle characteristics into an estimate of what vehicle type is represented by that set of attributes is the function of the classification algorithm used by the equipment. While many classification errors are caused by poor sensor input, many errors are simply the result of a classification algorithm that incorrectly associates a given set of vehicle characteristics with the wrong class of vehicle. With axle classification, this occurs in part because some vehicles from different classes have identical axle spacings. For example, FHWA Class 2 (cars) and FHWA Class 3 (light-duty pickups) have considerable axle-spacing overlap. Many small pickups have shorter axle spacings than larger cars. Thus, a considerable number of errors occur when classifiers try to differentiate between these two classes of vehicles. Recreational vehicles (especially those pulling trailers or other vehicles) are another class of vehicles that have axle spacings that frequently cause them to be misclassified, even when the classifier is working.

Errors associated with poor classification must therefore be separated into those due to poor sensor output and those related to the combination of a poor classification algorithm and/or vehicle characteristics that prevent a given set of sensor outputs (axle number and spacing or vehicle length) from correctly classifying a vehicle. Poor sensor output can be dealt with at the time of equipment installation, set up, and calibration. The other two problems must be dealt with through the rigorous design and testing of the classification algorithm used by the agency and through an extensive equipment acceptance-testing program that should be performed when a given brand or model of equipment is first selected for use. (That is, the agency needs to make sure the equipment will classify correctly if installed properly before purchasing large quantities of a given device. Only once the classifier has been shown to work as desired should the device be purchased in quantity. If, during the acceptance testing, a device appears to be working correctly but cannot classify specific types of vehicles, the agency should carefully examine the classification algorithm being used to determine if the algorithm itself needs to be fixed.)

5.8.5 A Final Word on Calibration and Equipment Installation

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

5.9 CONDUCT PREVENTIVE AND CORRECTIVE MAINTENANCE

Preventive maintenance keeps equipment operating. Perhaps more importantly, preventive maintenance helps keep data quality problems to a minimum by reducing the number of strange axle detections that occur during early phases of sensor and pavement failure.

Preventive maintenance includes tasks such as cleaning electronics cabinets, replacing parts that are showing wear but that have not yet failed, and even doing minor pavement repairs that are designed to improve pavement smoothness and life such as crack sealing on approaches to sensors.

Corrective maintenance is the process of bringing a sensor that is not performing properly back into correct operation. Corrective maintenance can include physical changes to sensors or pavement (e.g., sealing cracks in the pavement or repairing the bond between sensors and pavement), replacement of failing or failed electrical components, or simply adjustments to sensor calibrations used for computing speed, weights, or overall vehicle length.

Proper, timely maintenance increases sensor life, improves data quality, and decreases overall system life-cycle cost. States that have snow and ice conditions need to consider the added maintenance needed for traffic monitoring systems that may be affected by sand, snowplows, and corrosive anti-icing materials. Other specific types of environmental conditions, such as dust storms and lightning, are also renowned for frequently causing equipment problems that need to be addressed through timely preventive and corrective maintenance activities. Understanding when these types of environmental conditions are occurring and causing equipment or site damage, and timing site reviews to coincide with these conditions, will decrease the amount of data lost to these conditions and increase the quality of the data available from data collection devices.

Maintenance activity needs to be tied to data quality control systems. Data being collected often provide early warning signs that minor corrective maintenance is needed at a site. Quick intervention when data quality first becomes questionable both increases the amount of good data that are

collected and decreases the staff time spent examining questionable data.

If a site visit indicates that minor corrective action is unlikely to resolve problems, the data collection site can be shut down until more significant repairs can be performed. This dramatically reduces the effort wasted in retrieving and reviewing invalid data. Ongoing preventive maintenance also provides excellent input into the performance of different vendors' equipment and early warning of impending sensor failures. This information can be used both in the budget planning process and as part of sensor deployment planning efforts. For example, if it is known from maintenance activities that pavement at a given site has degraded, data collection staff can plan to move electronics to a new location, where pavement conditions are conducive to accurate data collection, until pavement maintenance activities upgrade conditions at the original site. This ensures the most productive use possible from the available data collection resources.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation