Technical Report Documentation Page

1. Report No.
FHWA/TX-06/0-4664-3

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
INVESTIGATION FOR TRAFFIC MONITORING EQUIPMENT EVALUATION FACILITY

5. Report Date
October 2005
Published: January 2007

6. Performing Organization Code

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8. Performing Organization Report No.
Report 0-4664-3

9. Performing Organization Name and Address
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
Project 0-4664

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Implementation Office
P. O. Box 5080
Austin, Texas 78763-5080

13. Type of Report and Period Covered
Technical Report:
September 2003-August 2005

14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Develop and Implement Traffic Monitoring Equipment Evaluation Facility
URL: http://tti.tamu.edu/documents/0-4664-3.pdf

16. Abstract
TxDOT’s Transportation Planning and Programming (TPP) Division routinely tests a wide variety of devices for counting axles or vehicles; measuring vehicle speed, headway, and gap; classifying vehicles by length and/or axle spacing; and weighing vehicles in-motion. However, TPP needs a traffic monitoring equipment evaluation facility to enhance its capabilities in conducting these tests, in facilitating training, and in allowing vendor comparisons and demonstrations. This project investigated funding sources, design options, and viable locations for this traffic monitoring equipment evaluation facility. The project provided research and development to design a generic facility to evaluate traffic data collection equipment and sensors and perform traffic data collection research. This report covers the entirety of this 2-year project, identifying potential funding sources and candidate sites for further consideration, developing site design aspects for the two most promising sites, and evaluating Kistler Lineas Quartz weigh-in-motion sensors. The most prominent funding sources are construction funds (include the site as part of a TxDOT construction project) and State Planning and Research (SPR) funds. The most promising sites identified thus far are on I-35 north of Georgetown near the Bell County line. Evaluation of the Kistler sensors in concrete was very promising, but future research should test them in asphalt.

17. Key Words
Weigh-in-Motion, Traffic Monitoring Equipment Evaluation Facility, Training Facility, Data Collection, Vehicle Detectors, Vehicle Counts, Vehicle Speeds, Vehicle Classification

18. Distribution Statement
No restrictions. This document is available to the public through NTIS:
National Technical Information Service
Springfield, Virginia 22161
http://www.ntis.gov

19. Security Classif.(of this report)
Unclassified

20. Security Classif.(of this page)
Unclassified

21. No. of Pages
138

22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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Report 0-4664-3
Project 0-4664
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DISCLAIMER

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ACKNOWLEDGMENTS

This project was conducted in cooperation with the Texas Department of Transportation and the Federal Highway Administration. The authors wish to gratefully acknowledge the contributions of several persons who made the successful completion of this research possible. This especially includes the program coordinator, Mr. Bill Knowles, and the project director, Mr. Jeff Reding. Special thanks are also extended to the following members of the Technical Advisory Committee: Ms. Catherine Wolff, Mr. Jim Neidigh, and Mr. Juan Paredez of the Texas Department of Transportation. Personnel from the Research and Technology Implementation Section who provided significant support of this project were Mr. Andrew Griffith, Ms. Dana Snokhaus, and Mr. Frank Espinosa. Finally, the Texas Transportation Institute members of the research team wish to acknowledge the valuable contributions of researchers from the Center for Transportation Research at the University of Texas at Austin, specifically Mr. Ron White, Professor Carl Haas, and Mr. Jongchul Song.

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CHAPTER 1.0 INTRODUCTION

1.1 PURPOSE

The purpose of the first phase of this project was to identify candidate sites and funding sources and to design a facility. The facility will provide a much needed test bed to research the performance of various types of traffic monitoring systems and sensors including off-the-shelf production systems and prototype units, conduct training, and perform traffic data collection research.

1.2 BACKGROUND

Statewide traffic data collection programs are the foundation for many uses of data within state Departments of Transportation (DOTs) and their external customers. State DOTs use these statewide data to report vehicle-miles traveled (VMT) and truck activity to the Federal Highway Administration (FHWA) for appropriations; design roadways for adequate geometric and pavement needs; and provide needed traffic information in those urban areas failing to meet National Ambient Air Quality Standards for their transportation/air quality modeling processes. It is important that a state DOT deploys traffic monitoring equipment that consistently returns accurate results and is also able to correlate the unique data differences during the time of collection between devices of different manufacturers.

From the perspective of the Texas Department of Transportation (TxDOT), the purchase of equipment to effectively collect the needed data occurs in a complex environment. Not only is there a large number of traffic monitoring systems and vendors to choose from, but also each piece of hardware from one vendor could be matched to traffic sensors from a completely different vendor. The resulting combination of these systems, whether due to incompatibility or other reasons, sometimes does not produce the desired result. This research, when implemented, will provide TxDOT with a tool to validate the operation of traffic data collection systems prior to committing large sums of money to the purchase of the equipment. The ultimate significance of this work is to save money for TxDOT by focusing resources on critical traffic data acquisition systems that satisfy the needs of TxDOT's traffic data collection program.

The Transportation Planning and Programming Division (TPP) could significantly improve its data collection given the necessary tools to properly evaluate existing and proposed data collection equipment. This project investigated funding sources, design options, and viable locations for a traffic monitoring equipment evaluation facility. The preferred location for this facility is near the Austin area where TPP has ready access to the site. However, if researchers cannot find the appropriate combination of location and funding, TPP could still utilize one of the existing test beds created by earlier research activities, one of which is in Austin and the other in College Station. A combination of new sites and existing test beds might also be viable.

1.3 OBJECTIVES

Overall project objectives were to:

- identify potential funding sources for a test facility,
- develop site selection criteria,
- utilize the selection criteria to identify the best site(s),
- develop plans and specifications to indicate pertinent site components,
- evaluate Lineas Quartz weigh-in-motion (WIM) sensors,
- establish pavement structural support criteria, and
- evaluate piezoelectric sensor failure modes.

1.4 ORGANIZATION OF THE REPORT

This research report consists of five chapters organized by topic. Chapter 2 provides an overview of test sites installed in other states. Chapter 3 presents findings related to funding sources. Chapter 4 provides a discussion of site selection criteria and the weights of each criterion. Chapter 5 is a discussion of the most promising candidate sites and the one recommended for TPP use. Chapter 6 is an evaluation of Kistler Quartz weigh-in-motion sensors based on the experience of other states and field studies in Texas. Chapter 7 provides information gathered from experts pertaining to pavement structural information for successful installation of sensors.

CHAPTER 2.0 EXISTING TEST FACILITIES

2.1 INTRODUCTION

The text that follows reflects the information gathered by the research team from literature sources and from jurisdictions that have installed devices that TPP uses. The information is organized by literature findings first, followed by input from states. Most of the individual findings pertain to one of a limited number of aspects of a TPP-like test site. For example, there are recent references pertaining to installation and maintenance of weigh-in-motion systems and other recent references that discuss installation of non-intrusive sensor test sites. Not all the agencies contacted or the literature findings produced useful results.

2.2 LITERATURE SEARCH

Of the equipment that TPP will evaluate at the test site, WIM equipment is the most challenging due to the various requirements to achieve optimum performance. For that reason, the literature search resulted in information mostly on the installation of WIM systems.

2.2.1 General Criteria for WIM Installation

A quote cited by McCall and Vodrazka underscores the importance of site selection for WIM: “The quality of the WIM data is dependent on the quality of the site selected” *(1)*. Designers should select the site for a WIM system based upon meeting the required “site design life” and accuracy necessary to support user needs. The roadway pavement condition is important in minimizing vehicle bounce near the WIM sensors. According to Deakin, “Vehicle bounce, resulting in variations in the vertical load imposed by a moving axle, increases with road roughness, leading to greater variations in the instantaneous axle loads” *(2)*. The American Society for Testing and Materials (ASTM) standard *(3)* specifies the use of a 20-ft straightedge to establish pavement smoothness before and after the WIM system.

A candidate site for WIM data collection should possess several characteristics to collect good data. These characteristics pertain to grade, curvature, cross-slope, width, speed, and visibility. The pavement grade at the WIM site should be level, to the extent possible, and more specifically, the longitudinal gradient of the road surface 200 ft in advance and 100 ft beyond the WIM sensors should not exceed 2 percent for permanent or site-specific WIM installations. No rutting should be evident in the roadway surface. The horizontal curvature of the roadway lane 200 ft in advance of and 100 ft beyond the WIM sensors shall have a radius not less than 5700 ft measured from the centerline of the lane for the WIM system. The cross-slope of the road surface shall not exceed 3 percent. The width of the paved roadway lane for 200 ft in advance of and 100 ft beyond the WIM sensors shall be between 12 and 14 ft. The roadway lane should be designated with a uniform speed limit. No exits or onramps should be near the WIM site. The requirement for constant vehicle speed is primarily due to the fact that braking and acceleration causes shifts in load from one set of axles to another. This speed requirement has limited the use of WIM equipment in many urban and suburban areas where routine congestion occurs. Finally, operators of the WIM system should have an unobstructed view across the entire roadway *(4)*.

Other needs of WIM sites pertain to the infrastructure. The needs can be categorized as surface smoothness, pavement structure, power source, data communication, and system calibration. The surface of the paved roadway 200 ft in advance of and 100 ft beyond the WIM sensors shall be smooth before sensor installation and maintained in a condition so that a 6-inch diameter circular plate 0.0125 inch thick cannot be passed beneath a 20-ft long straightedge. Smooth, flat pavements that reduce vehicle dynamics significantly improve WIM accuracy *(3)*.

Decreases in pavement strength invariably decrease system accuracy. To accommodate WIM sensors, the responsible agency must provide and maintain adequate pavement structure and surface smoothness throughout the service life of the system. These agencies should also install and maintain the sensors in accordance with the recommendations of the system vendor. A Portland cement concrete (PCC) pavement structure generally retains its surface smoothness over a longer period of time than a flexible pavement structure under heavy traffic conditions at a WIM site. Installations in pavements likely to rut are a poor investment of limited state data collection funds. Permanent WIM sites on highways and principal arterial highways should have a 300-ft long continuously reinforced concrete pavement or a jointed concrete pavement with transverse joints spaced at 20 ft or less. Installers should grind the surface of the roadway smooth after curing and before installing the WIM sensors. The installing agency should also ensure that the skid resistance of the roadway surface after grinding is as good as the adjacent surfaces *(4)*.

An adequate power source must be provided and maintained. The power required would be 230V 150 amp service for the project if a building is involved. If there is no building, the minimum service required is typically 15 to 20 amps per cabinet, depending on the expected power consumption of the equipment. There must also be an adequate data communication link between the WIM site and the remote host computer where data can be transmitted and processed. The availability of power and communications allows for extended operation of the WIM system.

WIM equipment requires a significant calibration effort each time the equipment is placed on a site. Without calibration the static weight estimates from the scale can be very inaccurate, even if the scale accurately reports the vertical forces applied to its surface. Because pavement conditions change over time, and because those changes affect WIM performance, the responsible agency must periodically calibrate even permanently installed WIM sensors. It should check the WIM system calibration annually, and more often if possible *(4)*.

2.3 STATE CONTACTS

2.3.1 California Department of Transportation (Caltrans)

Caltrans has three test sites that offer opportunities for testing detectors, but they are primarily for testing non-intrusive detectors. They are: 1) the University of California at Irvine (UCI) facility on I-405 northbound, 2) a site on a two-lane freeway connector at Highway 5 northbound to Highway 80 north of Sacramento, and 3) a test facility in District 7 (Los Angeles). One conclusion that the Caltrans representative admitted was that finding a suitable site for this type of testing is very difficult.

2.3.1.1 Caltrans WIM Installation Procedures

Quinley documented methods and procedures that have been developed by the California Department of Transportation for the planning, design, and installation of weigh-in-motion systems *(5)*. Caltrans began installing permanent WIM systems for its high-speed data collection master plan in 1987. As of February 1996, Caltrans had installed 63 WIM bending plate systems for high-speed data collection and eight WIM bending plate systems for high-speed weigh station bypass screening. Some of the points Quinley covered are pertinent to identifying and installing a test center for TxDOT. Most of the Caltrans systems are main line, high-speed, single-threshold bending plate systems, and the emphasis of Quinley's paper was on these same systems. Even so, much of his discussion applies to piezoelectric or other systems.

Caltrans attempts to minimize conflict with traffic, so there is always an attempt to re-open lanes as quickly as possible. The Caltrans system designs and installation techniques reflect this requirement.

Power and communication are two very important first considerations. Caltrans has not installed any solar-powered WIM systems; all sites require standard 110V alternating current (AC) power. Three of the Caltrans systems utilize cellular phone service (9600 bps). Caltrans attempts to locate sites that can reasonably be served by AC power and land line telephone utilities *(5)*.

Caltrans guidance on the location of the controller cabinet is as follows. They should:

- not be subject to being hit by errant vehicles,
- be easily and safely accessible and have adjacent vehicular parking,
- be in full view of the roadway near the WIM sensors,
- not be subject to flooding during heavy rains or be too near irrigation systems, and
- not require long conduit runs for the required sensors.

Bending plate systems must have adequate drainage of water from under the plates. Ideally, the lanes to be instrumented should all slope to the outside in a roadbed on an embankment to easily remove outflow. Crown section roadbeds need drains on both sides of the roadway. Installers should not consider bending plate systems in roadways in flat or cut sections unless they can tie the WIM drain pipes into existing drainage facilities or the soil conditions make a “sump” or a “French drain” feasible.

Traffic conditions are another critical consideration. The best WIM performance occurs when all traffic is traveling at a constant speed and vehicles are staying near the center of each lane. Tangent sections of roadway with little or no grade in rural areas normally best meet this condition unless there are only two lanes and passing is significant. Conditions to avoid include:

stop-and-go traffic, slow-moving traffic, lane changing, and passing. Vehicles stopping over the sensors result in useless data. The problem with slow-moving traffic is that WIM systems cannot compensate for accelerations or decelerations, compromising accuracy. Lane changing can result in partially or totally missing one or more sensors. Passing on two-lane roadways can result in crossing the loops in reverse order. Neither the bending plate WIM system nor the hydraulic load cell marketed by International Road Dynamics (IRD) correctly classifies these vehicles. For roadways with two or more lanes in each direction, passing is only a problem if passing vehicles are changing lanes over the WIM system *(5)*.

Roadway geometry is also critical for optimized WIM performance. Installers should only consider tangent (straight) sections of roadway. Lane width is a consideration in that weigh pads in a side-by-side configuration must be able to fit the available pavement width. Being too close to interchanges and intersections may increase lane changing and speed change and may be a factor in controlling traffic during setup or maintenance operations.

Grade is an important determinant in the accuracy of WIM. Anything in excess of 1 percent grade results in weight transfer between the steer axle and the drive axle of loaded trucks. Weight transfer can easily exceed 1500 lb, with resultant errors in the WIM's reporting of axle and axle group weights. The higher recording of weight for the drive axle will often result in a weight violation for the drive axle group. Other problems that may occur as a result of grades involve initial calibration and calibration monitoring. The grade may decrease the number of faster moving trucks, and adequate calibration requires the entire range of speeds. For Caltrans, which uses a software program to track truck weights by speed distribution, a larger speed range makes the weight/speed analysis much more difficult. Finally, grades that result in slow-moving trucks will result in increased passing within the WIM system by faster vehicles *(5)*.

The pavement profile and condition are critically important for WIM accuracy. The goal of the installation process is to minimize the dynamic effects induced by pavement roughness and profile. Caltrans avoids areas where major roadway reconstruction would be required to achieve the desired WIM performance. However, Caltrans considers pavement resurfacing and/or grinding appropriate items of a WIM installation contract. Caltrans recommends that a potential WIM site have a minimum 1000 ft of approach roadway with even profile. Pavement should be stable, considering that roadways settle around bridge and drainage structures.

If the roadway profile and overall pavement condition are acceptable, designers should next evaluate the pavement in the immediate vicinity of the WIM system. Caltrans criteria require that the pavement be absolutely smooth for 150 ft in advance and 75 ft beyond the bending plates. The pavement type is important to Caltrans as well; it only uses Portland cement concrete. Caltrans considers roadway improvements in terms of a "strategic importance" scale. For sites with high truck volumes on the upper end of this scale, the pavement should be improved to the highest quality that is affordable in terms of cost. Lower volume sites would justify less pavement improvement.

Pavement preparation criteria used by Caltrans are as follows *(5)*:

- For existing PCC pavement:

    - If in excellent condition (stable and smooth), grind 150 ft in advance of and 75 ft beyond the bending plates.

    - If in less than excellent condition, replace existing pavement with seven sack concrete as follows:

        - Remove existing PCC pavement and first level base, but no less than 12 inches in depth. Replace a minimum 50 ft preceding and 25 ft beyond the bending plates; longer replacement is based upon the condition of the existing pavement and importance of the truck weight data. Caltrans' longest replacement to date is 200 ft.

        - Grind existing and new PCC pavement, starting 100 ft upstream of the new pavement and ending 50 ft beyond the new pavement.

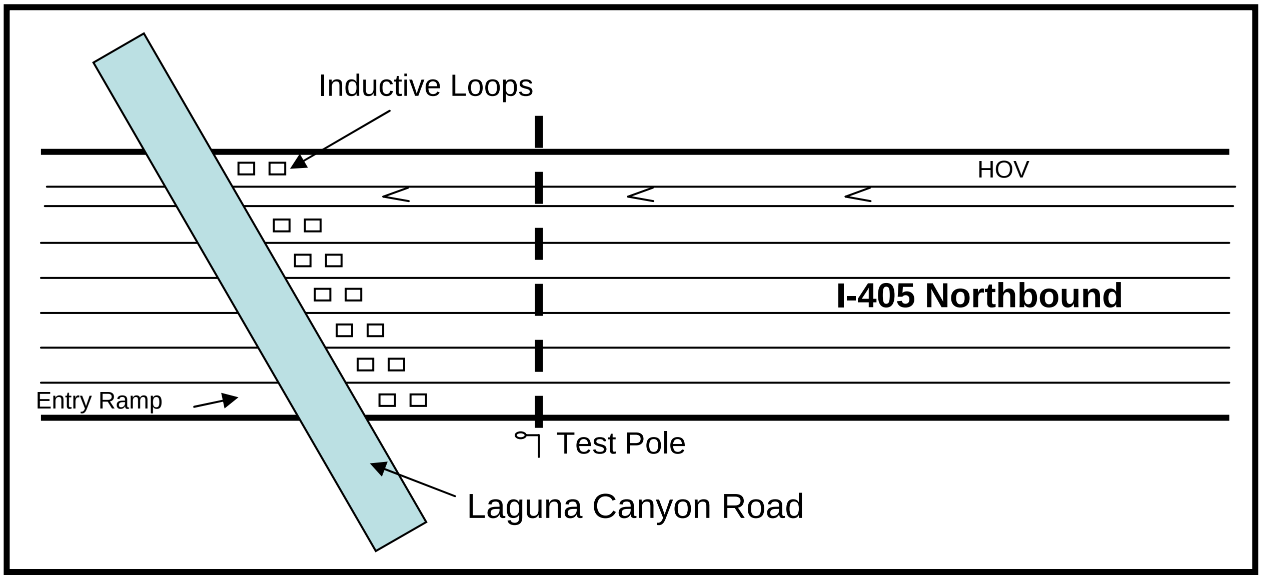
- For existing asphalt cement concrete (ACC) pavement, replace existing pavement with seven sack concrete as described above for PCC pavement replacement. Grind existing ACC pavement and new PCC pavement beginning 25 ft upstream of new pavement and ending 25 ft downstream of new pavement.

The Caltrans document recommends that, when reviewing a potential WIM site, the reviewer observe the traffic flow at various times of the day, watching for undesirable traffic conditions. The observer should carefully watch trucks passing through the site to determine if they are traveling at a fairly constant speed and that they are not bouncing due to pavement roughness or profile. The document also recommends contacting traffic engineers and maintenance personnel who are familiar with the traffic characteristics at the site for their knowledge and observations. It is also very important to confirm that there are no plans to widen or reconstruct the roadway soon after the WIM system installation *(5)*.

2.3.1.2 The UCI Test Facility on I-405

Testing of two non-intrusive detectors by the Detector Evaluation and Testing Team (DETT) of the California Department of Transportation *(6)* reveals some "do's" and "don'ts" of detector installation. Even though the TPP site will not primarily test non-intrusive sensors, the findings of this report will be helpful for both intrusive and non-intrusive detector testing and installation.

The Caltrans facility on I-405 near the University of California at Irvine has seven lanes northbound that serve the needs of a test site. Traffic volume at this site is about 3 million vehicles per week. Some testing at this site involved the Wavetronix radar sensor and the Remote Traffic Microwave Sensor (RTMS), as well as the Inductive Signature Technologies (IST) product that has the capability of tracking vehicles using inductive loop signatures. With successful re-identification of vehicles, UCI is determining the feasibility of determining travel times using link travel speeds. The UCI tests used facilities at Sand Canyon and Laguna Canyon for re-identification of vehicles. Figure 1 indicates the layout of the Laguna site, showing that the inductive loops in each lane fit the angle of the bridge. Caltrans installed the loops in this fashion so they are located immediately under a video camera mounted to the bridge and centered over that lane for verification purposes. This factor caused difficulties in testing of the radar products because the sidefire radar needs to be oriented at a 90-degree angle with the direction of passing vehicles. Loops farther from the test pole are increasingly separated from the detection zone of the non-intrusive detectors. This separation, and the fact that vehicles in each lane had different time stamps, created challenges for researchers in comparing test device counts with baseline counts. The complex site layout made it very difficult to collect accurate 30-second data. The unique processing by different detector technologies also caused a difference in the timing of detection of large trucks. These problems were not evident at longer time intervals of five minutes or longer. The lesson learned is keep the test device's detection zone and the baseline system very close to each other and separated by an equal distance across all lanes.



Source: Reference (6).

Figure 1. UCI Test Site in Irvine, California.

Due to the problems with tests of the radar detectors at the initial site, Caltrans moved from the UCI site on I-405 to another site to facilitate better measurement of the typical parameters of volume, speed, and occupancy. The new site was not a full-blown test site and still required much frame-by-frame manual analysis to accomplish the necessary evaluation. Results indicate that the ground truth inductive loops at this site overcount by 1.0 to 1.5 percent. This is due at least in part to lane changers who cross sensors in two adjacent lanes. The Wavetronix undercounted by as little as 1 percent to as high as 4 or 5 percent due to occlusion in the center lane and other lanes farther from the detector. At the closest lane to the detector, the Wavetronix detection zone is relatively short (as measured along the vehicle paths), so it missed some vehicles. Overall count accuracy was almost always within 95 percent of true counts and within 98 percent on some lanes. Speeds were also within 95 percent.

One difference between the Wavetronix and the RTMS X3 detectors was the difficulty of setup and calibration. The Wavetronix only required 15 to 20 minutes total to set up, whereas the factory representative took about one hour per lane for the RTMS. One of the complaints of Caltrans personnel regarding both of these systems is there is no verification of accuracy from remote locations during data collection compared to video imaging, which provides an image.[1]

More specifically on the subject of weigh-in-motion, Caltrans has installed some piezoelectric sensors in the past for WIM, but it was not pleased with the results; it now uses either bending plate or load cell WIM systems. Most of the problems have not been associated with the pavement itself but with the subgrade below the pavement. Some of the WIM systems are in PCC pavement as thick as 15 inches, but piezoelectric sensors are only in ACC pavements. The Caltrans spokesperson was not aware of any states with WIM or automatic vehicle classification (AVC) test sites. Caltrans is realizing a significant need for testing new devices because the agency has installed over 400 new units (all or mostly RTMS) statewide with little evaluation of detector accuracy.

Another lesson learned at the UCI site was to minimize the number of lane changers in the vicinity of the detection zones. Detection of lane-changing vehicles may occur in two lanes by some systems and in only one by another system. The ground truth loop system is likely to detect the same vehicle twice if it straddles the loops. A simple solution is to locate the site away from interchange ramps. At the UCI site, detection occurred where the on-ramp merged into the mainline such that only part of a car might be present over a loop or a truck could occupy loops in two lanes. Yet another consideration is to place cameras to minimize occlusion of vehicles in far lanes by vehicles (especially trucks) in near lanes. This requirement means planning for mounting of cameras well in advance of their actual installation.

2.3.2 Florida Department of Transportation (FDOT)

The Florida Department of Transportation has a WIM test site in ACC pavement on I-10 near the Suwannee River about 65 miles east of Tallahassee.[2] FDOT was unable to provide detailed plans for the site because no formal plans were available. FDOT used a contractor who had successfully installed all the components before at other locations, reducing the need for such plans. FDOT used a task ordering agreement and simply listed the number of devices by type to be installed. FDOT provided digital photos of the site showing the cabinet and the Kistler sensors installed there. The photos (see Figures 2 and 3) show two complete sets of Kistler quartz sensors in the right lane. The FDOT photos do not show the Measurement Specialties, Incorporated (MSI) “BL” sensors located about 100 ft from the Kistlers. Each Kistler system has the sensors staggered, with the first (as encountered by passing vehicles) in the right wheel path and the second in the left wheel path, with a square inductive loop (6 ft by 6 ft) located between the two sensor sets. There appears to be about 2 ft of separation between the sensors and the inductive loop. The site also has power and phone connections.

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[1] Phone Conversation with Mr. Bill Wald, California Department of Transportation, date: October 21, 2003.

[2] Phone Conversation with Mr. Richard Reel, Florida Department of Transportation, date: October 17, 2003.

Source: Florida Department of Transportation.

Figure 2. Kistler Sensor Layout before Installation.

Source: Florida Department of Transportation.

Figure 3. Kistler Sensor Saw Cuts during Installation.

The original intent was to test these two types of sensors along with the Peek ADR and PAT DAW 100 WIM electronics. The two sets of sensors (including the necessary inductive loops for presence detection) are about 100 ft apart. FDOT chose this site due to a weight enforcement site about 5 miles upstream (to the west of the site). Trucks exit the truck enforcement site and then encounter the WIM sensors. FDOT used static weight data from over 100 Class 9 trucks to calibrate the systems installed at the test site.[3]

At the time of this phone call, FDOT had only monitored the Kistler sensors for about four or five months, but at that time the Kistlers appeared to have accuracy comparable to bending plate systems. The initial cost was also comparable, but FDOT hopes the long-term maintenance of the Kistler system will be less. Florida DOT has significant problems with pavement rutting in ACC pavements, so it expects that the Kistler sensors will require maintenance to address the rutting issue. The real question in everyone's mind seems to be how long the sensors last, especially in asphalt. The FDOT spokesman indicated that bending plate systems need to go in concrete (either an existing concrete pavement or a concrete pad built specifically for the WIM), but he already has WIM systems in all the available concrete. From all indications, FDOT pavements personnel will probably not build any more concrete pavement, and there seems to be reluctance to even build concrete pads for WIM systems. The I-10 test site will not have a bending plate WIM since the pavement is asphalt.[3]

FDOT does not plan to use any more standard piezo sensors for WIM because the results indicate more than the desired amount of scatter. The FDOT spokesman gave the following recommendations:

- If a DOT uses piezoelectric sensors, they should be quartz.
- If a DOT is planning on installing WIM in a good pavement, choose bending plate.
- If a DOT cannot allocate sufficient resources to maintain the system, do not even install the WIM in the first place.

2.3.3 Illinois Department of Transportation (IDOT)

The Illinois Department of Transportation has a "test site" on I-55, but the agency has only used the site once – for an IRD system a few years ago. There are no as-built drawings or plans of the site. IDOT has a total of 14 Long-Term Pavement Performance (LTPP) WIM sites that use nothing but piezoelectric sensors. IDOT plans to install one bending plate WIM system in 2004 to complete its LTPP installations.[4]

An interesting feature of the IDOT data collection plan is its use of a length-based classification scheme for short-term 24- and 48-hour counts. IDOT does more actual vehicle counts (as opposed to estimates) than other states do, and that is probably why FHWA allowed Illinois to use lengths of vehicles rather than the standard FHWA Scheme F for its short-term

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[3] Ibid.

[4] Phone Conversation with Mr. Rob Robinson, Illinois Department of Transportation, date: December 10, 2003.

counts. In the 1990s, the Illinois count results were erratic because of the small samples, so the state increased the number of classification counts being done every year. Today, Illinois conducts about 5000 actual counts each year on its 13,000-mile road network, which is probably a higher percentage of its total network than other states. Illinois chose Nu-metric Hi-Star devices with five length bins (four without motorcycles) for classification. IDOT uses the Hi-Star devices instead of road tubes everywhere except the Chicago area.[5]

2.3.4 Minnesota Department of Transportation (MnDOT)

2.3.4.1 Non-Intrusive Detector Test Site on I-394

The Minnesota Department of Transportation installed an equipment test facility for testing non-intrusive detectors on I-394 at Penn Avenue near downtown Minneapolis. Phase I of the MnDOT Non-Intrusive Tests (NIT) was a two-year field test of non-intrusive traffic detection technologies that ended in May 1997; Phase II concluded in August of 2002 *(7, 8, 9)*. Figure 4 shows the site used in both research phases and the surrounding road network; Figure 5 shows a zoomed-in plan view of the site.

MnDOT installed a catwalk on the Penn Avenue Bridge for Phase II of this project to provide access to devices installed overhead. The test plan called for installing overhead sensors on three adjustable mounting poles attached to the catwalk, one over each lane of I-394 traffic, at varying heights ranging from 20 to 30 ft above the pavement and facing eastbound (departing traffic). MnDOT also installed an aluminum adjustable tower for testing sidefire-installed sensors. Field personnel can adjust the crank-up tower to accommodate mounting heights ranging from 10 to 45 ft and can move the tower among three bases with offsets of 15 ft, 25 ft, and 35 ft from the curb edge of I-394. Preinstalled concrete pads allowed the retractable tower to be moved as required. The retractable pivots at the tower base provided access to the tower top for sensor installation. Inductive loops on I-394 provided baseline data. Figure 6 illustrates the catwalk on the bridge, and Figure 7 shows the aluminum tower mounted on one of the three bases *(9)*.

Site amenities also included a 14-ft by 26-ft permanent building (as shown in Figure 8) and security fencing. Equipment installed in the building includes computers for running vendor-specific programs, computers for data storage and archive, and equipment components needed to interface with detectors.

The NIT site offered a range of traffic conditions, to include congestion in both the morning and afternoon peak periods and lower volumes with free-flow conditions in the evenings and on weekends. The site also offered a variety of lighting conditions, depending on the time of year. Low-angle sunlight created long shadows in the winter and bridge shadows year-round *(9)*.

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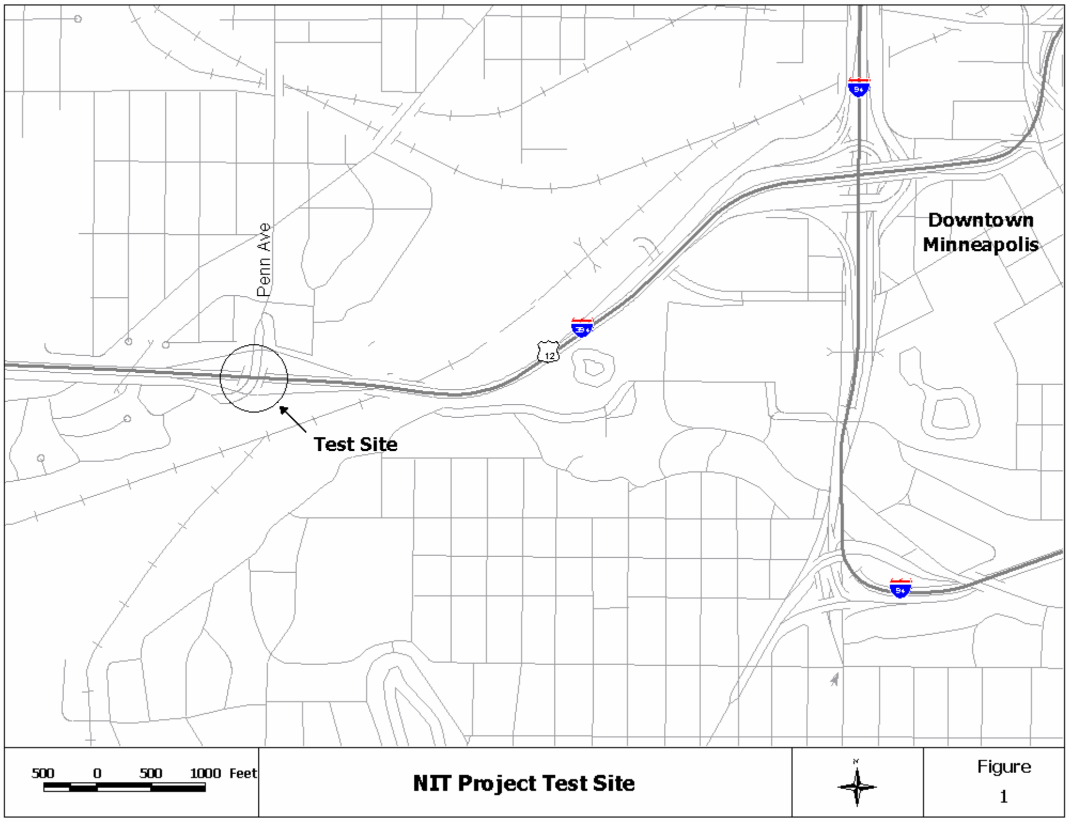
[5] Ibid.



Source: Reference (9):

Figure 4. MnDOT Test Site Location.

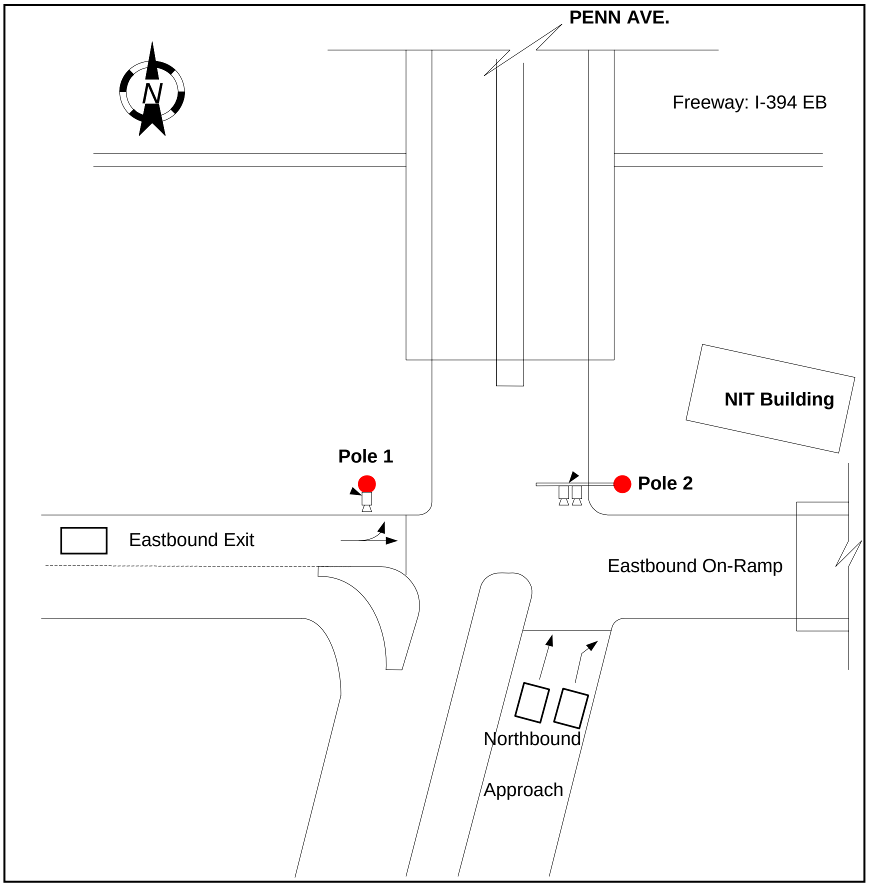
MnDOT's consultant, SRF Consulting Group, Inc., used the following data acquisition hardware inside the building for monitoring the test systems:

- Personal computers: used for sensor calibration, data download, data storage, and process through the interface software of different detectors.
- Television monitors: used for traffic monitoring and video detector calibration.
- Three videocassette recorders (VCRs): used for recording the traffic images during the official data collection for future data references.
- Equipment rack: used to hold data acquisition components such as television (TV), VCRs, AC power supplies, loop detector cards, vendor detector cards/processors, and the automatic data recorder.
- Peek ADR 3000: used to collect all of the loop emulation relay outputs into a single database. It allowed for the collection of all data outputs simultaneously. The ADR was programmed to collect the data from devices and baseline loops in 15-minute intervals for each 24-hour data collection period. Some data output was in the form of a simple

relay contact closure, whereas other data required a serial communication link to a personal computer housed at the shelter.

- A terminal panel: used for power supply and communication between the shelter and testing sensors installed on the overhead catwalk or sidefire tower. Installers numbered terminal ends on the panel that matched with the numbers of the corresponding ends in the junction boxes on the catwalk and sidefire tower.

Figure 9 shows the shelter schematic layout *(9)*.



Source: Reference (9).

Figure 5. MnDOT NIT Site Layout.

Source: Reference (9).

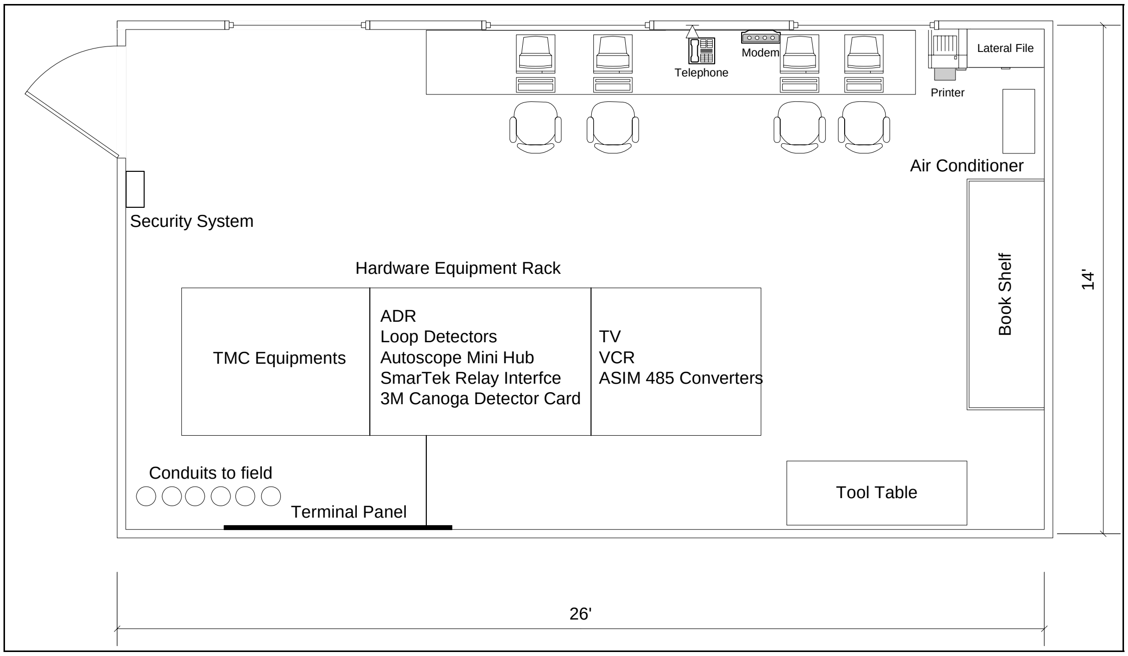
Figure 6. Catwalk for Mounting Detectors Overhead.

Source: Reference (9).

Figure 7. Aluminum Tower for Sidefire Mounting.

Source: Reference (9).

Figure 8. View of NIT Building from the Catwalk.



Source: Reference (9).

Figure 9. Shelter Schematic Layout.

2.3.4.2 Mn/ROAD

Since the summer of 1994, the Minnesota Department of Transportation has operated a large outdoor road research facility called Mn/ROAD. The design and construction of this facility was a joint effort between MnDOT, the University of Minnesota's Civil Engineering Department, the Federal Highway Administration, the U.S. Army Corps of Engineers/Cold Regions Research Engineering Laboratory (CRREL), the Minnesota Local Road Research Board (LRRB), and representatives from the local paving industry *(10)*. Research partnerships at work today or in the recent past at Mn/ROAD include the Finnish National Road Administration, a variety of universities, and private companies such as 3M Corporation. While most of the Mn/ROAD experiments focus on pavements, there is also research in the area of weigh-in-motion that might be helpful to TxDOT in its implementation of a test facility in Texas. Of course, pavements and the sensors that highway personnel place in them are interrelated and need to be studied together.

The actual Mn/ROAD facility, located 40 miles northwest of the twin cities of Minneapolis-St. Paul, consists of two road segments running parallel to I-94 outside Otsego, Minnesota. One is a 3.5-mile mainline roadway carrying live interstate traffic, and the other is a 2.5-mile low-volume loop where controlled truck weight and traffic volume simulate conditions on some rural roads. These 6 miles of pavement have 4572 sensors embedded within 40 road "cells" of differing pavement composition and depth, generating millions of bytes of data daily. These 40 test cells, each 500 ft in length, consist of concrete, asphalt, or aggregate pavements with varying combinations of surface, base, subbase, drainage, and compaction. There is also an automated weather station to enable roadside computers to capture information on pavement temperature, moisture and frost content, and other ambient environmental conditions. The data from these systems and the weigh-in-motion systems flow via fiber-optic cable to a data management network at the Minnesota Department of Transportation, where the University of Minnesota researchers can also share the data *(10)*.

The weigh-in-motion system at Mn/ROAD captures information on trucks traveling westbound on I-94. It consists of four platforms in a sealed frame, four loop detectors, and a microcomputer. Data output on every heavy vehicle includes axle weight, axle spacing, gross weight, vehicle speed, and vehicle length.

Minnesota installed three Kistler Lineas/IRD WIM systems in 2003: 1) one four-lane installation with a turnkey contract, 2) one on a two-lane road using MnDOT personnel, and 3) a single-lane system at the MnROAD research facility, also installed by MnDOT personnel. As noted above, the loading on the Mn/ROAD facility consisted of a test truck of known load, testing for seasonal variations, durability, and repeatability in hot-mix asphalt and Portland cement concrete sections. MnDOT was developing web-based reports for analysts and customers. When MnDOT installs a WIM system, it uses the following checklist of pertinent items:[6]

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[6] Phone Conversation with Ms. Margaret Chalkline, Minnesota Department of Transportation, date: October 21, 2003.

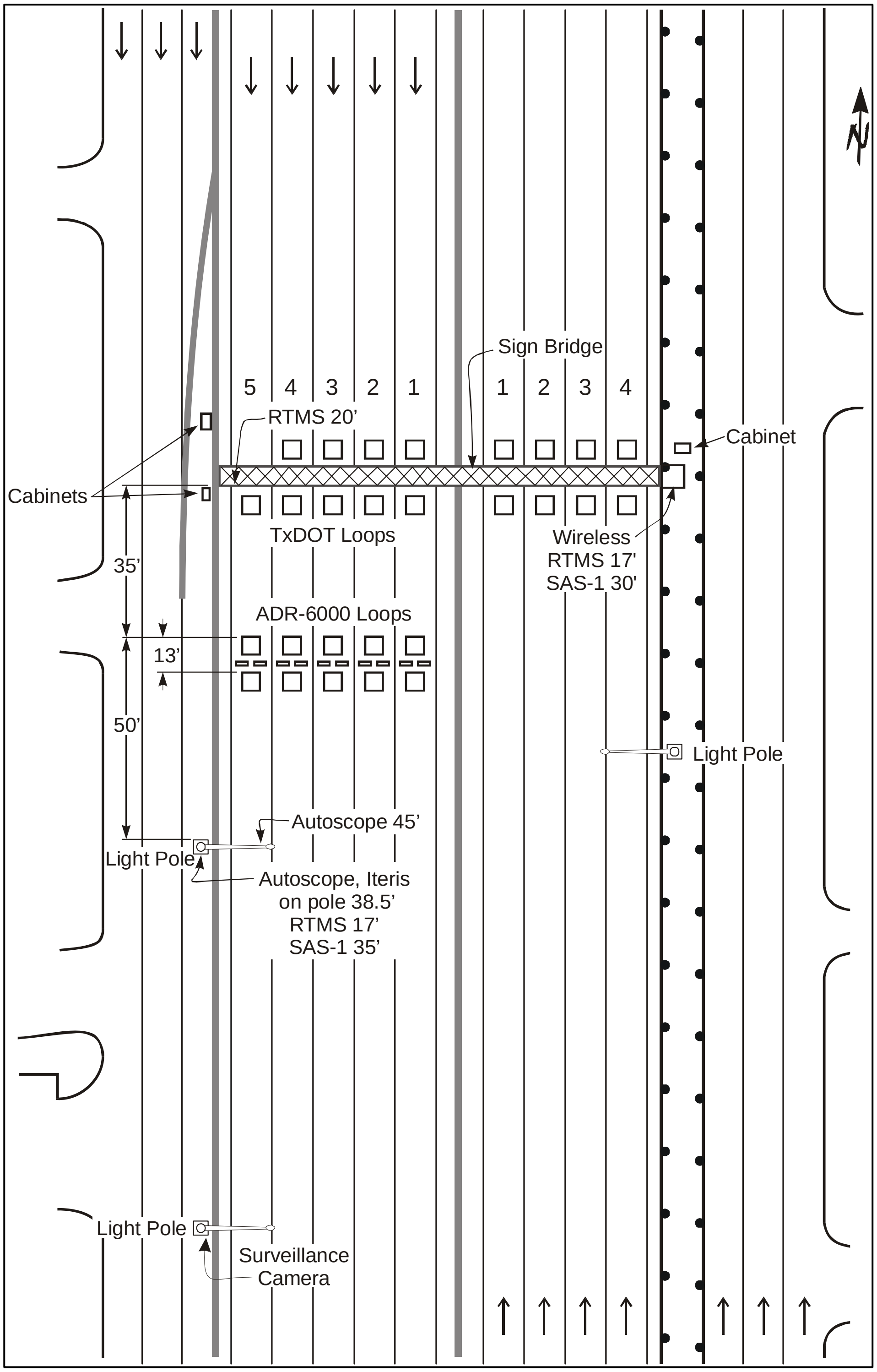
- Hand-sketched map
  - Direction
  - All lanes, shoulder, intersecting roads, reference post number
  - Width of lanes, medians, shoulders, lead lengths needed
  - Power, phone
  - Cabinet location (door facing north preferred)
  - Drainage, ditches
  - Parking spot
- Roadway history
  - Age of pavement
  - Planned rehab
  - Type of pavement
  - Smoothness, crown
- Sketch layout
- Location
  - Roadway name
  - Reference post
  - Relative position to nearest intersection
  - Relative position to nearest city
  - Directions from central office
- Calibration truck route

2.3.5 Texas Department of Transportation

2.3.5.1 TxDOT/Texas Transportation Institute (TTI) Test Bed in Austin

Figure 10 is a schematic of the TxDOT/TTI test bed on I-35 in Austin. The freeway has four through-lanes in each direction and a fifth lane on the southbound side, which is an exit lane to Airport Boulevard. This site is near the old Austin airport and near 47th Street, which is just north of the elevated section of I-35. The elevated section is a factor in dispersion of traffic by type and by lane because an unusually high percentage of trucks use the left two lanes to stay on the lower two lanes of the freeway and avoid the elevated section. On most multilane roadways, a higher percentage of trucks are in the right lanes *(11)*.

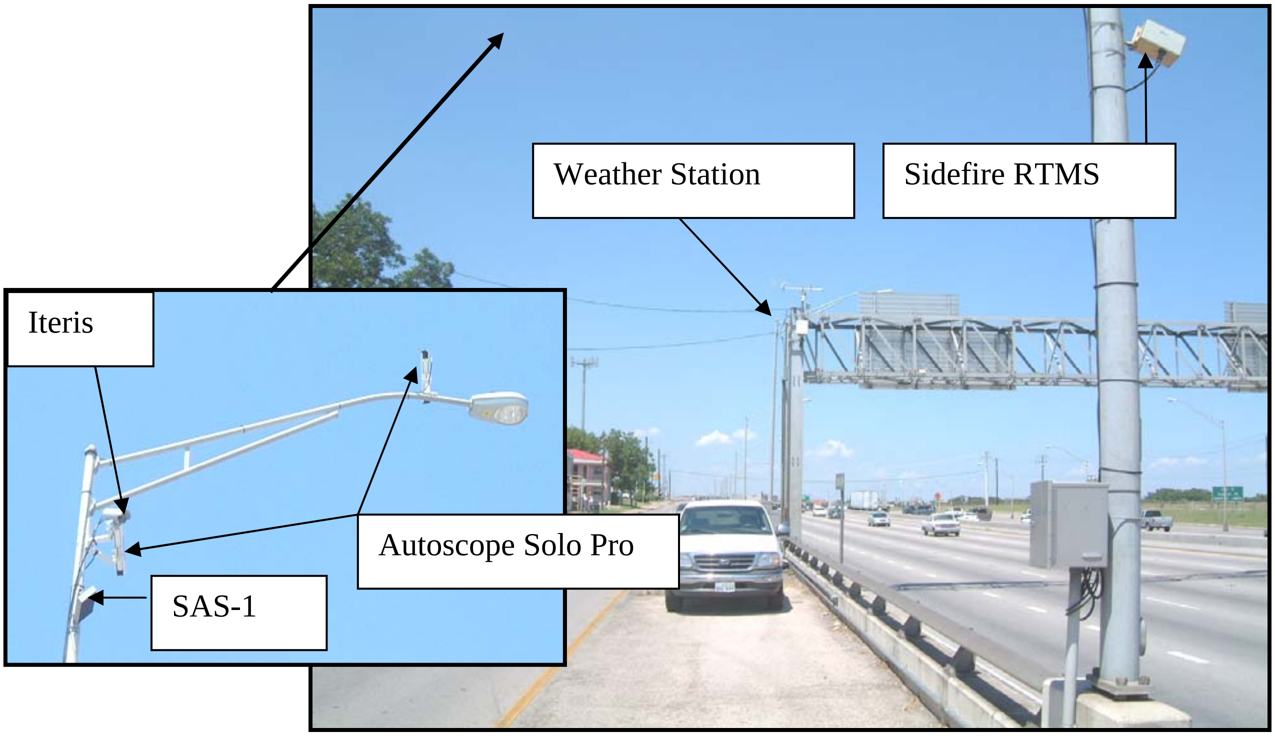
Before installation of the ADR-6000 loops, TxDOT had already installed 6 ft by 6 ft inductive loops under the overhead sign bridge. The through lanes had two loops (traps) installed, whereas the exit lane had only one 6 ft by 6 ft loop. TTI tested the loops prior to installing test equipment and found them all to be in good working order. As shown in Figure 10, the equipment installed on the sign bridge consisted of an RTMS on the west side facing south, an RTMS on the east side facing west (sidefire), and a SAS-1 on the east side facing west (sidefire). Installers also positioned one RTMS unit on the sign bridge to monitor only one lane in Doppler mode. In addition, TTI and TxDOT mounted two Autoscope Solo Pros, the Iteris Vantage, an RTMS, and a SAS-1 on a luminaire pole 85 ft south of the southbound cabinets (west side of the freeway). The TxDOT and TTI field installation crew mounted one Autoscope on the pole at 38.5 ft above the freeway and one to the mast arm supporting the luminaire. The



Source: Reference (11).

Figure 10. Layout of I-35 Site.

reason for placing them at two locations was to evaluate the effect of different offsets. Figure 11 is a photograph of the site looking northward, with an enlargement of the pole showing the detectors mounted on it for testing. Both Autoscopes faced oncoming traffic, whereas the Iteris (placed right beside the pole Autoscope) faced departing traffic. The RTMS on this same pole was 17 ft above the freeway and positioned in sidefire. The SAS-1 on this same pole was 35 ft above the freeway. Figure 10 indicates that the detection area for all pole-mounted devices was very close to the baseline ADR-6000 loops to minimize the effect of lane changing and changes in vehicle speeds.



Source: Reference (11).

Figure 11. Photo of I-35 Test Bed.

The field test plan for the northbound side of the freeway involved mounting the RTMS and SAS-1 on the east side of the sign bridge and sending wireless data to the cabinets on the west side of the freeway. Even though most wireless applications can send data over a longer distance, the tests were more a test of latency or other factors than determining the range of the wireless systems. Other items installed for northbound traffic included an equipment cabinet between the mainline and the northbound service road, 110V AC power from the sign bridge to the cabinet, and conduit across the sign bridge *(11)*.

TTI researchers chose high-speed Internet access to remotely monitor detector systems, upload data, check sensor configurations, and stream live video. This research project revealed many benefits of using Internet communications. One benefit was far fewer trips to the site and the associated travel and labor costs. The result was more productive use of staff time and increased monitoring of detector systems. Another very important benefit was allowing detector manufacturers and vendors remote access to the detector test site. Some of the manufacturers accessed their system remotely from across the U.S. and other parts of the world to check detector setup programs and upgrade algorithms and software. This cooperation with manufacturers helped them and TxDOT get a better product in the end.

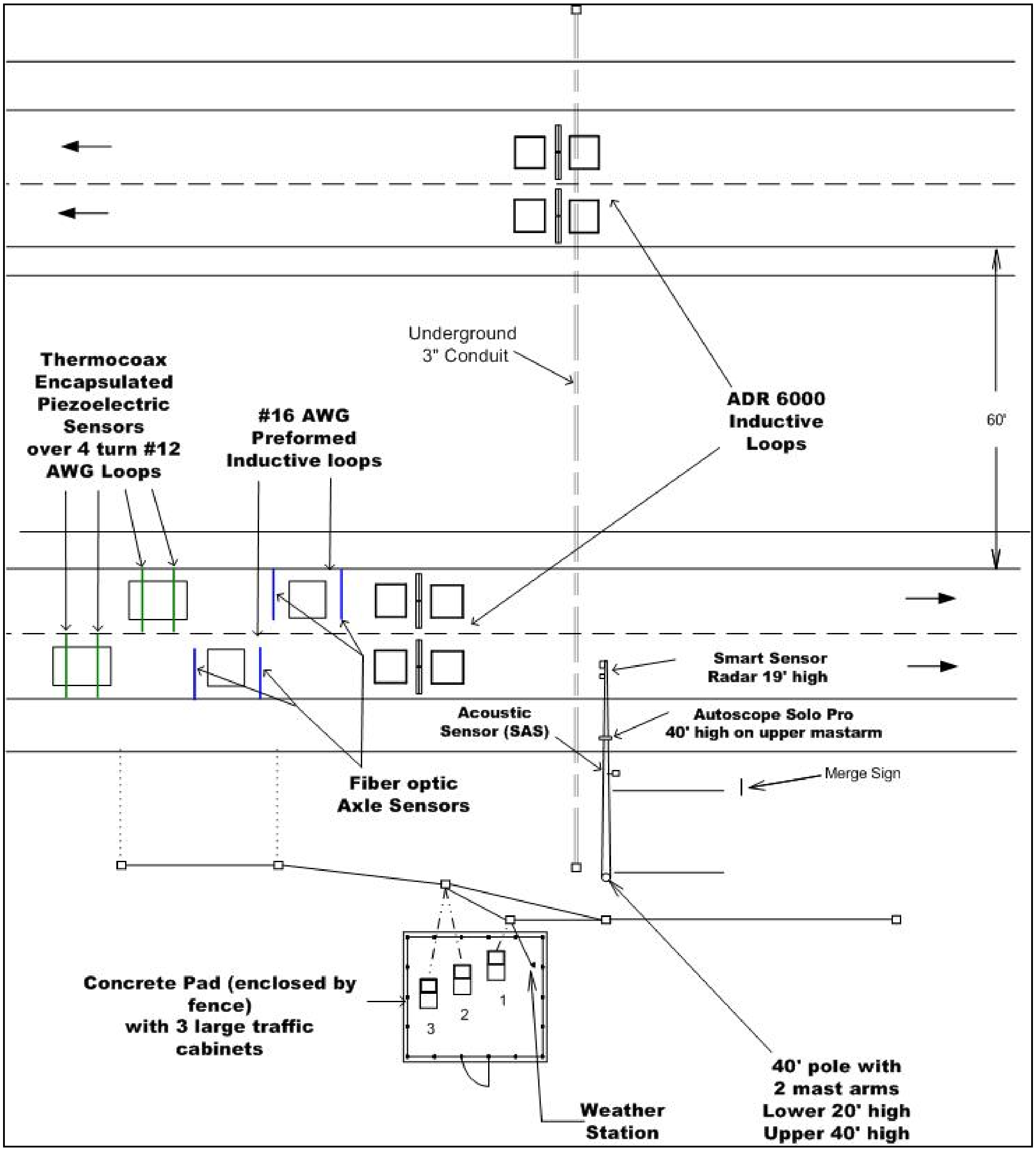
2.3.5.2 TxDOT/TTI Test Bed in College Station

The TxDOT/TTI test bed in College Station uses S.H. 6 just south of the F.M. 60 (University Drive) overpass. Figure 12 indicates some of the features of this site and its general layout. Typical weekday traffic (both directions) on S.H. 6 at this location is approximately 35,000 to 40,000 vehicles per day with 10 percent trucks (FHWA Class 5 and above). Traffic conditions are almost always free-flow, but the noise level and the dispersion of vehicles are at desirable levels for many activities such as group demonstrations and studies that need isolated vehicles. This site has ample parking and area for growth, as well as much of the infrastructure for adding new test systems, as indicated in Figures 13 and 14. It is within a 5 minute drive of Texas A&M University for employees and students, and is within 10 minutes of the TxDOT Bryan District offices *(11, 12, 13)*.

Equipment installed on the west side of S.H. 6 includes:

- three Type P equipment cabinets;
- an enclosed fenced concrete pad;
- a Campbell Scientific weather station;
- a 40-ft pole with two mast arms, one at 20 ft over the road and another at 40 ft;
- pan-tilt-zoom (PTZ) surveillance cameras; and
- roadway sensors that serve as part of the baseline system.

Sensors in or under the roadway include inductive loops, 3M microloops, Class I piezoelectric sensors, and fiber-optic sensors. A Peek ADR-6000 with inductive loops monitoring both the northbound and southbound directions serves as the baseline system. Communications elements include a 768 kb symmetrical digital subscriber line (DSL) for high-speed communication for data and live video. Non-intrusive detectors installed at the site include a 3M microloop (magnetic) detection system, a SAS-1 (acoustic) detector, two SmartSensor (radar) detectors with one covering a lane in forward mode and the other monitoring four lanes in sidefire, and an Autoscope Solo Pro video imaging vehicle detector. There is a weigh station with static scales about 10 miles to the north on S.H. 6, which is available for WIM verification purposes at the test bed site.



Source: Texas Transportation Institute.

Figure 12. Layout of S.H. 6 College Station Test Bed.

Source: Texas Transportation Institute.

Figure 13. View of S.H. 6 Test Bed Looking South.

Source: Texas Transportation Institute.

Figure 14. View of Equipment Cabinets and Weather Station.

2.3.6 Virginia Tech Smart Road

The Virginia Tech “Smart Road” in southwest Virginia is a unique full-scale research facility for pavement research and for evaluating Intelligent Transportation Systems (ITS) concepts and products. It is currently a 2.2-mile two-lane road, but future expansion will widen it to a four-lane limited access facility and will extend its length to 5.7 miles to connect I-81 and Blacksburg.

The Smart Road project included the installation of a weigh-in-motion system beginning around 2001. The primary objective for this project was to evaluate the accuracy, durability, and maintainability of a uniquely designed WIM system from a Finnish company, the Omni Weight Corporation (OWC). The test plan devised by Virginia Tech researchers involved a number of test scenarios including different vehicle speeds, acceleration levels, tire inflation pressures, axle loads, and environmental conditions. It also considered the effect of paving materials on the WIM response accuracy. Figure 15 shows the installation of this system on the Smart Road. The project received funding support (to include the cost of the WIM system) from the Virginia Tech Transportation Institute (VTTI), Virginia Department of Transportation (VDOT), and Virginia’s Center for Innovative Technology (CIT). At the time of the contact with Virginia Tech, their researchers did not know the current status of OWC. Based on limited information, it would appear that the company no longer has a business address in the U.S.[7]

Source: Reference (14).

Figure 15. Installation of Omni WIM System at Virginia Tech’s Smart Road.

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[7] Phone conversation with Dr. Amara Loulizi, Virginia Tech Transportation Institute, February 12, 2004.

As Figure 15 indicates, installing the OWC system in an existing roadway requires significant excavation and disruption to traffic. The Virginia Tech spokesman stated that the excavation length (as measured along the centerline) was about 12 to 13 ft long, and the WIM frame length (same direction) was about 5 ft. If this WIM system had been installed as part of a new roadway, it would be installed below the surface then completely covered with a pavement layer. The VTTI spokesman stated that since asphalt pavement is a visco-elastic material, its load transmission properties differ with temperature. Therefore, the WIM system must monitor and compensate for temperature variations.[8] Since the WIM element is embedded under the pavement, it appears to be more immune to wear and tear as compared to surface systems. A fiber-optic network connects the WIM server for broadcasting real-time information to a users' Web browser. OWC calibrated the system remotely from OWC's office over the Internet. A global positioning system (GPS) unit provided accurate vehicle speed and timing for the calibration. VTTI's Smart Road Control Center provided line-of-sight and video, as well as Internet access to the WIM site. At the time of the contact with Virginia Tech, there was no report available on its accuracy or other performance metrics *(15)*.

2.4 SUMMARY – LESSONS LEARNED

The following bullet list evolved from the information presented earlier in this chapter based on actual installation and use of test facilities for either pavement systems or non-intrusive systems. Researchers discovered these lessons from the literature and from talking to responsible agencies by telephone. The categories under which these items are organized are: site selection, site design, communication and power requirements, maintenance requirements, and baseline data. The last section dealing with electrical specifications comes from TTI's experience in installing detector test sites and from the experience of others.

2.4.1 Site Selection

- Site selection is the first and perhaps most critical decision in installing a weigh-in-motion system. Use the ASTM standard specification E 1318-02 for site selection.

- FDOT located its test site near an enforcement site so that accurate vehicle weights would be available when needed. The other method to check the accuracy of WIM systems and to calibrate the systems is to use at least one and preferably two calibration trucks. This process would require a single-unit truck and a five-axle combination truck to be loaded to a known weight and driven across the WIM systems at a range of speeds.

- If the roadway profile and overall pavement condition are acceptable, the pavement in the immediate vicinity of the WIM system should be evaluated next. Caltrans criteria require that the pavement be absolutely smooth for 150 ft in advance and 75 ft beyond its bending plate WIM. The pavement type is important to Caltrans as well; it only uses concrete.

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[8] Ibid.

- When reviewing a potential WIM site, the reviewer should observe the traffic flow at various times of the day, watching for undesirable traffic conditions. The observer should carefully watch trucks passing through the site to determine if they are traveling at a fairly constant speed and that they are not bouncing due to pavement roughness or profile.

- The best WIM performance occurs with all traffic traveling at a constant speed and when vehicles are staying near the middle of each lane. Conditions to avoid include: stop-and-go traffic, slow-moving traffic, lane changing, and passing.

- Being too close to (especially high-volume) interchanges and intersections may increase lane changing and speed change and may be a factor in controlling traffic during setup or maintenance operations.

- Grade is an important determinant in the accuracy of WIM. Anything in excess of 1 percent grade results in weight transfer from the steer axle to the drive axle of loaded trucks. Weight transfer can easily exceed 1500 lb.

- The grade may also decrease the number of faster-moving trucks, and adequate calibration requires the entire range of speeds.

- The MnDOT I-394 site offered a range of traffic conditions, to include congestion in both the morning and afternoon peak periods and lower volumes with free-flow conditions in the evenings and on weekends. This range of traffic is needed for non-intrusive tests, but it is a problem with WIM and most classification devices.

- Caltrans attempts to locate sites that can reasonably be served by AC power and land line telephone utilities.

- Traffic conditions at the S.H. 6 test bed in College Station are almost always free-flow. An often overlooked positive aspect of lower traffic volume is that the noise level and the dispersion of vehicles are at desirable levels for many activities such as group demonstrations and traffic studies that require isolated vehicles. Also, this site has ample parking with room to expand, as well as an excellent view of traffic in both directions. There is a weigh station 10 miles away that could be used for verification of weights if desired.

- The College Station site is within a 5-minute drive of Texas A&M University for faculty, staff, and students, and is within 10 minutes of the TxDOT Bryan District offices.

- Vehicular access to cabinets is important. TTI found that accessing a cabinet installed on the east (northbound) side of I-35 by vehicle was problematic. Access required using a busy high-speed exit ramp from northbound I-35 then immediately decelerating to a very slow speed to negotiate a 6-inch curb.

- It is highly desirable to place the building and/or primary equipment cabinets at a level that is above the road level such that TPP personnel and visitors can view both directions of traffic flow but not be too close to the roadway. The MnDOT I-394 building was higher than the roadway and well off the I-394 roadway, but it limited the view of eastbound traffic approaching the site.

2.4.2 Site Design

- Bending plate WIM systems need to be installed in concrete (either an existing concrete pavement or a concrete pad built specifically for the WIM).

- The catwalk installed by MnDOT on the Penn Avenue Bridge is an example of how to provide access to devices installed overhead, while maintaining security. Sensors mounted directly over lanes used three adjustable mounting poles attached to the catwalk, one over each lane of traffic, at varying heights ranging from 20 to 30 ft above the pavement.

- The MnDOT building size of 14 ft by 26 ft would not be large enough to house all equipment (used by MnDOT) plus hold workshops of about 20 or more people. Also, judging from the building schematic, it was apparently not equipped with restrooms.

- Both the DETT site on I-405 and the MnDOT site on I-394 considered in their design the likelihood of vandalism and attempted to keep facilities secure. Caltrans had devised a special camera mount on the I-405 bridge that would minimize theft and vandalism. The MnDOT site used tall security fencing to protect equipment.

- Mn/ROAD had an automated weather station to enable roadside computers to capture information on pavement temperature, moisture and frost content, and other ambient environmental conditions.

- For the TTI site on I-35, dispersion of traffic by type and by lane is a negative factor because an unusually high percentage of trucks use the left two lanes. This is a factor in testing the occlusion effects, especially due to these large trucks.

- Street lighting and site lighting are important considerations for security reasons and for tests of certain non-intrusive detectors that use the visible light spectrum.

- Equipment installed on the west side of S.H. 6 includes: three Type P equipment cabinets; an enclosed fenced concrete pad; a Campbell Scientific weather station; a 40-ft pole with two mast arms, one at 20 ft over the road and another at 40 ft over the road; PTZ surveillance cameras; and roadway sensors that serve as part of the baseline system.

2.4.3 Communication and Power Requirements

- Providing communication with the site will be a critical element for TxDOT, researchers, and vendors.

- The Mn/ROAD project used fiber optic cable to send data from its various sensors and the weigh-in-motion systems to a data management network at the Minnesota Department of Transportation and shared by the University of Minnesota for research purposes.

- When MnDOT installs a WIM system, it uses a checklist of pertinent items that include access to phone and power (see page 18).

- Collecting data and communicating with the site will be very important. The TTI sites use high-speed Internet access to remotely monitor detector systems, upload data, check sensor configurations, and stream live video. This research project revealed many benefits of using Internet communications. One benefit was far fewer trips to the site and the associated travel and labor costs. Another big benefit is its availability to vendors and manufacturers for remote access to test, modify, and upgrade their equipment.

- The test plan devised by Virginia Tech researchers involved a number of test scenarios including different vehicle speeds, acceleration levels, tire inflation pressures, axle loads, and environmental conditions.

- The Virginia Tech researchers set up a fiber-optic network connecting the WIM server for broadcasting real-time information to a users' Web browser.

2.4.4 Maintenance Requirements

- FDOT recommends that if a state DOT cannot allocate sufficient resources to maintain a (bending plate) WIM system, it should not install it in the first place. Ignoring this need for maintenance can result in traffic hazards and lawsuits.

2.4.5 Baseline Data

- For baseline weights for a WIM test site, FDOT located its site within 5 miles of a weight enforcement site.

- In its DETT report, Caltrans found it necessary to keep the test device's detection zone and the baseline system very close to each other and separated by an equal distance across all lanes.

2.4.6 Electrical Specifications

- Use separate conduit for coaxial video cables and telephone lines, keeping a minimum of 12 inches from any current-carrying conductors.

- Use direct burial gel-filled and copper-shielded telephone cable.

- Use Belden 8281 double-shielded coaxial video cable.

- Install lightning arrestors on the telephone lines, video feeds, RS-323, RS-485, or RS-422 communications cables going into cabinets or building.

- Install transient voltage surge suppressor protection on the load side of the building.

- Use one large 6-inch conduit for bore under roadway, but partition into six partitions with MaxCell from Clifford Cable to increase conduit capacity.

- If the test site is constructed in new pavement, during construction install two 3-inch conduits 16 ft apart for 3M microloops.

- Use large 2-ft by 4-ft Quazite pull boxes to allow plenty of room for future conduit.

- Consider using 802.11 wireless high-speed Ethernet for video and serial communications where possible to reduce the need for boring under the roadway.

CHAPTER 3.0 FUNDING SOURCES

3.1 INTRODUCTION

When TxDOT originally developed the project statement for Research Project 0-4664, it envisioned that construction of the traffic monitoring equipment evaluation facility would take place as part of this project. It later determined that construction of the facility was not considered research and the project could not pay for it. TxDOT anticipated the need for future funds to finance the construction of the facility and added a task during the development of the original project statement, which directed researchers to develop a comprehensive list of funding sources.

Discussions with TxDOT personnel and representatives of other agencies resulted in a number of potential funding sources. The research team investigated a number of alternatives and developed a list of potential funding sources:

- highway trust fund (construction projects),
- capital improvement funds,
- research implementation funding,
- district and division discretionary funds,
- vendor contributions (equipment and installation support), and
- State Planning and Research (SPR) funds.

3.2 HIGHWAY TRUST FUND

It is common for states to use pavement construction projects to pay for the cost of traffic monitoring equipment, installation, calibration, and support. These funds come from the Federal Highway Trust Fund, and motor fuel taxes are their source. Allowable uses of these funds are the construction, repair, and operations of the highway infrastructure. The construction or procurement of buildings is not an allowable use of these funds, but Capital Improvement Funds can cover such costs.

The research team met with TxDOT staff in the Waco and Austin Districts to discuss potential funding sources and district participation. In both cases, there was district support for the idea, suggesting that a planned construction project could include the site and the necessary pavement improvements (i.e., continuously reinforced concrete pavement [CRCP]) to accommodate the needs of the test facility.

Several promising construction projects under design are ideal candidates for the installation of the facility. Researchers found attractive alternatives along I-35 in the northern portion of Travis County (Austin District) and the southern portion of the Waco District on I-35. The Waco District is particularly interested in this project as it would provide the district with a bending plate weigh-in-motion data collection system. Chapter 5 provides more details.

There is potential synergy in the traffic detection arena between TPP and state-funded traffic management facilities such as Travis County's Combined Transportation, Emergency and Communications Center (CTECC), as well as the TxDOT Traffic Operations Division. The proposed facility can provide TxDOT with a centralized testing infrastructure close to Austin to safely and effectively train staff, evaluate new hardware and software technologies relevant to traffic sensing and data collection, and provide a venue to share experience and resources between state agencies.

A representative at CTECC provided valuable information to the research team and expressed significant interest in this research project. He identified three traffic management construction projects that have just been let or are currently in the process of being let. Coupling the construction of this facility with an ITS project presents a great opportunity for TPP to partner with the traffic management community and have this facility constructed with a focus on traffic data collection as well as intelligent transportation sensing and hardware.

The principal advantage of using trust fund money is the Federal government's 90 percent contribution for interstate highway projects versus a 10 percent state contribution. TxDOT could use these funds to purchase and install much of the basic infrastructure for the facility including:

- CRCP and/or other pavement structural improvements;
- conduit, pull boxes, and cabinets;
- equipment enclosures;
- power and telecommunications connections;
- video monitoring system;
- work platform; and
- parking area.

Trust fund monies can be accessed by:

- Change Order – A change order is a modification to an existing construction project that has been awarded and is under way. The advantage of a change order is that it allows construction of the facility to occur fairly rapidly. An area engineer has authority to issue a change order up to $25,000, and a district engineer has authority to issue a change order up to $150,000. Disadvantages of change orders include: 1) they are subject to extra scrutiny for approval, 2) the work must generally fall within the scope-of-work of the original project, 3) they are almost always more expensive (because of lack of competition), and 4) decision-makers consider them indicators of poor project scope control.

- Design Change – A design change is usually made before the letting during preparation of contract documents. TxDOT prepares Project Plans, Specifications, and Engineering (PS&E) for jobs based on estimated costs for construction and available funds. Adding the facility during this stage would necessitate diverting funds from one or more future projects to compensate for the additional cost of the facility. Approval for a design change must go through a TxDOT chain of command starting with the area engineer, followed by the district construction engineer, and finally the district engineer. The Design Division then reviews and approves the change and integrates the change into the project construction documents before the letting.

- Part of Original Scope – In this case, the facility would be incorporated into a construction project during the earliest planning and design phases, worked through the TxDOT project development system, and approved by the Advanced Transportation Planning and Development Group at the TxDOT district.

In general, the process for getting this project added to a highway construction project is as follows:

- Design – Technical documents are required to define the proposed facility. TxDOT would incorporate documents into plans and specifications for insertion into the bid documents.

- Cost – A cost estimate for the proposed facility must be prepared.

- Approval – The approval would begin with the area engineer responsible for the project who would take it before the Advance Transportation Planning and Development Office for review.

3.3 CAPITAL IMPROVEMENT FUNDS

In order to use capital improvement funds, the Legislature must explicitly approve each asset in a spending bill, and the typical use is for administration buildings. Because of the required coordination and timing, this source of funds is probably not appropriate for the facility.

3.4 RESEARCH IMPLEMENTATION FUNDS

Various research projects have recommended the construction of a facility to allow TxDOT to evaluate vendor products and installation procedures and to serve as a service facility for training of technicians from different districts. The director of the Research and Technology Implementation Office (RTI) stated in comments to TTI staff in March 2004 that RTI has a role in evaluating new technologies by coordinating with responsible divisions. Thus, such a site fits within the scope of "research implementation" and could be proposed as a "research implementation project." A project representative will present the project status at the Research Management Committee (RMC) meeting. This presentation will be followed by another shorter presentation to the Research Oversight Committee (ROC), who will collectively decide if the request is eligible for implementation funds and if they concur with the stated funding request and scope.

3.5 DISCRETIONARY FUNDS

Each TxDOT district and division has discretionary funds available. With sufficient contributions from TxDOT districts, there would be no need for highway trust fund financing, or there would be sufficient funding to pay for components that could not be covered by highway trust fund dollars.

A request from the TPP division head to the districts and possibly to the Traffic Operations Division would probably be most successful in soliciting district or division discretionary funds. Accompanying the formal request should be a complete description of the project and the intended use of the facility, to include training and benefits that would accrue to each district and the entire state. Complete funding for the construction of the facility through this mechanism, and not highway construction projects, offers several advantages:

- The facility can be constructed on the most appropriate section of road and not be tied to a road segment just because it is part of the construction contract.

- Construction contracts can take considerable time to complete, and/or delays can occur, which means the facility may not be constructed within a desirable time frame.

- There are fewer restrictions on how the funds can be spent for the construction of the facility (i.e., structures, equipment, sensors, etc.).

The disadvantage of this funding mechanism is the uncertainty of getting enough contributions to pay for the facility. The contributions made by the district may not be enough to pay for significant pavement upgrades such as CRCP, so the site might not be able to support a permanent bending plate WIM system.

3.6 VENDOR CONTRIBUTIONS

Vendor contributions will help lower the cost of acquiring software, hardware, sensors, and other related equipment. One vendor has already offered to contribute a WIM system for installation at the site, although this commitment has not been verified. Other vendors will be asked for contributions as appropriate. The researchers anticipate that vendors will contribute both equipment and installation services to prove that their systems perform as advertised. Successful vendor demonstrations provide strong evidence to TxDOT that the purchase of the equipment is an acceptable investment in its traffic data monitoring system.

3.7 STATE PLANNING AND RESEARCH (SPR) FUNDS

State Planning and Research funds represent a possible funding source. FHWA representatives in Austin and Washington, D.C., indicated that TxDOT could possibly use SPR funds to finance a portion of the facility, but this would be the first time SPR funds would be used for a facility like this one. SPR funds require a 20 percent local match, but TxDOT could meet the requirement either by direct funding or by innovative financing of their time and services to leverage the federal portion. TxDOT would need to submit the request in the current fiscal year for funding in the next fiscal year. These funds are not eligible for pavement construction and rehabilitation, but they are eligible for the operations building, sensors, electronics, tools, cabinets, pull boxes, and other basic infrastructure.

If TxDOT pursues SPR funding for a portion of the test facility, it would need to first initiate an amendment to its SPR program. The current description for this research project within the SPR document (pp. 50–51) *(16)* does not include the construction of a test facility. The amendment will have to advance through TPP administrative review and then to the FHWA Division Office for approval. The amendment should state what is proposed and how the completed facility will improve TxDOT's data collection efforts and its Highway Performance Monitoring System (HPMS) program.

3.8 SUMMARY

This chapter identified potential funding sources to finance the construction of the proposed facility. Each potential funding source listed above has its own advantages and disadvantages. The most serious disadvantages are the potential delays associated with construction projects and the uncertainty of district contributions. Despite these concerns, researchers will proceed with plans to combine the construction of the facility with an appropriate highway construction project.

The TTI and the Center for Transportation Research (CTR) team also pursued other funding possibilities identified herein including discretionary, research implementation, and SPR funds. Given sufficient funding from alternative sources, TxDOT could build an interim facility at a future highway trust fund construction site so it could commence research, testing, and training more quickly. The construction project would provide a permanent CRCP pavement structure for the facility, and bid documents could incorporate specifications for the replacement of all facility components damaged by the construction.

Researchers divided the site construction into modules. These modules include the following:

- Module 1 – Pavement construction and rehabilitation, under the road conduit, and guardrail;
- Module 2 – Portable structure, utilities, phone, fencing, parking, and base platform;
- Module 3 – Sensors and instrumentation;

- Module 4 – Interconnecting conduit, pull boxes, and cabinets;
- Module 5 – Remote communications and wideband wireless; and
- Module 6 – Additional systems such as video monitoring and a weather station.

In year two of the research project, TxDOT, in cooperation with project researchers, successfully petitioned the Research Management Committee for implementation funding to help finance construction of the test facility. Subsequently, the Research Oversight Committee approved implementation funding totaling $288,000 for construction of a test facility. Also, the Waco District has worked with TPP to include the facility as part of a highway re-construction project on a section of I-35 beginning at the Bell/Williamson County line. This construction is scheduled to begin in 2007 or 2008.

CHAPTER 4.0 SITE SELECTION CRITERIA

4.1 INTRODUCTION

Site selection criteria development began with a set of criteria to screen and prioritize candidate sites to identify the best possible site for the proposed equipment evaluation facility. The site selection criteria were principally based on general requirements for traffic data collection systems and input from TxDOT staff. The research team also developed additional criteria not normally considered for data collection sites but considered important for a successful research facility. The process applied a rating factor from zero to five to each criterion where a zero value essentially disqualified a site for consideration and a five rating satisfied the criterion completely.

Researchers initially developed the criteria and rating factors under the assumption that the site would be installed with no modifications or improvements to the highway alignment or pavement structure. They later revised this approach because there was a strong possibility of building the test site as part of a pavement reconstruction or widening project. This change meant that the reconstruction project would correct the poor pavement or other problems as part of the project. Researchers modified the related rating factors accordingly.

A final criterion added a requirement for a bending plate WIM system installed in CRCP pavement. This criterion impacted the selection criteria because it limited the sites to those where extended lane closures would be feasible. It also required the facility to be constructed in conjunction with a major pavement rehabilitation or reconstruction project to absorb the cost of CRCP.

4.2 DESCRIPTION OF CRITERIA

Table 1 shows the 21 selection criteria. Section 4.2.2 provides two examples of rating criteria followed by a general discussion of the remaining criteria. Appendix A contains a full list of the rating values used for each of the criteria.

4.2.1 Criterion 1 – Distance from TPP Shop

The distance of the proposed site from TxDOT offices at the Bull Creek Annex, near the intersection of Bull Creek Road and 45th Street, is important for convenient access of the facility to TxDOT staff. TxDOT used former test sites located in or near Seguin and Jarrell for testing traffic monitoring equipment and sensors but eventually abandoned these sites because of their distance from their offices. Travel times in excess of 40 minutes do not disqualify a site, but longer drive times reduce opportunities for TxDOT to use the site, so its rating drops respectively. Table 2 shows the values used for Criterion 1.

Table 1. Site Selection Criteria.

Criterion	Objective	Criteria
1	Distance from TPP shop	Drive time (minutes)
2	Roadway geometry	Alignment, cross-slope, lane width
3	Pavement structure	Thickness
4	Traffic mix	Percent trucks and total volume
5	Multiple lanes	Number of lanes
6	Power and communication	Distance to service
7	Right-of-way	Distance to safe parking
8	Adjacent space	Park calibration truck
9	Space for structure	Area for building
10	Sign bridge structure	For mounting overhead devices
11	Roadside pole	For mounting overhead devices
12	Lighting	Security and night visibility
13	Pavement condition	Rutting, cracking, smoothness
14	Pavement rehabilitation	Rehabilitation schedule
15	Circuit time for calibration truck	Cycle time
16	Sight distance	For clear visibility of traffic
17	Proximity to Department of Public Safety (DPS) enforcement site	For ground truth weights
18	Bending plate WIM	Existing, buildable, or not buildable
19	Access to satellite sites	Distance from primary site
20	Safety features	Longitudinal barriers
21	Traffic congestion	Free-flow or stop-and-go

Table 2. Criterion 1 – Distance from TPP Shop.

Criteria	Scale	Rating
Drive time from TPP to site	0 < 10 minutes	5
	11 < 20	4
	21 < 30	3
	31 < 40	2
	> 41	1

4.2.2 Criterion 2 – Roadway Geometry

Roadway geometry criteria utilize ASTM E 1318-02, the Standard Specification for Highway Weigh-in-Motion Systems with User Requirements and Test Methods *(3)*. The low weighting values represent conditions that are unacceptable according to the ASTM specification but correctable with alignment and/or pavement improvements. Tables 3, 4, and 5 indicate the values used for horizontal/vertical alignment, cross-slope, and lane width.

Table 3. Criterion 2 – Roadway Alignment.

Criteria		**Horizontal Alignment (radius of curvature - ft)**			
	Scale	**>10,000**	**10,000-8000**	**8000-5700**	**<5700**
Vertical Alignment - % grade (pos. or neg. grade)	0.0 – 0.5	5	4	1	1
	0.5 – 1.0	4	3	1	1
	1.5 – 2.0	2	2	1	1
	2.0+	1	1	1	0

Table 4. Criterion 2 – Cross-Slope.

Criteria	**Scale**	**Rating**
Cross-slope (%)	0 – 1	5
	1 – 2	5
	2 – 3	1
	3+	1

Table 5. Criterion 2 – Lane Width.

Criteria	**Scale**	**Rating**
Lane Width (ft)	12.5 – 14	4
	12.5 – 12	5
	12.0 – 11.5	2
	11.5 – 11.0	1

4.2.3 Criterion 3 – Pavement Structure

Pavement structure is a key criterion that directly reflects the usefulness of the site for a TPP research facility. Regardless of CRCP being installed at the site, asphalt pavement at a selected site must provide adequate stiffness to support the installation of various other road sensors.

4.2.4 Criterion 4 – Traffic Mix

Potential sites must have an appropriate traffic volume and mix of vehicle types. High volumes are desirable for evaluating traffic equipment and sensors to get performance results under extreme operational conditions. On the other hand, the volume cannot be so high as to preclude reasonable lane closure opportunities for sensor installations and maintenance. At high volumes, traffic congestion also becomes a problem since most traffic monitoring systems do not collect accurate data during stop-and-go conditions. The classification mix, including a large proportion of truck traffic, is essential.

4.2.5 Criterion 5 – Number of Lanes

The number of lanes is important insofar as it is desirable for the roadway to be divided by a median, which implies four or more lanes. The criterion considered a six-lane site the most desirable, but it also considered a four-lane section acceptable.

4.2.6 Criterion 6 – Power and Telephone

Access to electric power is essential for powering lighting, air conditioning, test equipment and research hardware, and sensors at the site. A site will also need telephone service for remote communications with the facility. Availability of high-speed Internet service is also desirable but was not part of the selection criteria.

4.2.7 Criterion 7 – Sufficient Right-of-Way (ROW)

Sufficient ROW is important to accommodate the structure and related facilities with adequate line-of-sight to view passing traffic. ROW must also be sufficient to accommodate on-site parking and access for vehicle operators. Safety is also a factor that affects the need for adequate ROW.

4.2.8 Criterion 8 – Adjacent Parking for Calibration Truck

On-site parking for the calibration truck facilitates communicating with the driver, and it offers a secure area for parking the truck. However, there are other ways to handle these issues so failure to satisfy this criterion does not significantly impact the site score.

4.2.9 Criterion 9 – Space for Operations Trailer

The use of this site as a training facility for TxDOT is an important factor. It is vital to have space for a structure that provides a comfortable environment – protection from weather and traffic noise – for on-site training purposes.

4.2.10 Criterion 10 – Sign Bridge or Overpass

A sign bridge or overpass structure is important for the installation of certain types of traffic sensors. An overpass would be ideal because it would also provide operators with convenient and safe access to both sides of the road. If a structure is not available, the site plans and specifications will incorporate the construction of a sign bridge and service walkway.

4.2.11 Criterion 11 – Roadside Pole

The availability of one or more roadside poles is important for mounting video cameras that allow remote viewing of passing traffic and evaluation of non-intrusive sensors requiring a roadside setup. This structure could be an existing luminaire support or sign pole with adequate height.

4.2.12 Criterion 12 – Lighting

The presence of street lighting, although not required, would improve safety for times when TPP personnel perform night work.

4.2.13 Criterion 13 – Pavement Condition

Pavement condition becomes an issue if a lack of funding prevents corrective actions to repair critical deficiencies. Failure to correct such problems would render a site unacceptable.

4.2.14 Criterion 14 – Pavement Rehabilitation Programming

This criterion applies to asphalt or Portland cement concrete pavements that will be resurfaced. Given the opportunity, the state should visit the site prior to the resurfacing operation (including milling if applicable) and create a map to record the location, severity, and extent of existing distresses (e.g., surface cracking). After the pavement overlay, the map will provide guidance to position sensors so they are not located on top of concealed distress points that can propagate into the new pavement surface. Also, installing sensors in a pavement that is scheduled for rehabilitation in the next three years is not desirable.

4.2.15 Criterion 15 – Test Truck Turnaround Time

The site should be located to provide reasonable turnaround times for both calibration trucks and test vehicles making test runs over the sensors to avoid long delays for data collection.

4.2.16 Criterion 16 – Sight Distance

Operators need to see vehicle traffic approach the site before it crosses the sensors to give them the opportunity to collect special research data (e.g., sensor signals) from specific vehicles on specific sensor arrays.

4.2.17 Criterion 17 – Proximity to Department of Public Safety Scales

For research on WIM sensors, it is highly desirable to occasionally obtain matching static axle weights from mixed truck traffic to evaluate the accuracy of WIM sensors and systems. One way to meet this need is to locate the site relatively close to an enforcement facility with permanent static scales. However, TxDOT also intends to use this site as a WIM data collection site, so it should not be so close to the DPS activity as to bias the weight data. If a static scale is not available, the next best alternative is to use loaded test trucks of known static weight and have them make multiple runs.

4.2.18 Criterion 18 – Bending Plate System

TxDOT desires that the research facility also have a permanent bending plate WIM system collecting traffic data on all lanes to help satisfy statewide truck weight planning data requirements. If properly maintained and calibrated, this WIM system would also provide a data resource for verification of data from other sensors and devices.

4.2.19 Criterion 19 – Satellite Sites

The use of satellite sites will be an important component of the research facility to effectively evaluate traffic monitoring electronics and sensors. The primary site will permit the evaluation of traffic monitoring systems at normal highway speeds under free-flow conditions. Satellite sites will enable operators to evaluate equipment and sensors under different traffic conditions, pavement types, pavement stiffness, environments, and so forth. Researchers do not expect TxDOT to construct satellite sites specifically for this purpose; it would probably use existing traffic monitoring sites and evaluation facilities and connect them to the primary site and to TxDOT offices by communication links.

4.2.20 Criterion 20 – Safety Features

A critical issue in selecting and designing a facility is consideration of safety features. Safety features are important for the operators, who will work at the facility for extended periods of time, and for the traveling public. For example, depending on the physical separation of roadside hardware from traffic, an important safety feature may be a positive barrier to protect people and facilities from errant vehicles. Also, the site selection and design must provide adequate and safe access for operators or visitors arriving by car.

4.2.21 Criterion 21 – Traffic Congestion

The ideal site is one that never experiences stop-and-go traffic. Traffic congestion is sometimes necessary to verify vendor’s claims of accuracy under these conditions, but TxDOT could handle this requirement by an appropriate satellite site.

4.3 GLOBAL RANKING FOR SITE SELECTION CRITERIA

The rankings of site criteria described previously only consider individual criteria. To effectively score a site, researchers needed an overall (global) ranking to address the relative significance of one criterion compared to the others. For example, the proximity or location (criterion number 1) of the facility relative to TxDOT offices is more important than sight distance (criterion number 16). Researchers ranked location with a weight of 5 and sight distance as 3.

Table 6 recommends an overall ranking/rating for the different site selection criteria that identifies the relative importance of each. The most important criteria have a rating of 5, with objectives of lesser importance given a lesser ranking.

Table 6. Overall Ranking of Criteria.

Objective	Ranking
1 Location	5
2 Geometry	5
3 Pavement structure	4
4 Traffic mix	5
5 No. of lanes	3
6 Power and communication	3
7 Sufficient ROW	3
8 Calibration truck parking	2
9 Space for shelter	3
10 Sign bridge	3
11 Roadside pole	2
12 Lighting	1
13a Rutting/Cracking	2
13b Smoothness	3
14 Planned rehabilitation	2
15 Turn around for calibration truck	3
16 Sight distance	3
17 DPS weight enforcement	4
18 Bending plate WIM	2
19 Satellite sites	1
20 Safety features	2
21 Congestion	4

CHAPTER 5.0 RECOMMENDATIONS FOR FACILITY

5.1 INTRODUCTION

Using a general site selection process, the research team selected corridors and locations that might generally fit the needs of TPP. Based on the anticipated frequency of trips from the TPP shop to the site, researchers looked first at locations in central Texas as close to Austin as possible but still avoiding congested areas. There were several sites that deserved a closer look. Then, based on the site selection criteria and knowledge of the area highway network, the research team narrowed the number of candidate sites to four. Then, following the selection of a preferred site of these initial four, a rest area just north of the preferred site became an option. TxDOT was refurbishing the rest area, and the timing seemed appropriate to identify a portion of the rest area for a test facility if the Maintenance Division and the Waco District could resolve any concerns with this modification to the plan. This chapter includes consideration of these five sites. All five sites are on I-35; three are in northern Travis County (Austin District), and two are in southern Bell County (Waco District).

5.2 GENERAL SITE SELECTION PROCESS

The final selection process used general criteria prior to applying the site selection criteria presented in Chapter 4 to narrow the investigation to corridors that could be surveyed in detail. These general criteria were:

- The TPP offices in Austin are the base of operations from which staff will frequently travel to the demonstration facility.
- Locate the site on a roadway with significant daily truck volume and variations of truck types.

The most significant daily truck volumes are on interstate corridors. The preliminary corridors within a two-hour drive of the TPP offices are:

- the I-35 corridor from Hillsboro south to Pearsall,
- the I-10 corridor from Kerrville east to Columbus, and
- the I-37 corridor from San Antonio south to Campbellton.

Figure 16 provides a reference for these corridors in relation to their proximity to Austin.

Project staff performed an HPMS query to find roadway sections with acceptable existing horizontal and vertical geometry to provide as straight and level conditions as possible for the demonstration facility. The HPMS curve and grade criteria were curve class A (degree of curvature is 0.0 to 3.4) and grade class A or class B (0.0 to 0.4 and 0.5 to 2.4). This query used Year 2002 data submitted to FHWA for the initially identified corridors. Figure 17 shows the

Source: Reference (17).

Figure 16. Regional Highway Network around Austin, Texas.

matching results as a heavier line compared to other roadways. Significant gaps occurred within the query results for sections of roadway. Closer review of these gaps indicated some familiar sections (e.g., Georgetown to the Williamson/Bell County line) that met the query criteria but were not included as matching results. In the final analysis, the HPMS dataset did not prove to be a reliable source of information for all sections of roadway, but only for sections in the HPMS sample set.

From the outset, travel time from the TPP shop was a critical consideration in the selection of the site. For that reason, researchers considered travel times greater than about one hour excessive, eliminating locations in or near San Antonio and along the I-10 and I-37 corridors, as well as the portion of I-35 south of New Braunfels. Sections of the I-35 corridor north of the city of Belton also exceeded the desired drive time. After these exclusions, the only corridor remaining from ones initially selected was I-35 from the city of New Braunfels north through the city of Belton.

S.H. 130, which is presently under construction (August 2005), will be a toll facility from Georgetown (located north of Austin) to I-10 to the south. Traffic forecasts indicate that this road will serve a significant amount of truck traffic from the I-35 corridor through the Austin and San Marcos areas. A 1998 TxDOT study predicted that 27 percent of the through truck trips would choose S.H. 130 *(18)*. More recent TxDOT studies indicate that 13 percent of the projected daily traffic in 2025 will be trucks.[9] The first segments from the S.H. 130/I-35 interchange south to its intersection with U.S. 183 near the City of Austin will open to traffic in 2007.

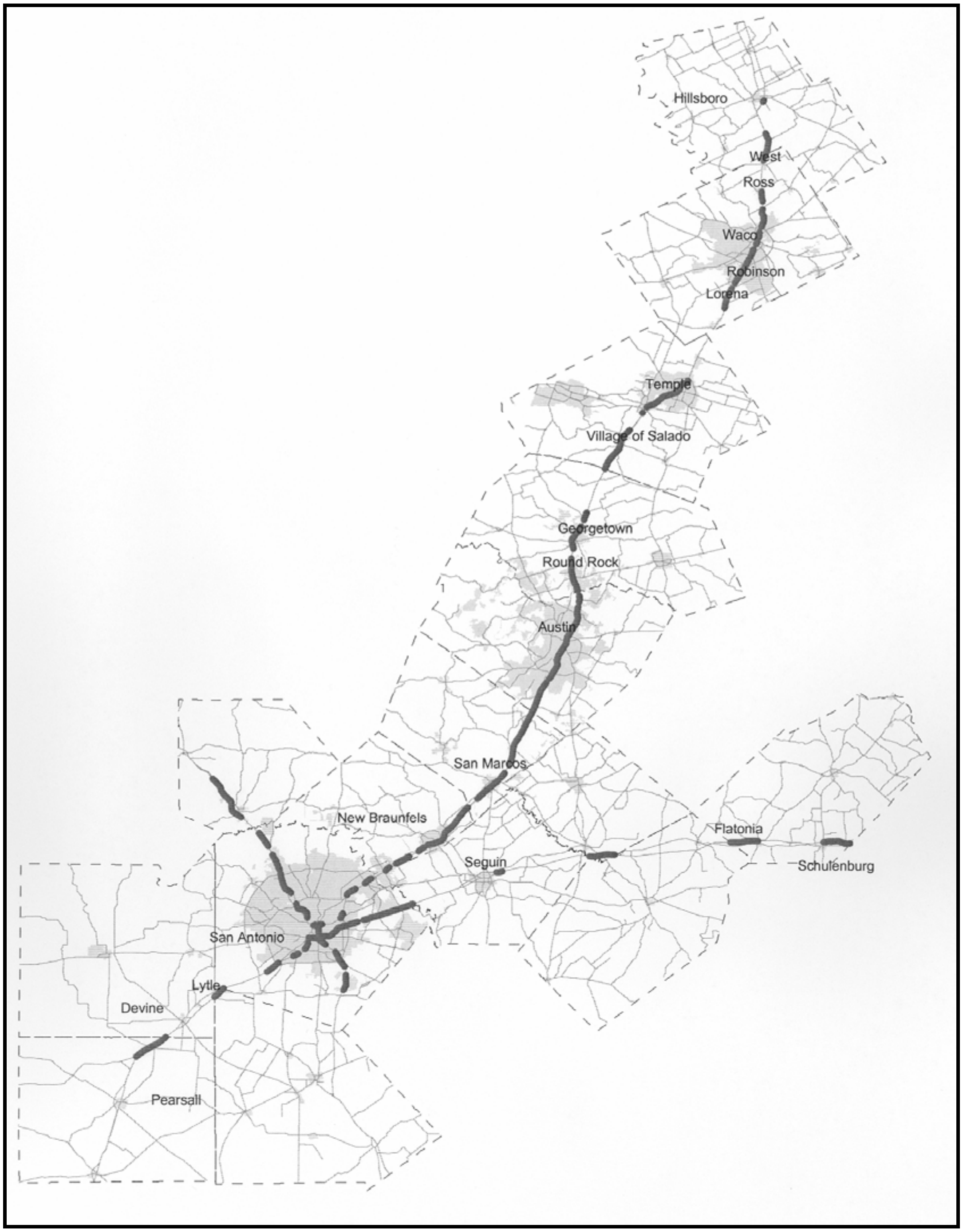

Figure 17. HPMS Query Results.

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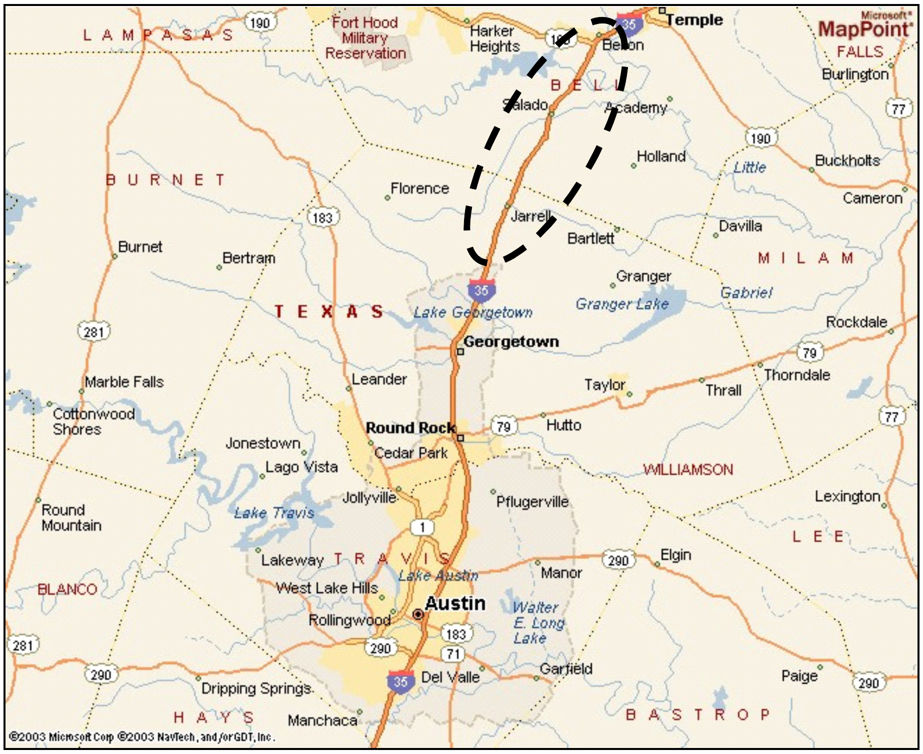
[9] Personal communication with John Buttenob, March 31, 2004.

Because of this anticipated diversion of trucks, researchers reduced the candidate corridor to sites located north of the proposed S.H. 130/I-35 interchange on the north side of Georgetown. The northern terminus of the candidate section was the shared city limits of the City of Belton and the City of Temple at mile marker 296. By selecting this roughly 27-mile corridor, the location of the demonstration facility maximizes both the amount of total traffic and truck traffic for testing equipment and training TxDOT staff in the use of data collection equipment and reduces excessive travel time to other more remote locations. Figure 18 shows the selected portion of the I-35 corridor.



Source: Reference (17).

Figure 18. I-35 Corridor from Austin to Temple.

Tables 7 and 8 show the criteria used for a second query, which utilized the Texas Reference Marker (TRM) database. The limits of this query along the I-35 corridor were from immediately north of the S.H. 130 interchange to Hillsboro. The selection process used these criteria to locate points along the mainlanes where overhead features were available for mounting overhead traffic sensors. These existing features would reduce the cost of the test facility by mitigating the need to construct an overhead structure. Crossover structures also provide access to staff to walk or drive above the mainlanes to the opposite side of the roadway. Table 9 shows TRM query results.

Table 7. TRM Query Conditions for Rigid Pavements.

Property	Query Conditions
Rural Urban Code	Rural OR Small Urban
Roadway Feature Code	Intersection
Intersecting Feature Type	On-System Mainlane OR Local Road OR Crossover OR Overhead Sign
Intersecting Type	Grade Separated Intersection
Roadway Feature Grade	Feature is Up Above Grade
Shoulder Type	Surfaced with Bituminous (one or two course and asphalt concrete pavement [ACP]) OR Surfaced with Concrete (not tied to mainlane pavement) OR Surfaced with Concrete (tied to mainlane pavement)
Surface Type	High Rigid - Reinforced Jointed Concrete Pavement OR High Rigid - Continuous Reinforced Concrete Pavement

Table 8. TRM Query Conditions for Bituminous Pavements.

Property	Query Conditions
Rural Urban Code	Rural OR Small Urban
Roadway Feature Code	Intersection
Intersecting Feature Type	On-System Mainlane OR Local Road OR Crossover OR Overhead Sign
Intersecting Type	Grade Separated Intersection
Roadway Feature Grade	Feature is up above Grade
Shoulder Type	Surfaced with Bituminous (one or two course and ACP) OR Surfaced with Concrete (not tied to mainlane pavement) OR Surfaced with Concrete (tied to mainlane pavement)
Surface Type	High Flexible-mixed, Bituminous 7" Base and Surface

Table 9. TRM Query Results from Proposed S.H. 130/I-35 Interchange to Belton.

Record	Hwy	Marker	Disp	RU	Int_FTyp	Int_Typ	Feat_Grd	R_Sh_Typ	L_Sh_Typ	Surf_Typ	ADT	Trk_Pct	Trk_Vol	TDFO
1	IH0035	267	0.409	1	93		U	2	2	61	52640	26.3	13844	266.85
2	IH0035	267	0.44	1	93		U	2	2	61	52640	26.3	13844	266.881
3	IH0035	268	0.553	1	93		U	2	2	61	49460	27	13354	267.994
4	IH0035	269	0.027	1	21	B	U	2	2	61	49460	27	13354	268.468
5	IH0035	269	0.304	1	93		U	2	2	61	49460	27	13354	268.745
6	IH0035	271	0.782	1	21	B	U	2	2	61	49460	27	13354	271.223
7	IH0035	271	0.782	1	21	B	U	2	2	61	49460	27	13354	271.223
8	IH0035	273	0.867	1	93		U	2	2	61	49460	27	13354	273.308
9	IH0035	274	0.136	1	21	B	U	2	2	61	49460	27	13354	273.577
10	IH0035	274	0.69	1	93		U	2	2	61	47010	27.7	13022	274.131
11	IH0035	275	0.895	1	93		U	2	2	61	47390	27.6	13080	275.336
12	IH0035	276	0.633	1	93		U	2	2	61	47390	27.6	13080	276.074
13	IH0035	277	0.062	1	21	B	U	2	2	61	47390	27.6	13080	276.503
14	IH0035	280	0.213	1	21	B	U	2	2	61	47770	27.5	13137	279.733
15	IH0035	282	0.886	1	11	B	U	2	2	61	47770	27.5	13137	282.409
16	IH0035	283	0.974	1	21	B	U	2	2	61	47610	27.5	13093	283.49
17	IH0035	284	0.889	1	21	B	U	2	2	61	47610	27.5	13093	284.406
18	IH0035	286	0.193	1	11	B	U	3	3	61	47610	27.5	13093	285.712
19	IH0035	287	0.637	3	21	B	U	2	2	61	52300	26.3	13755	287.158
20	IH0035	289	0.29	3	21	B	U	1	2	61	52300	26.3	13755	288.813
21	IH0035	290	0.691	3	21	B	U	1	2	61	52300	26.3	13755	290.219
22	IH0035	291	0.884	3	11	B	U	2	2	61	52470	26.3	13800	291.407
23	IH0035	293	0	3	11	B	U	2	2	61	69070	18.8	12985	292.532
24	IH0035	294	0.434	3	11	B	U	2	2	61	69070	18.8	12985	293.968

Other corridors included in preliminary considerations were U.S. 290 from the east side of Austin toward Houston; U.S. 79 from Round Rock toward Taylor; U.S. 183 from I-35 toward Loop 1; and S.H. 6 in Bryan (the current TTI test bed site). Figure 19 shows all of these locations except for S.H. 6. The upper left shows U.S. 79 (Round Rock to Taylor); the upper right shows U.S. 183 (I-35 to Loop 1); the lower right shows I-35 (Austin to San Marcos); and the lower left shows U.S. 290/S.H. 71 (south Austin).

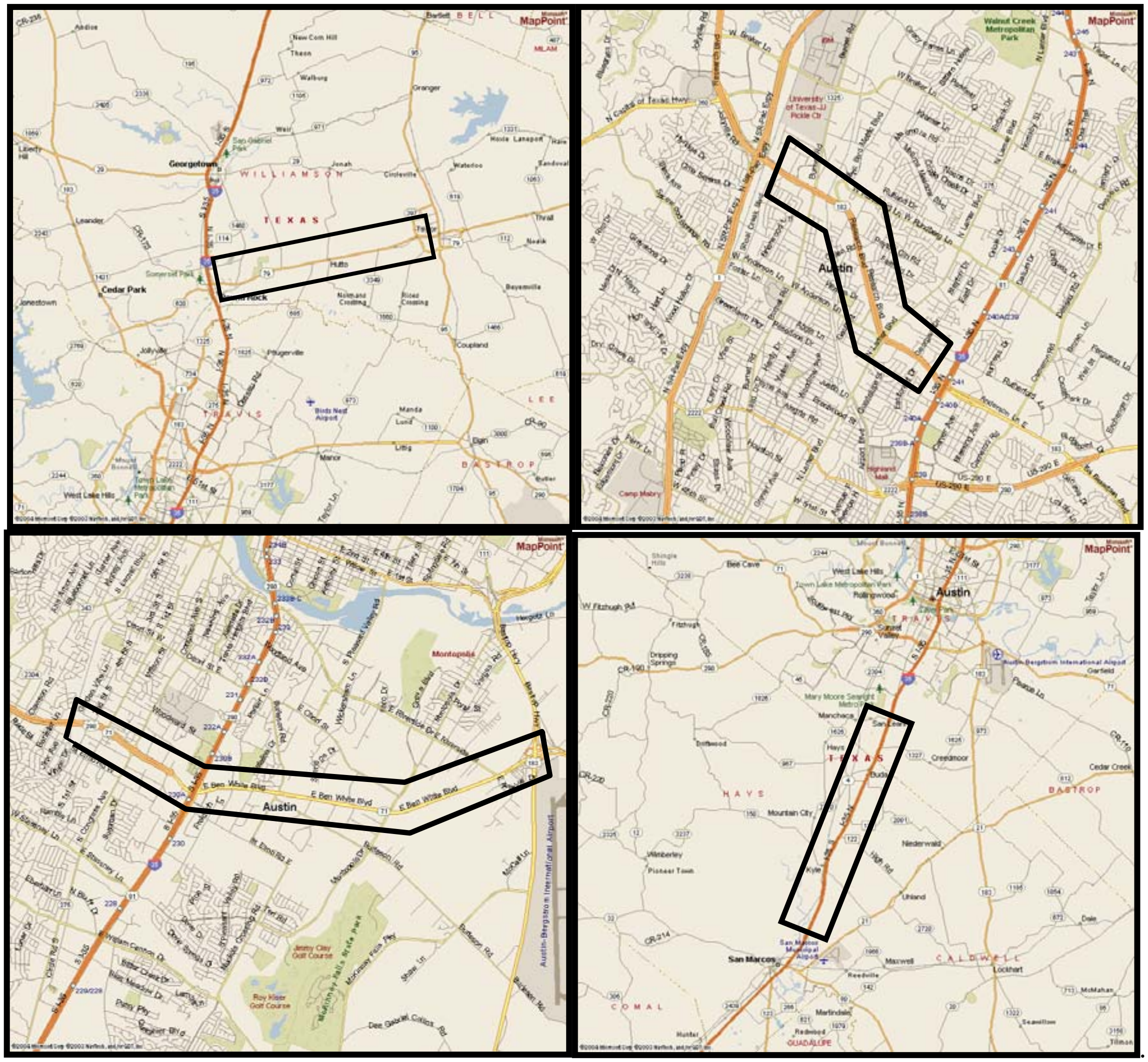


Figure 19. Other Candidate Locations.

U.S. 79 has significant truck traffic but it did not compare closely with I-35, either in truck volume or the variety of truck types. Other shortcomings of this corridor were limited sections of divided roadway and limited right-of-way for building a test and training facility. A possible location west of the F.M. 1460 intersection would require the section be upgraded to four-lane divided.

TxDOT had previously installed some traffic monitoring equipment on U.S. 183 that it was not using. Although this site would provide a very attractive travel time for TxDOT staff, it also has elevated structures, limited right-of-way, and recurrent urban congestion. Also, the vehicle mix at this location would have considerably more passenger cars and light-duty trucks and fewer heavy trucks.

Early discussions included a candidate site located south of Austin on I-35 near San Marcos and the DPS enforcement area. A site visit revealed that the roadway has three travel lanes in each direction separated by a concrete median barrier, and the surface on the mainlanes is asphalt. The diversion of truck traffic onto S.H. 130 when completed is expected to significantly reduce the truck volumes at this location. Discussions with TxDOT indicated that the traffic volume at this site would be excessive for reasonable access to the pavement.

The research team also considered candidate sites on U.S. 290/S.H. 71, but their location in the Austin urbanized area was a negative factor. The section under consideration extended from the Southern Pacific Railroad to the U.S. 183 interchange. Sites within this corridor are not candidates for a permanent WIM system because of: 1) recurrent congestion, 2) limited right-of-way for the placement of a building, and 3) limited sight distance along the roadway. Video surveillance equipment could help overcome the third shortcoming. There would also be a potential benefit of teaming with the Combined Transportation, Emergency and Communications Center (CTECC) in Travis County.

Figure 20 shows the S.H. 6 candidate site, but its distance from Austin of about two hours drive time was an impediment to it being selected as the primary site. However, it would not be expedient to completely ignore the site either. Funding for the significant infrastructure that already exists there came largely through state-funded programs, and it is within 5 minutes of Texas A&M University and the Texas Transportation Institute. It is already equipped with surveillance cameras and high bandwidth communication for viewing video or accessing data from operating systems via the Internet.

This site might serve TPP needs as a satellite site where TxDOT personnel could conduct some hands-on demonstrations in an environment of low to moderate traffic volume. Typical weekday traffic (both directions) on S.H. 6 at this location is in the range of 35,000 to 40,000 vehicles per day, with 10 percent trucks (FHWA Class 5 and above). Traffic conditions are almost always free-flow, but the noise level and the dispersion of vehicles are at desirable levels for many activities such as group demonstrations and studies that need isolated vehicles. The site has a unique high-end vehicle classifier that uses vehicle signatures to accurately determine vehicle speeds, counts, classifications, and occupancies. The site also has Class I piezoelectric sensors, several overhead non-intrusive sensors, and a 3M microloop detector system under the roadway. While there is no building on-site, the TransLink® Lab in TTI’s Gibb Gilchrist Building has served as an ideal venue for teaching purposes by receiving video and data from field test beds, supplemented by specialized equipment inside the lab.

Figure 20. S.H. 6 Test Bed in College Station.

5.3 INITIAL RESULTS USING SITE SELECTION CRITERIA

As the selection process continued, researchers narrowed the list to the four candidate sites shown in Figure 21, designated as Sites “A,” “B,” “C,” and “D.” At this point in the project, researchers had not considered a nearby rest area, which became designated as Site E. Three of the four sites are in Williamson County, north of the City of Georgetown, and one is in Bell County just north of the Williamson County line. The text that follows provides more detail on each of these candidate sites. Considering access and right-of-way needs led to focusing attention at interchanges, and only those interchanges with over-crossing roadways.

The location of Site “A” (see Figure 22) is in Bell County at milepost 280.213. The NE and SW quadrants are attractive locations. Figure 22 shows photos indicating some site features. The current cross-section is four-lane, divided with a depressed median. The Waco District is planning to reconstruct this section, beginning around mid-year 2006. Available turnarounds are located 2.66 miles to the north and 1.05 miles to the south. The estimated circuit time[10] is 15.2 minutes. The SW quadrant offers a large flat area that is elevated from the mainlanes, where the NE quadrant is also a large area but is only slightly elevated from the mainlanes. The NE quadrant also poses a drainage issue with the exposed culvert, which opens into an open area and naturally drains toward a storm sewer inlet in the NNE portion of this quadrant. The elevated area in the SW quadrant offers better sight distance of both northbound and southbound traffic than the NE quadrant. Because this section is currently being designed, there is an opportunity to work with the design consultant and the Waco District to incorporate the test facility into the larger process.

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[10] The definition of circuit time is twice the distance between turnarounds divided by an assumed 40 mph average speed times 60 minutes added to an assumed 2 minute delay at each turnaround (4 minutes total).

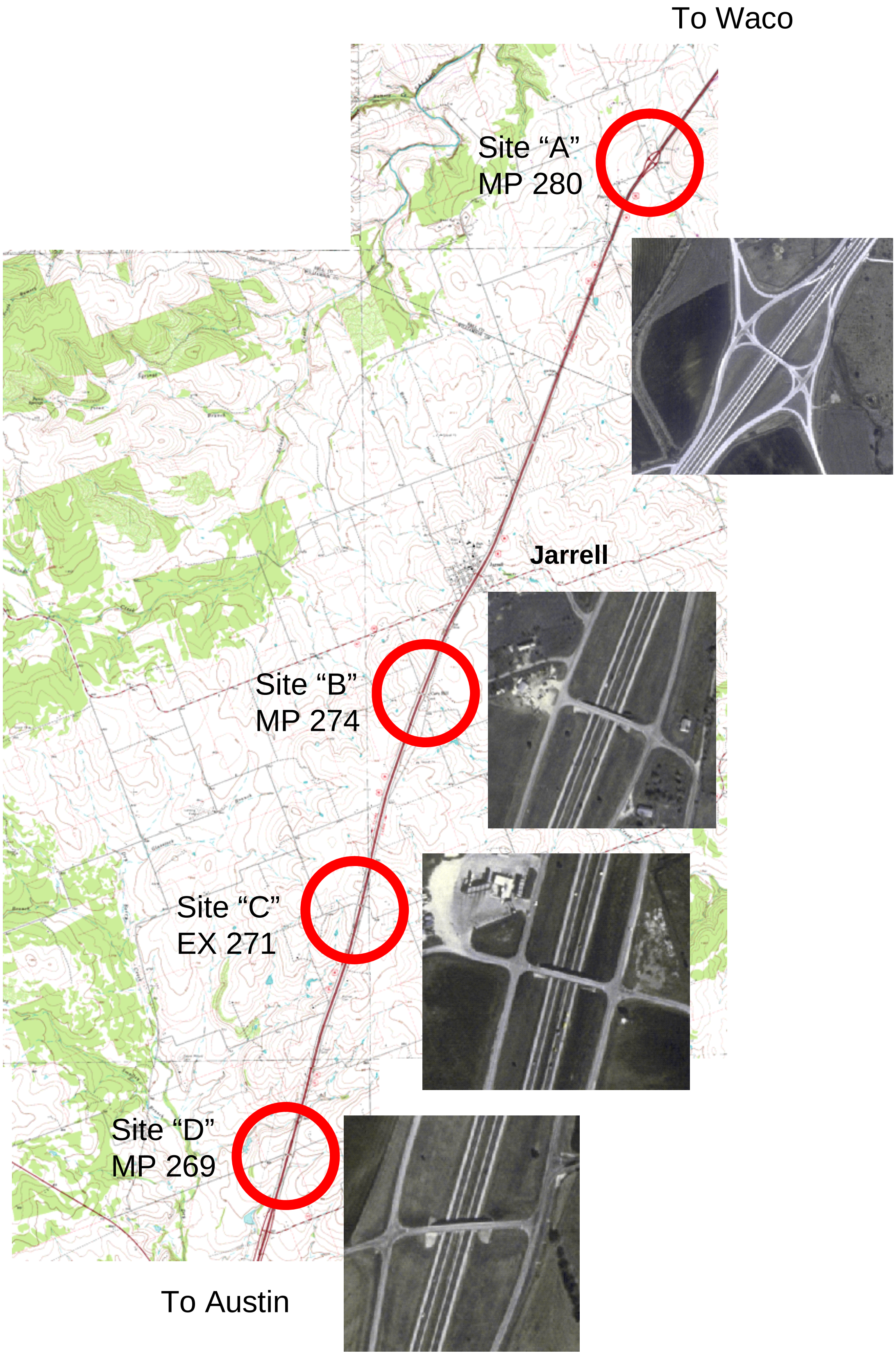

Figure 21. Locations of Proposed Demonstration Facility Sites along I-35.

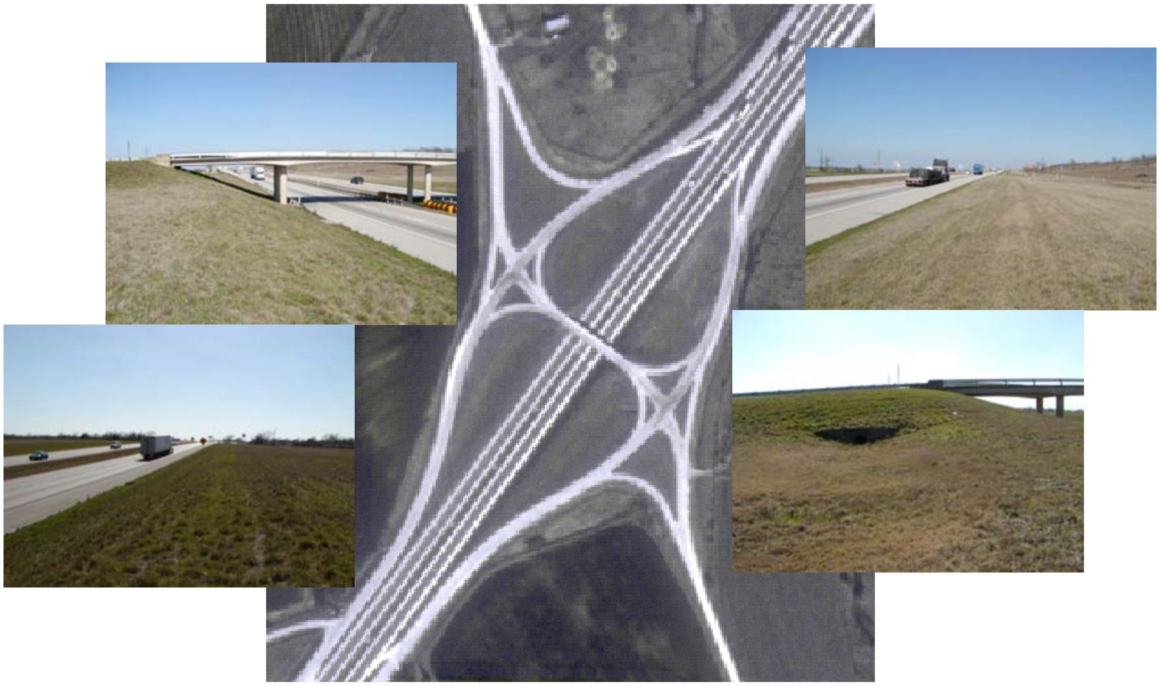

Figure 22. Site "A" Aerial Photo with Ground Photos Looking North and South from the NE and SW Quadrants.

The location of Site "B" (see Figure 23) is milepost 274.136. The NE quadrant is the only attractive location within this interchange. The cross-section is six-lane, divided with a permanent barrier. TxDOT reconstructed this section within the last 24 months. There are available turnarounds 1.4 miles to the north and 2.36 miles to the south. The estimated circuit time is 12.2 minutes. The median barrier on the north side of this interchange has anchor bolts for future overhead median lighting. The east side of the right-of-way has access to power. The Austin District plans to replace the crossover structure in the near future. Designs are underway to convert many of the diamond ramp configurations to an x-ramp design. Figure 24 displays the difference in these designs.

The location of Site "C" (see Figure 25) is milepost 271.782. The NE or SW quadrants are attractive locations. The cross-section is six-lane, divided with a permanent barrier. TxDOT reconstructed this section within the last 24 months. There are available turnarounds 2.36 miles to the north and 2.75 miles to the south. The estimated circuit time is 19.2 minutes. The slope of the embankment very near the overpass would require considerable work to provide a level and protected base. However, shifting the facility farther north on the east side would reduce this slope issue. Both sides of the right-of-way have power lines. The Austin District indicated that it will replace the crossover structure in the future. It also indicated that designs are underway to convert many of the diamond ramp configurations to an x-ramp design.

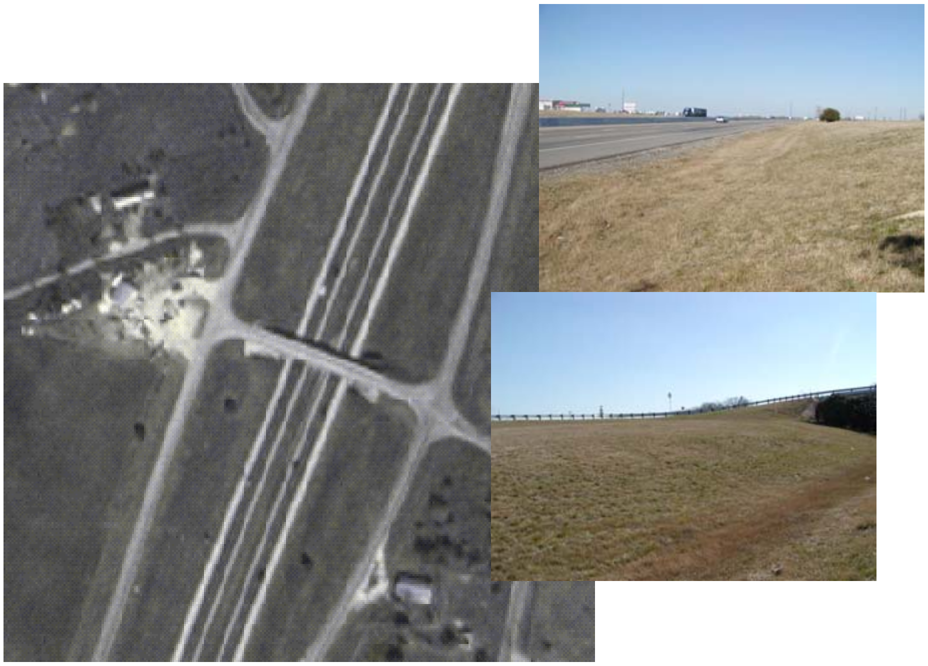

Figure 23. Site "B" Aerial Photo with Ground Photos Looking North and South from the NE Quadrant.

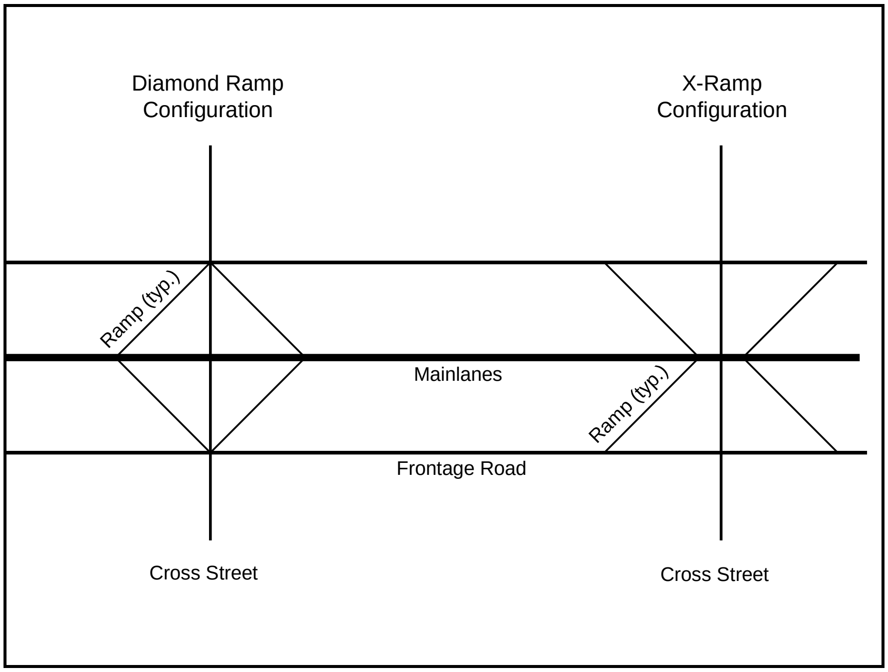

Figure 24. Diamond Ramp versus X-Ramp Configuration.

Figure 25. Site “C” Aerial Photo with Ground Photos Looking North and South from the NE Quadrant.

The location of Site “D” (see Figure 26) is milepost 269.027. The NE or SW quadrants are attractive locations. The cross-section is six-lane, divided with a permanent barrier. TxDOT reconstructed this section within the last 24 months. There are turnarounds available 2.75 miles to the north and 2.49 miles to the south. The estimated circuit time is 19.8 minutes. The area between the mainlanes and frontage road is greater at the NE quadrant than the SW quadrant. Because this area also extends northward, the building could be located slightly farther north of the current overpass to allow greater sight distance upstream and downstream from the selected vantage point. The large ROW area would also provide adequate space for the structure well outside of the clear zone of the mainlanes and provide ample parking for TxDOT staff and calibration vehicles. Another advantage to this location is the existing overhead sign mast north of the overpass on the southbound lanes. The right-of-way has power lines on both sides. The Austin District indicated that it will replace the crossover structure in the future. Designs are underway to convert many of the diamond ramp configurations to an x-ramp design.

Figure 26. Site "D" Aerial Photo with Ground Photos
Looking North and South from the NE and SW Quadrants.

5.3.1 Site Rankings

Researchers scored each of the four candidate sites against the previously presented selection criteria. Tables 10 through 30 display the characteristics for each selection criterion.

Table 10. Criterion 1 – Travel Time from TPP Offices.

Site	Travel Time (min)
A	41
B	36
C	34
D	32

Table 11. Criterion 2 – Geometric Characteristics.

Site	Radius of Curvature	Grade (%)	Cross Slope (%)	Lane Width (ft)
A	Tangent	1.8-2.5	2.0	12.0
B	Tangent	0.5-1.0	1.0-2.0	12.0
C	Tangent	1.5-2.0	1.0-2.0	12.0
D	Tangent	1.5-2.0	1.0-2.0	12.0

Table 12. Criterion 3 – Pavement Structure.

Site	Existing Pavement Type	Pavement Depth
A	AC	> 8"
B	AC	> 8"
C	AC	> 8"
D	AC	> 8"

Table 13. Criterion 4 – Traffic Volume and Truck Percentage.

Site	AADT	Percent Trucks	AADTT
A	47,770	27.5	13,137
B	49,460	27.0	13,354
C	49,460	27.0	13,354
D	49,460	27.0	13,354

Table 14. Criterion 5 – Multiple Lanes.

Site	Number of Lanes	Divided/ Undivided
A	4	Divided
B	6	Divided
C	6	Divided
D	6	Divided

Table 15. Criterion 6 – Access to Power and Telephone.

Site	Distance (ft) to Power	Distance (ft) to Telephone
A	30-100	100-300
B	30-100	100-300
C	30-100	100-300
D	30-100	100-300

Table 16. Criterion 7 – Distance to Safe Parking.

Site	Distance (ft)
A	0
B	0
C	0
D	0

Table 17. Criterion 8 – Space to Park Calibration Truck.

Site	Space for Truck
A	Yes
B	Yes
C	Yes
D	Yes

Table 18. Criterion 9 – Space for Permanent or Portable Structure.

Site	Space for Structure
A	Yes
B	Yes
C	Yes
D	Yes

Table 19. Criterion 10 – Structure for Mounting Detectors or Cameras (within 200 ft).

Site	Structure for Mounting
A	Yes
B	Yes
C	Yes
D	Yes

Table 20. Criterion 11 – Roadside Mast or Street Light to Mount Cameras.

Site	Roadside Mast/Light
A	No
B	No
C	No
D	No

Table 21. Criterion 12 – Lighting.

Site	Lighting
A	No
B	No
C	No
D	No

Table 22. Criterion 13 – Pavement Condition.

Site	Cracking	Rutting	Smoothness
A	No	No	PSR=5
B	No	No	PSR=5
C	No	No	PSR=5
D	No	No	PSR=5

Table 23. Criterion 14 – Pavement Rehabilitation Schedule.

Site	Months to/ from Rehab
A	12
B	12-24
C	12-24
D	12-24

Table 24. Criterion 15 – Calibration Truck Circuit Time.

Site	Circuit Time (min)
A	15.2
B	12.2
C	19.2
D	19.8

Table 25. Criterion 16 – Sight Distance.

Site	Sight Distance (ft)
A	> 1000
B	> 1000
C	> 1000
D	> 1000

Table 26. Criterion 17 – Proximity to DPS Enforcement Site.

Site	Distance to Enforcement (mi)
A	None
B	None
C	None
D	None

Table 27. Criterion 18 – Availability of Bending Plate WIM System.

Site	Bending Plate Availability
A	Buildable
B	Buildable
C	Buildable
D	Buildable

Table 28. Criterion 19 – Access to Satellite Sites.

Site	Distance (mi) to Satellite Sites
A	0.0-0.5
B	0.0-0.5
C	0.0-0.5
D	0.0-0.5

Table 29. Criterion 20 – Safety Features.

Site	Safety Features
A	Mostly in place
B	Mostly in place
C	Mostly in place
D	Mostly in place

Table 30. Criterion 21 – Presence of Congestion/Stop-and-Go Conditions.

Site	(avg times/week)
A	0
B	0
C	0
D	0

5.3.2 Other Considerations

The only site where TxDOT is planning upcoming construction is Site "A." The other three higher ranking sites are within recently reconstructed roadway sections. There may be negative public perception associated with pavement replacement in these sections.

The pending x-ramp designs within these higher ranking sites are also a negative characteristic for two reasons. First, the x-ramp designs will increase the circuit time for the calibration truck and drive those scores lower. Second, an entrance ramp located immediately upstream of the test facility is not desirable due to increased vehicular acceleration and lane changing. Lane changing will induce data errors because of incomplete vehicle occupancy in the lane as it crosses the sensors.

5.3.3 Site Selection Recommendations

Table 31 is a summary of the results of applying the site selection criteria to the four initial short-listed sites. Based on straight summation of scores and criteria, the sites rank from most attractive to least attractive as follows: "B," "C," "D," then "A." Upon applying the weighting criteria, the summation of weighted scores shows that the sites' decreasing attractiveness still ranks as: "B," "C," "D," and "A."

The only site where TxDOT expects construction is Site "A." Although Sites "B," "C," and "D" rank higher, TxDOT recently reconstructed those segments. There may be a negative public perception associated with pavement replacement in these recently reconstructed sections. With Site "A," future opportunities may exist to coordinate final geometric design with the Waco District to accommodate geometric design needs for the demonstration facility. It would also be advantageous to negotiate the placement of CRCP at Site "A" within the limits of the demonstration facility during reconstruction of a larger section of roadway in order to minimize additional project and construction expenses and motorist delays.

The foregoing text already noted the problems associated with the pending x-ramp designs at the higher ranking Sites "B," "C," and "D." The x-ramp design would increase the circuit time for the calibration truck and decrease the associated site-ranking scores, which the current rankings do not reflect. Also, an entrance ramp located immediately upstream of the

Table 31. Summation of Criteria Scoring by Candidate Site.

	Potential Site ID - Direction						
Critiera	A - NB	A - SB	B - NB	C - NB	D - NB	D - SB	General Notes
MP	280.213	280.213	274.136	271.782	269.027	269.027	
1	1	1	2	2	2	2	
2a	2	1	4	2	2	2	
2b	5	5	5	5	5	5	
2c	5	5	5	5	5	5	
3a							Not applicable to any candidate sites
3b	5	5	5	5	5	5	
4	5	5	5	5	5	5	
5	4	4	5	5	5	5	
6	4	4	4	4	4	4	
7	5	5	5	5	5	5	
8	5	5	5	5	5	5	
9	5	5	5	5	5	5	
10	3	3	3	3	3	3	Bridge structure located at all sites
11	3	3	3	3	3	3	
12	4	4	4	4	4	4	
13a	5	5	5	5	3	3	Score from FY2004 PMIS Distress Ratings
13b	5	5	5	5	5	5	Score from FY2004 PMIS Ride Score
14	4	4	4	4	4	4	Site A: expect to let in Jan '05; Sites B-D recently reconstructed
15	3	3	4	3	3	3	
16	5	5	5	5	5	5	
17	2	2	2	2	2	2	
18	3	3	3	3	3	3	
19	3	3	3	3	3	3	
20	5	5	5	5	5	5	
21	5	5	5	5	5	5	

Total	96	95	101	98	96	96
Composite	297	292	318	305	301	301

demonstration facility is not desirable because of the undesirable increase in both speed changes and lane changing through the test sections. Lane changing will induce data errors because of incomplete vehicle occupancy in the lane as vehicles pass the sensors.

Sites “A” and “D” also have the greatest available right-of-way located between the interstate mainlanes and the frontage roads to accommodate placement of a demonstration facility and its associated parking needs. The natural grades at these locations also are more desirable so that more extensive earthwork (and likely construction of retaining walls) need not be included in the construction costs of the demonstration facility. Despite the ranked scores, the influence of the aforementioned factors and use of judgment indicated the ranking of sites to be from highest to lowest: “A,” “D,” “B,” and “C.”

5.3.4 Consideration of the I-35 Rest Area (Site E)

As noted elsewhere, the research team became aware of the rest area just north of Site “A” after the initial selection process had ended with the selection of Site “A.” Compared to the other four sites, the rest area would offer much better access to utilities (including high bandwidth communication for Internet access), sufficient room to construct the needed facility, adequate access and parking for WIM calibration vehicles and TPP vehicles, and perhaps other advantages. Making this choice a successful one hinged on satisfying the needs of three groups within TxDOT: TPP, the Maintenance Division (MNT), and the Waco District.

Initial discussions with the Maintenance Division were promising even though some MNT personnel expressed concerns. These concerns seemed to be offset, at least initially, by the fact that TPP would install a vehicle count system at the entrance ramp to the facility and provide the data to Maintenance. However, MNT was very sensitive to the architectural design of the building, its placement, and the visibility of any equipment cabinets.

5.3.4.1 General Comparison of the Two Sites

The research team first prepared all conceivable pros and cons of switching from Site “A” to Site “E.” The next section provides a cost comparison. Besides cost, some of the other issues were: diversion of trucks from the mainline to the rest area, ample right-of-way at Site “E,” availability of parking at Site “E,” wireless Internet access at Site “E,” expedited scheduling of construction for Site “E,” no means of crossing directly to the opposite side of the freeway at Site “E,” and possible differences in visibility of approaching traffic. The advantages of Site “E” seemed to far exceed its disadvantages, especially when MNT began to entertain the idea of providing the building needed by TPP. This building would house TPP personnel and others who would visit the site for demonstration, training, or other possible uses.

5.3.4.2 Cost Comparison of Site “A” and Site “E”

To compare the costs of the two sites, the research team prepared spreadsheets and cost estimates. The analysis indicated that the total cost for Site “A” would be lower than that of Site “E” at $409,000 versus $442,000. The higher cost at the rest area was a direct result of the higher cost of the “site-built” building (940 sq. ft. at an estimated cost of $70/sq. ft.) versus the cost of the smaller portable building (480 sq. ft. at a cost of $56/sq. ft.) planned for Site “A.”

The estimates adjusted the total cost estimate for the rest area downward to reflect reduced parking required for the facility (due to the proximity of rest area parking) and did not include costs for a security fence, pedestrian gate, or Americans with Disabilities Act (ADA) ramp access to the building (assuming the research/training facility would be built at-grade). Researchers did not include the additional costs for Site “A” of sewer hookup and the significant cost of highway realignment to make the horizontal grades through Site “A” acceptable.

Clearly, having the facility at the rest area will provide for a superior operations/training structure and would reduce the cost of the overall system due to the relative proximity of existing facilities including phone lines, Ethernet, sewer hookup, and acceptable highway alignment. In addition, the rest area would provide improved security and should not require a security fence or pedestrian gate. The required parking area would also be greatly reduced at a savings to the project. The total cost estimate for the rest area facility includes a barrier to improve safety and inhibit public access to the facility.

5.3.4.2 Other Considerations

One of the overarching concerns expressed in most, if not all, meetings with the Maintenance Division was that aesthetics was very important. Therefore, the design of the proposed building, the location of equipment cabinets, and any other modifications to the refurbished rest area must be in accordance with the overall theme. Some of the specific discussion issues were the building location, the need for a barrier along the east side of the facility for safety of on-site personnel, and roadside equipment such as cabinets and camera poles. From an equipment perspective, the cabinets had to be located reasonably close to the roadway to keep the overall lengths of cables connecting roadway sensors to a workable length. From the perspective of MNT, there should be no cabinets in full view. Due to the length of the roadway that TPP would potentially monitor and the limitations of the equipment pertaining to locations of cabinets, there was no way to keep all cabinets far enough from the traffic lanes to satisfy the concerns of MNT.

5.3.4.3 Final Decision

After a series of meetings among researchers, MNT, and TPP, and much deliberation among researchers, there was a point reached where some of TPP’s critical needs could not be met by this site and still remain within the overall theme desired by MNT. The final decision was that Site “E” would not be a workable site after all, leaving TPP without an immediate solution to its need for a test site and facility. Ongoing efforts as this research project neared its end (August 2005) focused on I-35 near the town of Jarrell, Texas, which is near Site “A.”

5.3.5 Demonstration Facility Site Schematic

The research team conducted several iterations apart from and with the participation of TxDOT staff to develop a list of infrastructure and equipment needs for the demonstration facility. Figure 41 in Appendix B displays the site schematic for the demonstration facility. This appendix also contains tabulated cost estimates of the proposed facility. Even though most of the effort by project staff focused on Site “E” for the latest version of the site details, most of the features will apply to other sites. If the selected site uses a diamond interchange, the flaring of the frontage road provides a wider area for locating cabinets and possibly a small building. Also, locating the facility on a downstream interchange quadrant allows the bridge structure to act as a natural visual barrier for oncoming traffic to minimize changes in driving behavior. Locating it south of the overhead bridge (as in the initial Site “A”) provides the best sun angle throughout the year as well.

Following are some considerations that might be helpful to TPP, depending on the site finally selected. The site layout could include a small portable structure, surrounded by a chain link fence, located 15 to 30 ft from the edge of the roadway shoulder and at a point where occupants within the building have sufficient view of traffic passing through each demonstration zone. The structure will have a small entrance deck equipped with both stairs and a wheelchair accessible ramp.

Parking should accommodate about eight to 16 cars or pickup trucks, two calibration trucks of varying lengths, and two handicap-accessible parking spaces. It is desirable to locate the calibration truck parking in an area that will easily accommodate both the storage space and turning radii for a single unit and a single trailer calibration truck. Walkways should connect parking areas and the enclosed area around the structure.

The research team developed a conceptual plan that divides the section of mainlanes adjacent to the structure into 10 zones, each 50 ft in length. The authors suggest a total of five zones per direction of travel. Zone 0 begins at the near edge of the overhead bridge structure. One use of this zone could be monitoring non-intrusive devices attached to overhead structures. Zone 5 could include a pole (possibly with mast arm) for mounting non-intrusive devices. Two locations should have cameras. The first location is on a pole 150 ft downstream of the last zone on the nearest mainlane side. The second location will be on the structure on the far side from the portable structure. The plan provides for guardrail on each side throughout the demonstration zones and just beyond the most downstream pole to protect both the traveling public and TxDOT staff or vendors who may be working alongside the roadway.

Other site-specific considerations include pavement type, overhead lighting, and pavement markings. Because it is desirable to test data collection devices in both concrete and asphalt pavements, the plan includes CRCP in one direction – on the near side beginning 375 ft in advance of the structure and continuing 100 ft beyond the last zone. The plan proposes asphalt pavement for the opposite side. The plan should also consider overhead lighting. Although lighting is not a critical element to the design, it may be desirable in the future to test equipment under conditions that replicate urban freeway lighting. Also, it may be desirable to have continuous solid white lane stripes through the demonstration zones to discourage lane changing. Lane changing could negatively affect the results of equipment evaluations.

The preliminary cost estimate for this demonstration facility is approximately $450,000. This cost does not include the placement of CRCP, but it does include the material and labor costs of other aspects of the demonstration facility. Appendix B shows a breakdown of these costs. Removing the cost of traffic sensors and related equipment reduces the estimated cost of the facility to $286,000.

5.4 JUSTIFICATION FOR CONTINUING THE PROJECT

At the outset of this project, TxDOT intended to have a “go” or “no-go” decision at the end of six months of work. However, this decision assumed that the remaining work would rely on having a test site available to conduct the research. Researchers proposed ways to make the remaining tasks productive even without the proposed test site. Appendix C contains more information on the justification to continue the project.

CHAPTER 6.0 EVALUATE KISTLER QUARTZ WIM SENSORS

6.1 INTRODUCTION

Several states have already explored using quartz piezoelectric sensors for weigh-in-motion. These sensors have exhibited improved properties compared to piezoelectric ceramic sensors, although their cost is considerably greater. The initial installations in the U.S. relied on results of tests conducted in Switzerland as part of a COST 323 study *(19)*. In that study, researchers determined that the sensors were independent of temperatures and speeds down to 2.5 mph.

A quartz-piezoelectric sensor consists of a quartz-sensing element placed in a high-strength aluminum alloy extrusion and surrounded by elastic material. The sensors come in 3.28 ft and 2.46 ft lengths (1.0 meter and 0.75 meter). A 3.28-ft length sensor has 20 quartz disks under a pre-load and distributed evenly throughout the length. A force applied to the sensor surface causes the disks to yield an electric charge which is proportional to the applied force. A charge amplifier converts the electric charge into a proportional voltage *(20, 21)*. An appropriate electronics interface converts this signal to axle or wheel loads.

6.2 METHODOLOGY

The research team contacted state DOTs in Connecticut, Illinois, Maine, Michigan, Minnesota, Montana, and Ohio to discuss their experiences with the Kistler quartz sensors. The information requested by telephone included: number of sensors installed, number of failures by type, accuracy data compared to baseline at available time intervals, truck and total traffic volume, installation details such as sensor and inductive loop layout, type of epoxy used, pavement type, related weather factors, and any other documented information. Researchers also asked each DOT representative whether that state plans on continuing the use of the Kistlers and the exact application. The performance of these sensors in ACC was of particular interest.

The second way in which this research project investigated the Kistler sensors was to purchase enough components to install three lanes of WIM sensors in central and south Texas. TxDOT crews and the research team installed one lane of sensors in College Station at a TTI test bed on S.H. 6, one lane of sensors near Falfurrius, and one lane at Los Tomates in the Rio Grande Valley. Each site consisted of four individual quartz sensors, two were 3.28 ft in length and two were 2.46 ft in length. The layout consisted of a total detection width of 5.74 ft in each wheel path placed in a staggered pattern, with the leading detectors in the right wheel path and the trailing detectors in the left wheel path (or vice versa) and separated by a distance of approximately 10 ft. This chapter covers the findings from other states first, followed by the experience in Texas of installing and monitoring the three lanes of sensors for a period of several months.

6.3 EXPERIENCE OF OTHER STATES

The sections that follow provide information on number of sensors installed, failures, splices, maintenance activities, accuracy, installation details, epoxy, weather factors, and each state's intentions regarding continued use of the sensors.

6.3.1 Connecticut

Table 32 summarizes the number of Kistler weigh-in-motion sensors that Connecticut DOT (ConnDOT) installed and the approximate dates of installation. It also indicates the average annual daily traffic (AADT) for some sites.

Table 32. Connecticut DOT Kistler Installations.

Date Installed	WIM System Used	No. Installed in ACC	No. Installed in PCC	Highway No.	AADT	Truck Volume
October 1997	IRD	8 sites 4 elements	0	Rt. 2	22,300	4%
Summer 2003	IRD	2 sites 2 elements	0	Rt. 117	100	--
Summer 2003	IRD	0	2 sites 2 elements	I-84	--	--
Summer 2003	IRD	2 sites 2 elements	0	I-84	--	--

A research report documents the initial ConnDOT evaluation of the Kistler sensor technology *(22)* based on the site installed in October 1997. Several reinstallations were necessary due to reduced signal strength; these were accomplished in July 1998. There was moisture infiltration into the cables at the time of installation, so Kistler revamped the recommended installation procedure to correct the problem. Another re-installation became necessary for five of these sensors in September 1998. In October 1999, ConnDOT had to regrind a sensor in lane 3 that was protruding ¼ inch above the pavement. ConnDOT replaced this lane 3 sensor and another sensor in lane 1 in November 2000 due to reduced signal strength. ConnDOT found evidence of mice chewing on wires in the lane 3 hand hole during this replacement. This discovery raised suspicions about more widespread damage from mice in connection with previous sensor failures. At the remaining three sites, there have been no sensor failures. The sensor design has also been slightly revised since the first installations. There were no splices in the lead-in cable. ConnDOT used the grout that Kistler recommended and supplied. There were no weather factors related to the life of the sensors.

Cracking occurred in the asphalt pavement at the first site adjacent to the sensors, but none of these cracks contributed to sensor failures according to ConnDOT personnel. Maintenance personnel sealed the cracks. ConnDOT had to recalibrate/validate the site on Route 2 a number of times from 1998 to 2005. ConnDOT had to calibrate sites installed in 2003 once in 2004 and it planned on validating the sites again in June 2005.

These sensors connect to IRD electronics using a typical IRD installation array. This array consists of two loops and two strips of WIM sensors. The Kistler WIM sensors were 12 ft apart, with one 6 ft by 6 ft loop installed 6 ft upstream of the first WIM sensor and the second loop 6 ft downstream of the second WIM sensor. The summer 2003 installations used the same spacings in the lanes but only covered half of the lane width in each case as opposed to the full width in the 1997 installations. These more recent sites used two 3.28-ft sensor elements end-to-end to form a 6.56-ft left wheelpath WIM component followed by a 6.56-ft right wheelpath WIM component (or vice versa) separated by a distance along the centerline of 12 ft. Selection of left half-lane or right half-lane sequence was based on site and pavement conditions.

ConnDOT plans to install more Kistler quartz-piezoelectric sensors for research applications. The state has only installed these sensors to collect research quality data for LTPP. ConnDOT selected these sensors for this purpose due to their level of accuracy, low or no temperature dependence, low or no speed dependence, and relative ease of installation. ConnDOT will select other installations on a site-by-site basis.

6.3.2 Illinois

Illinois DOT uses Kistler sensors in its PrePass system as a sorter to determine the need for static weighing. IDOT started installing these sensors around 1999 or 2000, so the state has about four years of experience with these sensors. The initial decision to use these sensors considered a quick installation time, along with their accuracy. There are 18 weigh stations that weigh about 2.7 million trucks per year using these Kistlers, bypassing about 2 million of these trucks.

The average life of these sensors, based on the Illinois experience, is about 2 years. A few of the sensors failed immediately after installation (thought to be due to the installation process). IDOT installed some of the sensors in concrete and some in asphalt, and some in CRCP overlaid with 2 inches of asphalt. The IDOT spokesman did not know of any splices of the sensor leads. The ambient temperature during installation is important for adequate curing of the grout, but the IDOT spokesman believes that curing will be acceptable if temperatures remain above freezing.

The configuration used by IDOT is a staggered array using one set of sensors in each wheelpath, then another in the opposite wheelpath separated by a distance of 6 to 8 ft. Some sites use two sensor groups in this configuration, and some use four. In the latter case, the WIM system weighs each wheel set twice. IDOT recommends this staggered array so that when failures occur, replacing the leads of the failed unit will not damage adjacent sensor elements.

IDOT uses hydraulic load cells at 17 of its 20 interstate weigh stations; it uses no bending plate systems. Overall, the state prefers load cells because they do not fail as often as the Kistlers or bending plates, and the state does not have to request replacement money as often.

IDOT calibrates the Kistler sensors about three to four times per year, typically based on complaints from PrePass personnel. If the system starts weighing trucks a little heavy, PrePass usually asks for correction right away, but if it weighs a little light, PrePass does not react with quite the same sense of urgency. When asked if the state would continue to use the Kistler sensors, the IDOT spokesman stated that in most cases they will replace failed sensors with new Kistlers. However, in other cases, IDOT will replace some Kistlers with load cell systems. Kistlers installed by IDOT in concrete seem to last longer and perform better than in asphalt.

6.3.3 Maine

Maine DOT (MDOT) currently has 13 WIM stations installed with Kistler sensors for a total of 132 sensors. Table 33 summarizes these sites. Figure 27 shows a typical site layout used by MDOT to install the Kistler sensors. Table 34 indicates the failure and replacement history for Maine DOT Kistler sensors.

Table 33. Maine DOT Kistler WIM Systems.

Site Name	Date Installed	Location	WIM System	AADT	Truck Volume
Kittery	6/6/1999	I-95	ECM	58,950	4853
Howland	7/31/2000	I-95	ECM	6808	980
Cumberland	6/5/2000	I-295	ECM	8163	522
Gray	7/17/2000	I-495	ECM	19,980	2214
Masardis	6/4/2001	Rt. 11	ECM	879	238
Montecello	7/9/2001	US Rt. 1	ECM	3376	566
Bingham	7/27/2001	Rt. 201	ECM	2818	410
Lebanon	6/10/2002	Rt. 202	ECM	7825	482
Turner	9/9/2002	Rt. 4	ECM	10,181	688
Verona [a]	7/14/2003	Rt. 1 & 3	ECM	NA	NA
Prospect 1 [a]	7/21/2003	Rt. 1 & 3	ECM	NA	NA
Prospect 2 [a]	8/11/2003	Rt. 174	ECM	NA	NA
Old Town [a]	4/29/04	I-95 Weigh Sta. Ramp	ECM	NA	NA

[a] WIM stations used for overweight vehicle detection only.

Table 34. Maine DOT Kistler WIM Failures.

Site	Date Replaced	Lane No.	Comment
Kittery	7/26/2000	Lane 03, P1 Lane 00, P2	Replaced 4 sensors
Kittery	9/13/2000	Lane 01, P1	Replaced 2 sensors
Howland	8/30/2001	Lane 01, P1	Replaced 2 sensors
Howland	8/31/2001	Lane 00, P1	Replaced 2 sensors
Gray	10/16/2001	Lane 00, P1	Replaced 2 sensors
Cumberland	4/22/2002	Lane 00, P1	Replaced 2 sensors
Howland	9/12/2002	Lane 01, P2	Replaced 2 sensors
Montecello	5/26/2004	Lane 00, P1	Replaced 2 sensors

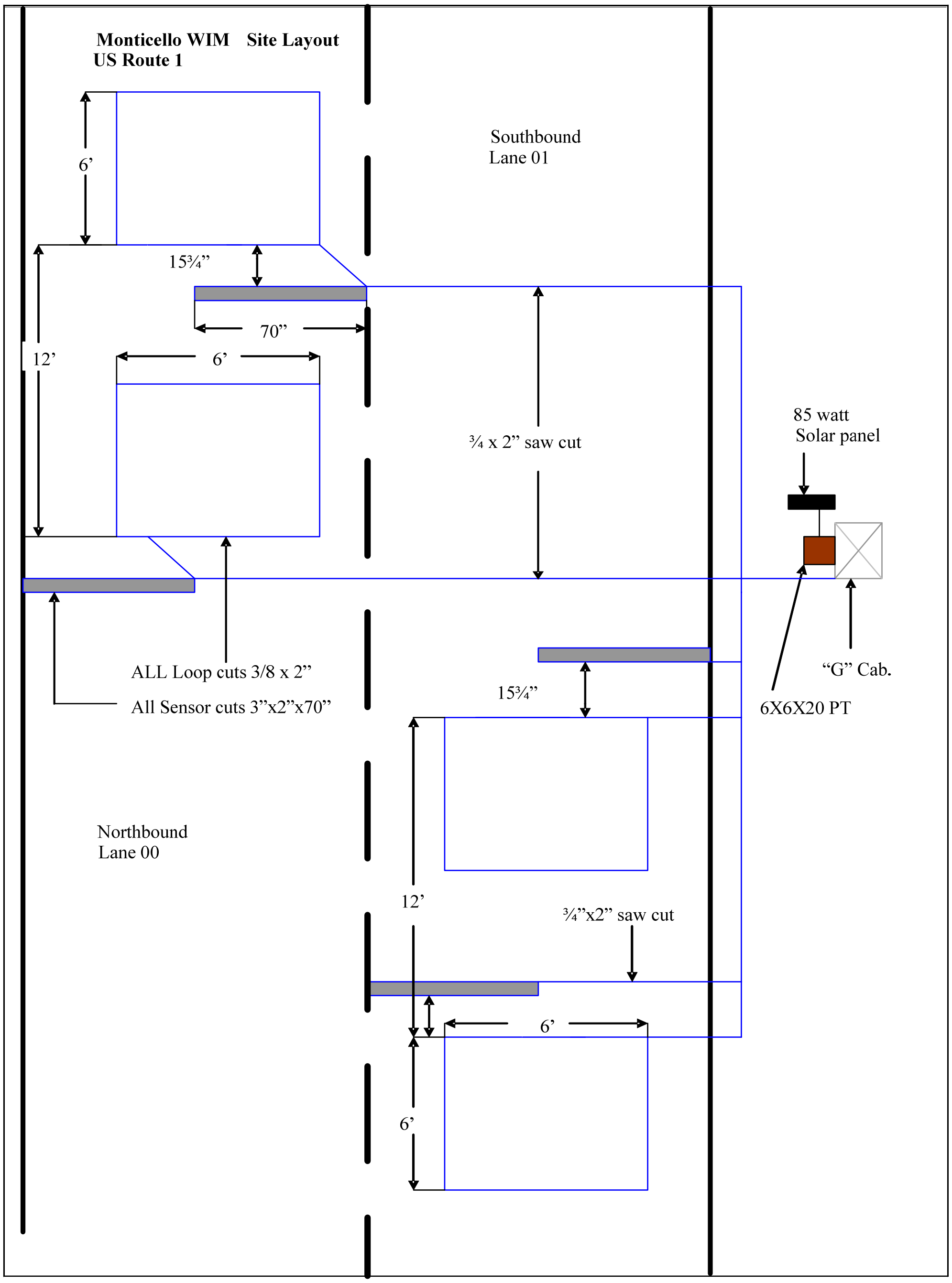

Figure 27. Maine Site Layout Schematic.

Sensor failures in all cases were internal to the sensor; there were no bad connections or sensor lead failures. Since installers mounted the sensors flush to the pavement and ground them smooth, some the sensor failures may have been due to the pavement settling faster than the sensor grout. The resulting effect might have caused the sensor to fracture, but this effect was never proven. In all cases of failed sensors, when field tested, the meter reading indicated low impedance to ground. Kistler representatives also thought that MDOT might have gotten a "bad batch" of sensors. MDOT has not had a single second generation Kistler sensor fail. Its

Lebanon, Turner, Verona, Prospect, and Old Town WIM stations all have the second generation sensors.

MDOT has lead-in cable splices at its Cumberland and Gray WIM stations, but there have been no problems associated with these splices to date. The agency used 3M epoxy splice kits to seal connections.

Once MDOT finishes a WIM site installation, it sets the WIM system to auto calibration mode. MDOT manually calibrates each site sometime afterward, turning off auto calibration once the site is "dialed in." MDOT calibrates all sites once a year and checks sites on a weekly basis for any discrepancies in the data. MDOT has found the Kistler sensors to be "extremely accurate." It has calibrated sensors to within 2 percent error compared to test vehicle gross vehicle weight.

MDOT used the Kistler resin kits for the sensors and "Frost Rock" for loops. MDOT experience indicates that the Kistler sensor/resin kits are extremely durable and hold up well throughout freeze/thaw cycles. In many cases, this material outlasts the surrounding pavement.

MDOT plans to continue using Kistler sensors even though their failure rate is of great concern. The accuracy of the sensor is the overriding factor causing the agency to continue installing and using them.

6.3.4 Michigan

Michigan Department of Transportation (MiDOT) has a total of eight sites that use Kistler sensors for weigh-in-motion data collection. None of these sites are enforcement sites. In 2004, the oldest of the Kistlers were 3 years old, and the most recent installations occurred in early October 2004. The eight sites represent a total of about 30 lanes. Only six of these lanes are in asphalt pavements, with the oldest installed about 1½ years ago. One of these installations is in a 6-inch asphalt overlay with concrete underneath.

MiDOT has had no failures that were the fault of the sensors. One site had a pavement failure – a cavity underneath the sensor – that took a while to diagnose. MiDOT replaced one sensor at this site, which failed after one year. The new sensor then failed after another year before MiDOT discovered the real problem.

MiDOT currently uses nothing but PAT systems with the Kistler sensors. It used a few IRD units initially but now prefers the PAT. The original system from PAT was a DAW 100, but now the DAW 190 has universally replaced the DAW 100s. PAT personnel supervised the first installations of Kistlers, but since then, MiDOT has done the installations completely by itself.

PAT evaluated the temperature correction needed for Kistler sensors and now builds that correction into its WIM electronics using a temperature probe in the pavement. MiDOT personnel believe the correction is quite small for the full range of temperatures experienced – in the 2 to 3 percent range.

Truck and total volume on roadways with Kistler sensors varies significantly. The lowest volume roadway carries 5209 total vehicles per day, with 421 of these vehicles being trucks. The highest volume carries 66,340 vehicles per day, with 22,435 of those vehicles being trucks.

The best conditions for installation of the sensors to achieve good cure time is in ambient temperature of 70 degrees F or higher. The grout will cure in cooler temperatures, but the time required to keep the lanes closed might become an issue. In some cases where temperatures are cooler, MiDOT has used a box fabricated by PAT to cover the grouted sensor and applied a moderate heat source. For the period from October through April each year, MiDOT does not generally install sensors such as the Kistlers.

Splicing has been a real problem with these sensors. The coaxial cable (coax) that comes with the sensors is smaller than the coax this agency typically works with and the size is at least part of the problem in being able to successfully splice the cable. Also, mice in ground boxes seem to be more a problem with this coax than they are with other ones.

MiDOT uses its own installation crews for installing the sensors, so its installations are probably superior to those installed by contractors, especially ones in which there is not full supervision and/or inspection. Results from early piezoelectric sensors indicate longer life for MiDOT installations compared to most others. MiDOT wet-cuts all installations, then hydro-blasts the saw cuts and lead-in saw cuts. Completely drying the saw cuts prior to installing the sensors and leads is very critical to a successful installation.

MiDOT has not expended much effort on calibration of the Kistlers, although it is now considering regularly scheduled calibration. Its normal procedure has been for a MiDOT engineer to set the calibration initially then use the PAT auto-calibration feature unless excessive drift occurs.

MiDOT has modified the installation procedure originally conceived by Kistler. With sensor pairs staggered in alternate wheel paths (MiDOT's preferred layout is leading left wheel path followed by trailing right wheel path), Kistler recommends installing a small conduit (say ½-inch diameter) in a saw cut for the coaxial cable leads from each sensor. The Kistler rationale for using the conduit was to be able to replace one sensor of the pair without disturbing or destroying the other one. MiDOT does not use the conduit, instead putting leads for the two sensors in the same $^{5}/_{16}$-inch saw cut. MiDOT would typically replace both sensors at the same time anyway, since the second one would probably get damaged during the replacement of the first one.

MiDOT has experienced significant problems with its piezoelectric sensors over the past few years, so some of the older piezoelectric sensors may be replaced with Kistlers in the near future. A big part of the problem with piezoelectric sensors appears to be related to unpredictable variations with temperature and is perhaps somewhat related to properties of the grout.

6.3.5 Minnesota

MnDOT completed its most recent Kistler WIM installation on September 29, 2004, bringing the total number of lanes of Kistler sensors in asphalt to six and to eight in concrete. The installations in asphalt are newer than the ones in concrete, but none of the sensors have been installed for a sufficient length of time to draw strong conclusions. MnDOT installed an additional system on the MnROAD project with one set of sensors in asphalt and one in concrete to test for seasonal drift and durability. MnDOT has not milled the pavement around the sensors because it selected sites with smooth existing pavement. The Mn/ROAD site was smooth as well, but even it was not necessarily consistent with the ASTM specification for smoothness.

MnDOT has had no problems at all with the Kistler sensors, but the installation process for these sensors requires complete attention to detail. For example, MnDOT encountered a situation in which the sensor leads were too short at one of its sites. One option would have been to simply use a junction box, but Kistler literature warns against it. It is possible to successfully splice the cable (e.g., for repairs), but Kistler does not recommend it as part of a “normal” installation. The signal from the sensor is so small that splicing the cable is risky.

Another installation issue that MnDOT encountered had to do with the height of the sensors relative to the pavement surface. Upon completion of each installation, the Kistler sensors should be flush with the pavement surface. MnDOT’s recent installations left the top of the sensors slightly below the surface because getting them flush in earlier installations required over-tightening of the leveling bars. This over-tightening left a tiny gap along the sensor, which could allow moisture penetration. The gap was due to the foam isolation strip extending above the top of the sensor. Over-tightening the leveling bar caused this strip to be separated from the sensor. In the most recent installs, the installation contractor chose not to tighten the leveling bar completely to avoid creating the gap, but installers then improperly positioned the sensors slightly below the pavement surface instead of slightly above as desired. The installer compensated by putting epoxy on top of the sensor, but it subsequently chipped off leaving the sensor slightly below the surface. The Kistler Corporation is investigating the need to change its installation procedure.

The Kistler sensors are delicate instruments that must be protected and installed properly. The MnDOT experience with these sensors indicates that once they properly install the sensors by following the detailed instructions from the manufacturer, the sensors have a good bond with the existing pavement and seem to be very durable.

The MnDOT spokesperson did not believe that Kistler sensors change with the temperature. In lab tests, there was insignificant variability, indicating that the minor changes from hot weather to cold weather, once installed in the pavement, are probably a result of changes in the stiffness of in-situ materials. For example, asphalt becomes less flexible in the colder winter temperatures compared to summer, so this phenomenon could be responsible for the observed difference of around 3 percent. The possible variability is small enough that the system still operates within acceptance testing standards without adjusting the weights.

MnDOT uses IRD WIM electronics with the Kistler sensors simply because MnDOT personnel are familiar with the equipment and the database loading code has been written to match its ASCII output files. There are other companies that offer hardware and software that are compatible with Kistler sensors (e.g., ECM Inc. of Austin, Texas; Golden River Traffic in the United Kingdom; and PAT America in Chambersburg, Pennsylvania). MnDOT personnel would prefer to store the data in raw format, but IRD considers the format of its binary files proprietary. MnDOT must process the data with IRD Office software before it can be loaded into an ORACLE database. MnDOT would also prefer a simpler system that could be solar-powered and communicate wirelessly but has not yet found a cost efficient option.

6.3.6 Montana

Table 35 is a summary of the Kistler WIM sensors installed by Montana DOT (MtDOT). MtDOT discovered a sensor problem at sites 1 and 2 (U.S. 87) in November 2002, which a Kistler representative later verified, indicating it was a grounding problem due to a manufacturing defect. Kistler replaced the sensors, and the state reinstalled them in May 2003. Following calibration by MtDOT in the fall of 2003, the weights agreed closely with static scale data. MtDOT retested the sensors in December 2003 and found an instability problem in one charge amplifier. There were no splices and no problems with lead-in cables. Weather was not a factor during the installation. MtDOT has not performed any in-road maintenance. Prior to replacement, there was no sign of cracks or damage.

Table 35. Kistler Sensors Installed by Montana DOT.

Date Installed	WIM System used	No. Installed in ACC	No. Installed in PCC	Highway No.	AADT	Truck Volume
May 2001	ECM	2 – wheelpath	0	U.S. 87 WB	4000	20%
May 2001	ECM	2 - wheelpath	0	U.S. 87 EB	4000	20%
July 6, 2004	ECM	2 - wheelpath	0	I-15	12,000	15%

Montana State University (MSU) collected data from the original sensors and found that the accuracy was "good." A recalibration performed in the spring of 2004 required little or no calibration adjustment.

A Kistler representative was on-site during the reinstallation to ensure that the installation went according to plan. All sites used the following sensor configuration. Each sensor array consists of two Kistler sensor elements – a 2.46-ft element and a 3.28-ft element. The layout used a 7-ft spacing between sensors, with a 6-ft square four-turn loop between them. Each site used the Kistler-supplied grout around the sensors.

Based on very limited experience, MtDOT plans on continuing to use the Kistler sensors as long as their durability is adequate. There is a four-lane installation planned in Rocker, Montana, as part of a Pre-Pass system. The state of Montana will perform any future installations.

6.3.7 Ohio

At the time of the contact, the Ohio Department of Transportation (ODOT) had not installed any Kistler sensors but planned on installing some soon. ODOT has done some significant preparations for these upcoming installations in terms of contacting others who had installed the sensors or who have been involved in related WIM research.

ODOT is planning on installing the Kistler sensors in a somewhat different array compared to some other states. They will not use either the standard “staggered” array or the full width array, which uses the full lane width. Instead, ODOT plans on using two sets of staggered sensors, using the same number of overall sensors as the full lane width array but separated by 6 ft. This layout is thought to provide better data in case one of the sensors fails. Each side of the vehicle will be weighed twice if all sensors are working, but if one sensor fails, it will still weigh both sides (one side only once).

ODOT emphasized the importance of selecting a good installer for the sensors. The installation process is very important to the accuracy and life of the sensors. The sensor is rigid, so placing it in flexible pavement will probably continue to be challenging. Still, ODOT will be placing some of its first sensors in asphalt.

6.4 TXDOT EXPERIENCE

The research team assisted TxDOT field installation crews in the installation of Kistler weigh-in-motion sensors at three sites of one lane each in Texas. Each site used four sensor elements—two 3.28 ft length and two 2.46 ft length sensors—at each one-lane site. Figure 28 shows the general layout for each site. One member of the research team was a certified Kistler-trained installer, so the research project did not have to request a Kistler factory representative to oversee the installation. As of the publication date for this report, TxDOT had not installed the fourth Texas site. The important information provided below for each site is pavement information, sensor calibration information, accuracy data and discussion, and recommendations regarding additional Kistler purchase and installation.

ECM, Inc., was the manufacturer of the WIM electronics package used for this research, identified by the trade name “HESTIA.” One exception was the use of a PAT system during part of the College Station tests. The State of Texas provided the ECM equipment to researchers for the duration of this study. Kistler Instrument Corporation manufactured the Quartz sensors used for this evaluation. The research project budget covered the purchase of the sensors, buying and installing them specifically for this research. It also covered the cost of charge amplifiers from Kistler to interface between the sensors and the WIM electronics. Installers tested all of the Quartz sensors for capacitance and insulation resistance “in the box”

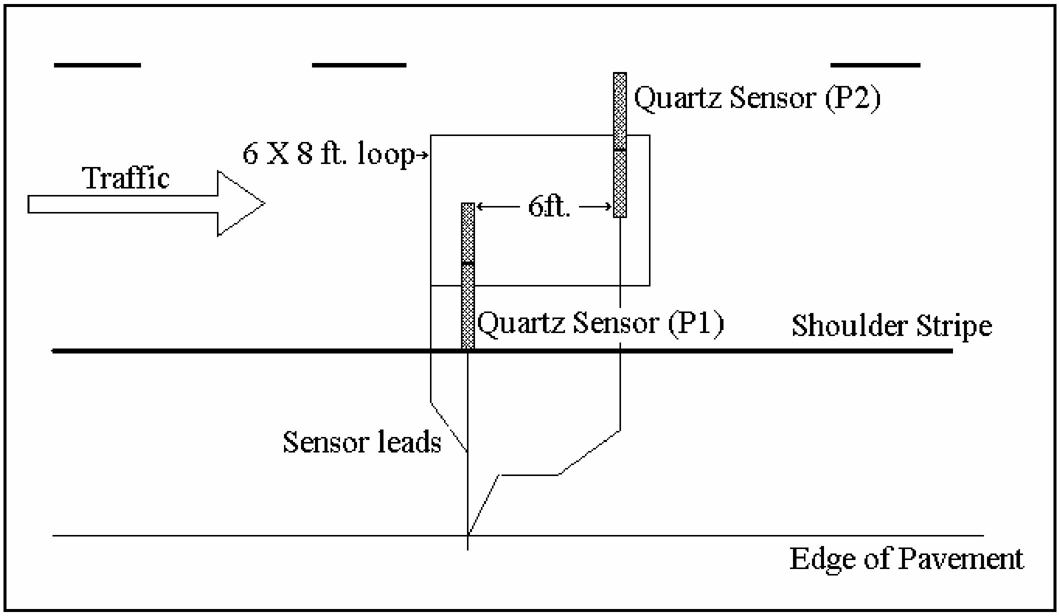

Figure 28. WIM Sensor Array (Typical).

and on-site just prior to installation. Some sensor elements did not pass this test and had to be returned to the manufacturer for replacement.

Data collection for this study included the periodic collection of repeated runs of trucks with known static weights. For repeated runs of these trucks, the principal truck that researchers used was the TxDOT calibration truck. In one instance, a contractor who was performing a special calibration on behalf of the FHWA provided two additional trucks. On another occasion, researchers collected the static weights of randomly selected trucks from the traffic stream. Truck weight enforcement scales provided the static weights of these trucks. After site installation, researchers polled data remotely from the WIM electronics using polling software and dialup modems. They collected this traffic data continuously from all sites for the duration of the study.

6.4.1 S.H. 6 in College Station

6.4.1.1 Site Description/Installation

S.H. 6 in College Station is a four-lane divided freeway with continuously reinforced concrete pavement overlaid with approximately 2.5 inches of asphalt. The average daily traffic on this roadway is about 45,000 vehicles per day with 10 percent trucks. This site serves as a test bed for TTI research pertaining to weigh-in-motion and non-intrusive detectors. TTI has equipped this site with a variety of video cameras and a power and communication network.

The College Station Kistler WIM sensor installation occurred on October 26, 2004. During pre-installation checks of the selected four sensor elements using the Kistler insulation tester, the first 3.28-ft sensor failed, forcing the use of another sensor. Installers measured and recorded resistance on all four sensors to be installed and performed the function test. They again measured the resistance after running the coax cables to the equipment cabinet and replacing Bayonet N-Type Compact (BNC) connectors.

The PCC pavement was in reasonably good condition at the time of installation; however, it would not satisfy the ASTM specification for WIM systems due to wheel path rutting. Rutting in the right wheel path was approximately 0.25 to 0.31 inches and 0.12 inches in the left wheel path. Installers did not measure longitudinal roughness, but they drove over the site and detected minor roughness through the car suspension.

TTI and TxDOT had installed fiber optic axle detector sensors several months prior to this installation, but all the fiber optic sensors had failed, so TTI elected to install the Kistler sensors in the same saw cuts as the failed 10-ft long fiber optic sensors. Kistler slots are 3 inches wide by 2.25 inches deep and about 6 ft in length. After removing the fiber sensors, installers filled the unneeded portion of the 1-inch by 1-inch slot with ECM P5G resin. The installation plan involved adding an additional 6-ft by 6-ft loop upstream of the lead Kistler sensor (P1). TxDOT installed this inductive loop using 12-gauge IMSA Spec 51-5 wire and winding it with four turns. The leading edge of this upstream loop was 10 ft from the leading edge of the downstream loop, leaving a 4-ft space between the two loops. The lead Kistler (P1) was 1 ft upstream of the existing 6.5-ft by 6.5-ft preformed loop sensor made with three turns of 18-gauge wire, and the exit Kistler (P2) was 1 ft downstream of the preformed loop. Therefore, P1 and P2 were about 8.5 ft apart. Figure 29 shows the layout.

Once installers had placed the two-sensor array in the partially grout-filled slot, they used weights to maintain the level of the sensors to hold them approximately flush with the road surface. The sensors were higher than the surface in the ruts (¼ inch to $^{3}/_{16}$ inch deep), requiring substantial grinding (see below) to make them flush across their entire length. Installers failed to remove the protective clear plastic film from the foam tape on both 3.28-ft and 2.46-ft sensors for P2 in the same saw cuts as the failed 10-ft long fiber optic sensors. However, the manufacturer did not believe that this oversight should impact the performance of this sensor.

After the sensor grout hardened, installers ground them to be exactly flush with the surface in the rutted wheelpaths using an angle grinder. Installers checked the surface for smoothness at regular intervals using a short section of straight aluminum and continued grinding until completely smooth. Aluminum leaves a perceptible mark on the sensor if the sensor is still higher than the surrounding pavement.

Installers added to the end of the 1¼-inch schedule 40 polyvinyl chloride (PVC) conduit a short 2½-ft section of 1-inch seal-tight flexible conduit. This formed a flexible connection between the end of the existing conduit (connecting the nearest pull box) and the edge of the pavement where loop and Kistler coax sensor leads exited the pavement. The flexible conduit conformed to the bottom of the trench, with the intent being to relieve stress on the lead-in cables near the edge of the shoulder.

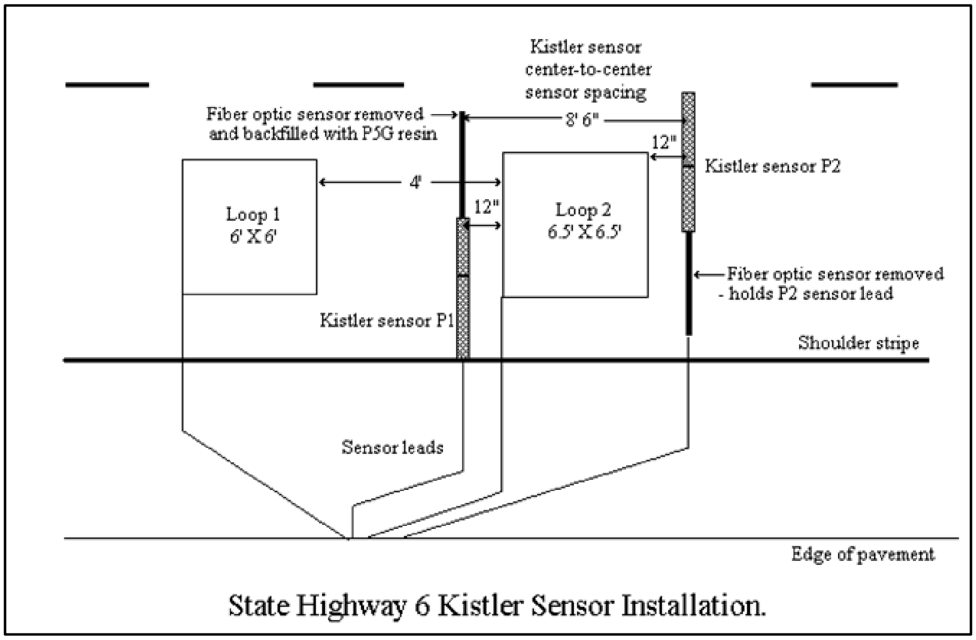

Figure 29. College Station Kistler Sensor Layout.

The 3.28-ft P2 sensor's red protective tubing was not long enough to reach the nearest roadside pull box, so installers added extra protection against rodents and moisture penetration. They ran the four Kistler coax lead-in cables through flexible ½-inch plastic tubing as further protection. This tubing ran the entire distance from the first roadside pull box through a second pull box then into the cabinet. Three of the four cables had the red tubing extending into the ½-inch plastic tubing (in the first pull box nearest the road), but the fourth was too short. A 3-M Scotchcast 82-A1 inline resin splice kit sealed the three red tubing-covered cables and the fourth coax lead-in cable watertight at the end of the ½-inch tubing. Installers grounded each Kistler sensor array prior to grouting using 8-gauge copper wire. They connected the two ground wires to a single 8-gauge copper wire by the edge of the road before entering the seal-tight flexible conduit. Then, installers connected the single 8-gauge copper wire to the equipment cabinet through conduit to a ground rod.

6.4.1.2 Calibration

Researchers and TxDOT performed calibrations at all sites shortly after installing the systems. The College Station site used the TxDOT calibration vehicle exclusively for the initial and the follow-up calibration checks. This Class 9 truck had airbag suspension on the drive tandem and leaf springs on the trailer and had a gross vehicle weight (GVW) of 57,480 lb. Table 36 values were slightly different in its College Station calibration compared to this same truck's weights elsewhere.

Table 36. Description of TxDOT Calibration Truck.

1. TxDOT Calibration truck - Class 9 5-axle tractor semi-trailer
    Axle weight 1 – 10,220 pounds
    2 – 12,300
    3 – 12,300
    4 – 11,330
    5 – 11,330 GVW = 57,480
    Axle Spacing 1 – 12 ft 2 in
    2 – 4 ft 4 in
    3 – 33 ft 1 in
    4 – 4 ft 1 in
    Length 59 ft 7 in

The main parameters used to perform the calibration at each site included: 1) speed factor (PZ-DIST), 2) length factor (LOOP_LNG), and 3) calibration factors (CAL1, CAL2). The speed calibration happened first since an accurate speed value is critical for the WIM electronics to perform the vehicle length and dynamic weight calculations. Installers can adjust the speed that the WIM system calculates by changing the parameter PZ-DIST, which is the distance between the staggered sensor strips. Calibration used the as-constructed distance (6 ft) initially and adjusted until the system produced an accurate speed. The process adjusted the vehicle length calculated by the WIM system by changing the longitudinal loop length variable LOOP_LNG. The starting point was the as-constructed loop length (8 ft).

The calibration factors CAL1 and CAL2 were the inputs used to calibrate the weight sensors Piezo 1 and Piezo 2. Installers adjusted these values independently for each piezo sensor until the average dynamic GVW from several runs of the calibration vehicle matched the measured static GVW.

6.4.1.3 Calibration Data Collection

Researchers allowed the College Station system to auto-calibrate using the default parameters shown in Table 37 from the time of installation until the calibration truck became available on December 22, 2004. Second and third calibrations occurred later.

Table 37. Existing Auto-Calibration Parameters.

Class	Subclass	Target Front Axle	Target GVW	Min GVW	Group Size	Weighting of group
9	37	10.6	75.6	60.0	5	3
9	38					

The first calibration on the TxDOT-supplied ECM Hestia started at 8:40 a.m. on December 22, 2004. On-site personnel turned off the auto-calibration feature for the duration of the calibration process and did not restart it after completing the calibration. The calibration truck only made six runs at 65 mph while researchers recorded the data. Table 38 indicates the initial and final gain control (manual) calibration factors. Upon analyzing the data, researchers determined that the system was properly calibrated and made no adjustments. Field personnel did not record the sensor capacitance reading. The "DVDT" column is for Delta Voltage/Delta Time, or change in voltage divided by change in time.

Table 38. Gain Control (Manual) Calibration Factors (First Calibration).

Lane	Piezo	Initial			Final		
		Cal	Amp	DVDT	Cal	Amp	DVDT
07	P1	634	2.63	60	634	2.63	60
	P2	683	2.63	60	683	2.55	60

The S.H. 6 site was the only one of the three evaluated in this report which used both EMC and IRD/PAT electronics for part of the Kistler tests. TTI calibrated the PAT/IRD DAW 190 unit on May 16, 2005, and operated the system until around June 28, 2005. Replacing the original ECM unit with the PAT unit required recalibration. A PAT/IRD representative brought the portable WIM system with built-in Kistler charge amplifiers to the site and assisted in the calibration. TTI disconnected the ECM system and the Kistler charge amplifiers and directly coupled the Kistler coax lead-in connectors to the input of the PAT/IRD system using BNC connectors. TxDOT logged data to a laptop computer while the calibration truck made five runs at 60 mph and seven runs at 70 mph. Table 39 summarizes the calibration run data factors.

Table 39. Gain Control (Manual) Calibration Factors (Second Calibration).

Lane	Piezo	60 mph		70 mph	
		Correction	Sensitivity	Correction	Sensitivity
04	P1	1100	1000	1050	1000
	P2	1100	1000	1050	1000

TTI used the loaned IRD/PAT DAW 190 system until around June 28, 2005. On that date, TTI resumed the use of the original ECM system, which came from TPP. Installers turned off the auto-calibration feature for the duration of the calibration process and did not restart it until after completing the calibration. The process ran the calibration truck five times at speeds ranging from 68 to 71 mph and recorded the data. Field personnel analyzed the results of all runs and made appropriate adjustments to the calibration factors. Table 40 summarizes the changes made to the calibration parameters.

Table 40. Gain Control (Manual) Calibration Factors (Third Calibration).

Lane	Piezo	Initial			Final		
		Cal	Amp	DVDT	Cal	Amp	DVDT
00	P1	812	?	60	785	2.16	60
	P2	861	?	60	830	2.06	60

6.4.1.4 Calibration Data Analysis

Analysis of the initial S.H. 6 calibration data for the original ECM system (December 2004) involved six runs of the calibration truck, indicating proper calibration and no need for adjustments. The second calibration effort for the PAT/IRD WIM system (May 2005) involved eight runs of the TxDOT calibration truck and two runs for researchers to record Kistler sensor signals while using the Kistler charge amplifier. Field personnel analyzed each run after the truck passed the WIM sensors. TxDOT adjusted the PAT/IRD correction factors once for 60 mph and once for 70 mph (none for 50 mph). Table 41 reflects the 60 mph and 70 mph calibration runs for this second calibration. Both calibration results satisfy ASTM weight accuracy specifications for Type I WIM systems for GVW, single axle, and tandem axle weights.

Table 41. Accuracy Results from Second Calibration Runs.

Error	GVW	Steer Axle	Drive Tandem	Trailer Tandem
±2.5%	6	5	2	7
±5.0%	2	1	6	1
±7.5%	0	0	0	0
±10.0%	0	2	2	0
±12.5%	0	0	0	0
±15.0%	0	0	0	0
>±15.0%	0	0	0	0
Total	8	8	16	

Data collected during the third set of calibration runs indicated that installers did not need to make any adjustment to the calibration factors. Table 42 shows the results based upon the five runs made by the calibration truck at or near 70 mph. These results satisfy ASTM weight accuracy specifications for Type I WIM systems for GVW, single axle, and tandem axle weights.

Table 42. Accuracy Results from Third Calibration Runs.

Error	GVW	Steer Axle	Drive Tandem	Trailer Tandem
±2.5%	2	5	1	2
±5.0%	2	0	2	2
±7.5%	1	0	2	0
±10.0%	0	0	0	1
±12.5%	0	1	0	0
±15.0%	0	0	0	0
>±15.0%	0	0	0	0
Total	5	5	10	

6.4.1.5 Polled Data Collection and Analysis

In addition to calibration data, researchers collected mixed truck traffic continuously after installing the sites to evaluate the accuracy of weights produced by the Quartz sensors and the stability of the measured weights over time. They polled continuous truck traffic data from the WIM systems and analyzed it based on front axle weights and gross weight distribution of Class 9 trucks. To assist with data processing and analysis, they developed a spreadsheet program on a Microsoft Excel platform using its programming language, Visual Basic for Applications. The developed spreadsheet program worked with continuous truck traffic data that the vendor's software had saved as multiple files. Upon importing multiple files into Excel, the spreadsheet program performed the following steps:

- highlighted possible duplicate records and eliminated them from analyses,
- presented a summary of daily and weekly traffic volume in tabular and graphic forms,
- unstacked gross vehicle and front axle weights for each day and each week, and
- presented daily and weekly weight distributions in charts.

Figures 30 through 33 graphically portray the results of polled data at S.H. 6. Figures 30 and 31 show data for each full week plotted as weekly averages of gross vehicle weight and front axle weight, respectively. The plot also indicates values of one standard deviation above and below the mean values for the week. Figures 32 and 33 show the distributions of these same values. The gross vehicle weights in Figure 32 indicate a bimodal distribution with peaks centered on about 30,000 lb and 80,000 lb. The front axle weight distribution plotted in Figure 33 indicates a peak at 11,500 lb.

6.4.1.6 Condition Survey

Researchers monitored the condition of the Quartz sensors and surrounding pavement over time, looking for cracking in and around the sensor, loss of installation grout, and changes in sensor capacitance and resistance measured across the dielectric material (core to shield). To date, there is no distress or degradation to report. There has been no cracking or grout loss observed, nor is there visible distress in the surrounding pavement. Also, there have been no significant changes in the capacitance or insulation resistance of the sensors. This good performance report is undoubtedly due in part to the short duration these sensors have been installed (10 months). Also, the sensors are in Portland cement concrete overlaid with asphalt, which provides a very stable support structure for the sensors.

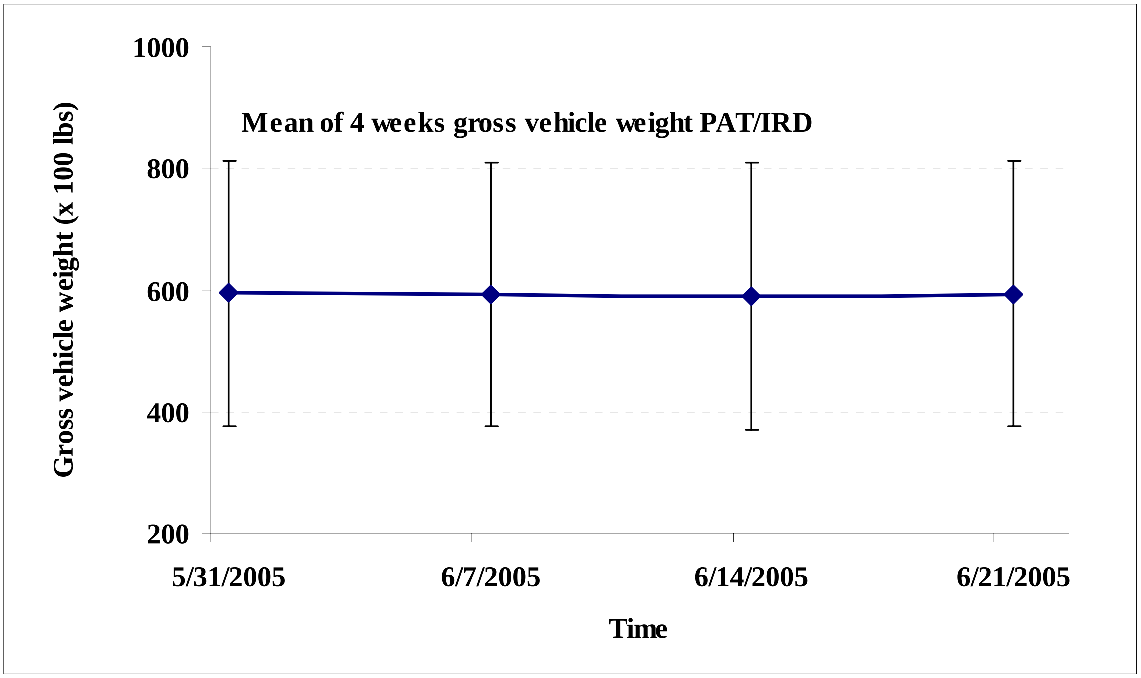

Figure 30. Weekly Averages ± One Standard Deviation of Gross Weight for S.H. 6 Site.

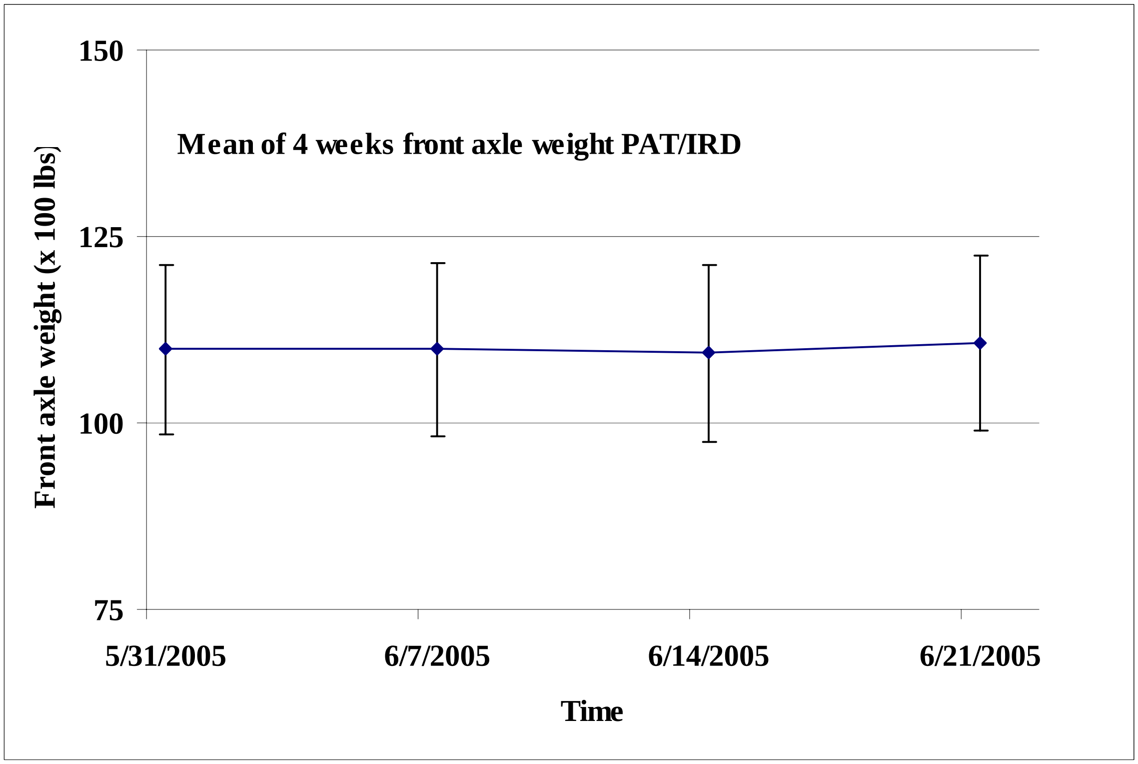

Figure 31. Weekly Averages ± One Standard Deviation of Front Axle Weight for S.H. 6 Site.

Figure 32. S.H. 6 PAT/IRD Gross Vehicle Weights (5/25/05-6/26/05).

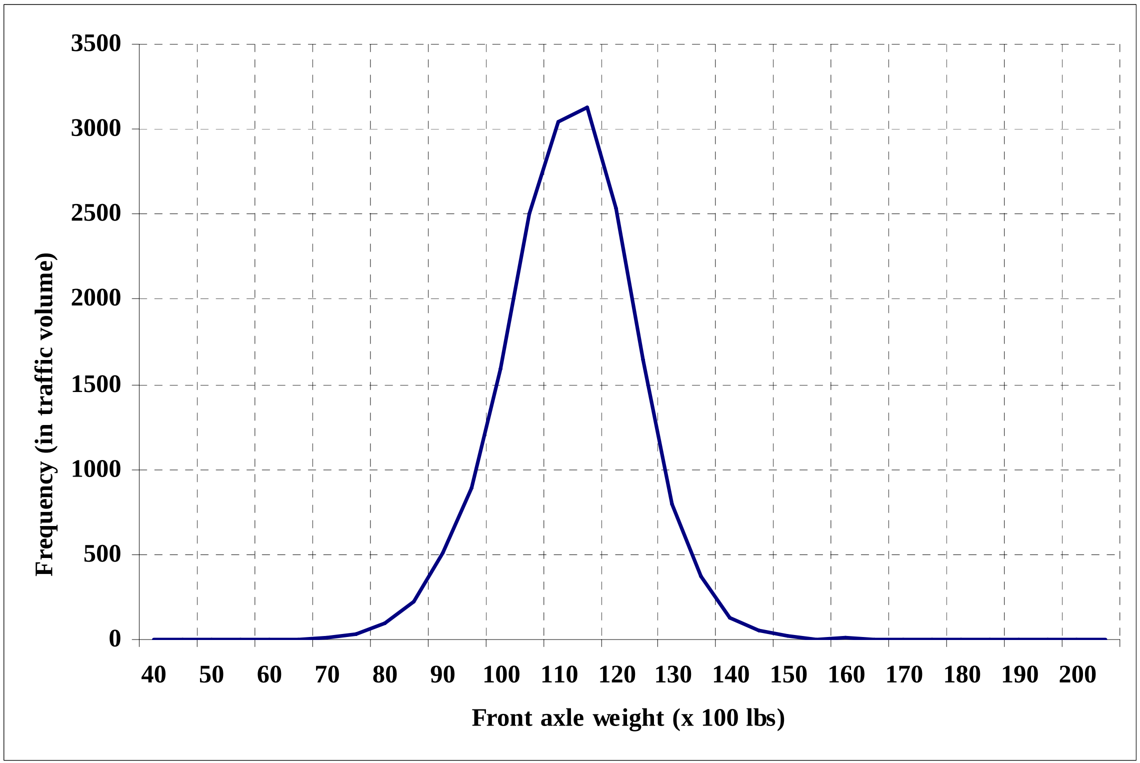

Figure 33. S.H.6 PAT/IRD Front Axle Weights (5/25/05-6/26/05).

6.4.2 U.S. 281 in Falfurrius

6.4.2.1 Site Description/Installation

The location of the Falfurrias site is on U.S. 281, 170 miles south of San Antonio. U.S. 281 is a four-lane, divided highway with an asphalt surface and an average vehicle speed of 70 mph. TxDOT replaced the pavement at this site with 500 ft of CRCP installed in all four lanes and ground smooth. A Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) section is located in the southbound-outside lane downstream of the site. TxDOT installed a four-lane bending plate system in January and February of 2005 and installed the Kistler sensors in the SHRP lane in February of 2005 approximately 75 ft downstream from the bending plate sensors. The sensor layout is identical to the Los Tomates site (presented below) with two half-lane Quartz sensors spaced 6 ft apart and a 6-ft by 8-ft loop installed between (and under) the sensors. TxDOT installed these sensors under the supervision of a factory trained and certified installer.

6.4.2.2 Calibration

The initial Falfurrias calibration used three trucks, one of which was the TxDOT calibration truck. Table 43 provides information on the other two calibration trucks. These two additional trucks used at Falfurrias had airbag suspensions. The weights and specifications of the calibration trucks are provided below.

Table 43. Description of Falfurrias Calibration Trucks.

1.Contractor supplied calibration truck - Class 9 5-axle tractor semi-trailer		
Axle weight	1 – 11,100 pounds	
	2 – 16,200	
	3 – 16,200	
	4 – 17,100	
	5 – 17,100	GVW = 77,700
Axle spacing	1 – 12 ft 1 in	
	2 – 4 ft 5 in	
	3 – 32 ft 6 in	
	4 – 4 ft 1 in	
2. TxDOT calibration truck - Class 10 6-axle tractor semi-trailer		
Axle weight	1 – 12,100 pounds	
	2 – 13,900	
	3 – 13,900	
	4 – 13,200	
	5 – 13,200	
	6 – 13,200	GVW = 79,500
Axle spacing	1 – 13 ft 10 in	
	2 – 4 ft 6 in	
	3 – 31 ft 0 in	
	4 – 4 ft 2 in	
	5 – 4 ft 2 in	

6.4.2.3 Calibration Data Collection

TxDOT installed the site at Falfurrias in March 2005 and performed the calibration six weeks later on April 26 – 27, 2005. Because of the time delay before calibration, researchers calibrated the site by modem. Using downloaded data, they calibrated the sensors by reviewing the gross weight bi-modal distribution of Class 9 trucks and adjusted the calibration values to center the unloaded peak distribution on 30,000 to 35,000 lb. When the calibration began six weeks later on April 26th, they ran three different calibration trucks over the sensors 43 times to validate speed and length calibrations. Using these data, installers analyzed the stability and repeatability of the WIM output without calibration changes. On April 27th, installers changed the CAL1 and CAL2 values to calibrate the weights. They performed this calibration effort under the supervision of a contractor, who was on site for a SHRP LTPP acceptance test of a bending plate system located 75 ft upstream of the Quartz sensors.

6.4.2.4 Calibration Data Analysis

The contractor in charge of the calibration asked that the weight calibration not be adjusted during the first day when the three calibration trucks made a total of 43 passes over the WIM sensors. The contractor used these runs to verify the speed and length measurements produced by the WIM system. Although the weights produced by the WIM system were not accurate when compared with the static weights, they served to test the ability of the WIM system to produce repeatable results. On the following day, researchers adjusted the weight calibration parameters in the morning before each truck made four additional passes. Figure 34 shows the GVW output for each of the three calibration trucks over the course of the day on April 26th before weight calibration and on April 27th after calibration. The data visually illustrates the consistency of the measurements before and after the calibration. Table 44 summarizes the results of the post-calibration runs on April 27, 2005 (Group 1). On June 21, 2005, TxDOT staff collected five runs with the TxDOT calibration truck to verify the calibration of the site. Table 44 presents the results (Group 2). Results of the five runs produced an average GVW of 57,900 lb, with a standard deviation of 1200 lb.

6.4.2.5 Polled Data Collection and Analysis

Data sets polled from the Falfurrias site cover a period of 51 days, beginning March 23 and ending May 12, 2005, with a total truck traffic volume of approximately 51,000. As shown in Figure 35, gross weights from Class 9 trucks produced by Kistler sensors during this period had a bimodal distribution with two comparable peaks at the ranges 30,000 to 35,000 lb and 75,000 to 80,000 lb. As with the Los Tomates site (presented below), a single peak characterizes the distribution of front axle weights, yet shifted to the range 10,000 to 11,000 lb.

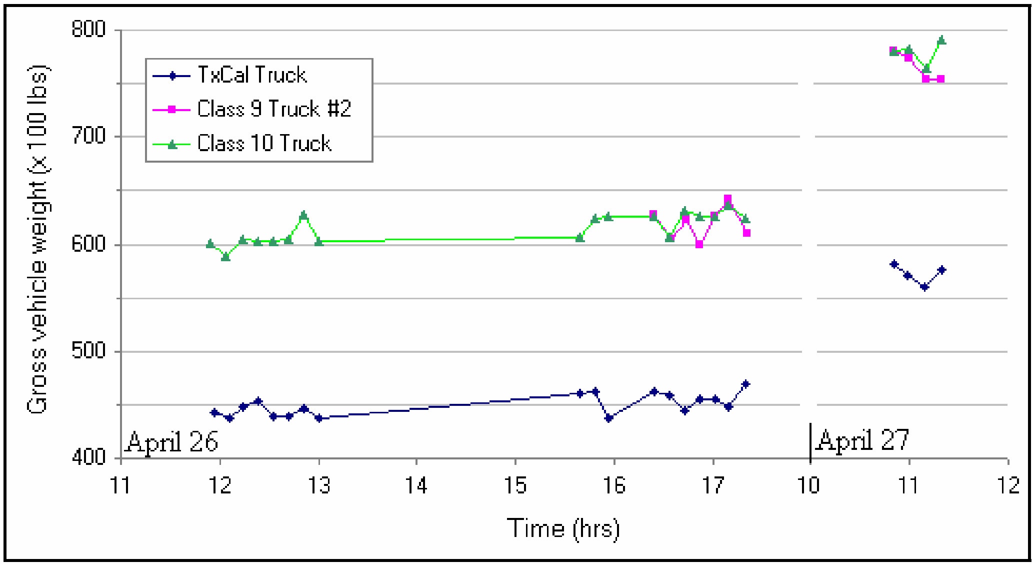

Figure 34. Falfurrias Calibration Truck Runs before and after Calibration.

Table 44. Falfurrias Truck Weight Accuracy Results.

Error Range	GVW (No. Obs.)	Steer Axle (No. Obs.)	Drive Tandem (No. Obs.)	Trailer Tandem (No. Obs.)	Tridem. (No. Obs.)	% Cum. Obs.
Group 1 - Post-Calibration Runs at Falfurrias (April 27, 2005)						
±2.5%	11	0	6	4	3	50
±5.0%	1	0	5	2	1	69
±7.5%	0	0	1	2	0	75
±10.0%	0	6	0	0	0	88
±12.5%	0	4	0	0	0	96
±15.0%	0	2	0	0	0	100
Total	12	12	20		4	
Group 2 - Falfurrias Calibration Verification with TxDOT Cal Truck (June 21, 2005)						
±2.5%	2	2		2	0	30
±5.0%	2	3	2	1	0	70
±7.5%	1		2	1	0	90
±10.0%				1	0	95
±12.5%			1		0	100
Total	5	5	10		0	

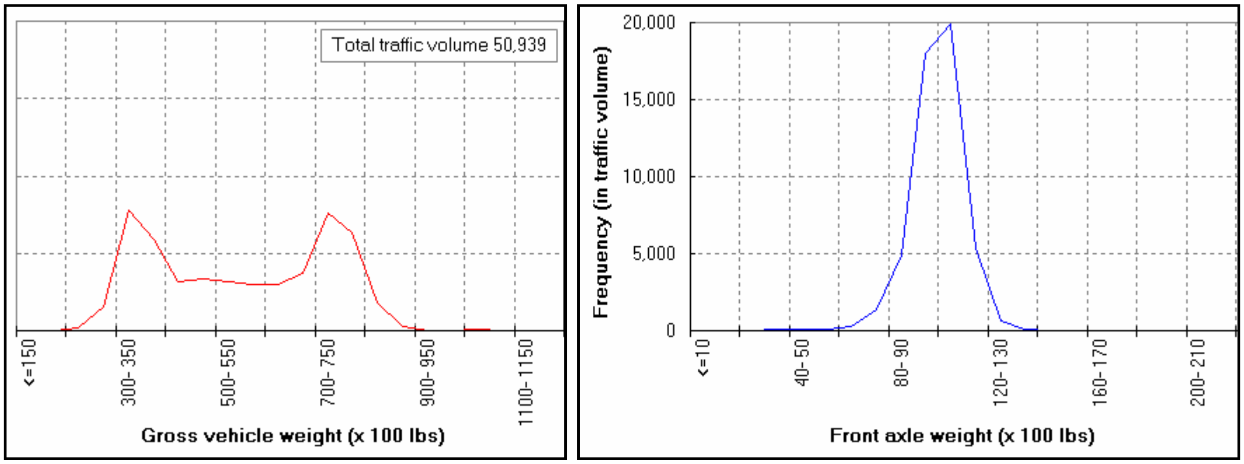

Figure 35. Distribution of Gross Weight (Left) and Front Axle Weight (Right) of Class 9 Trucks Passing the Falfurrias Site.

Figure 36 shows the weekly distributions of the measured weights. Although they have a similar shape as the overall distribution curve, the weekly distribution curves are not aligned as well as monthly distributions from the Los Tomates site (presented below). These curves exhibit more variation than Los Tomates data because only two weeks of these data were available after the calibration on April 27. Prior to this, researchers were making calibration adjustments by modem based on the statistical evaluation of truck traffic collected from the site. Figure 37 shows plots of weekly average weights ± 1 standard deviation. However, the accuracy and stability of the measured weights over time could not be evaluated given the relatively small size of the data sample polled after calibration.

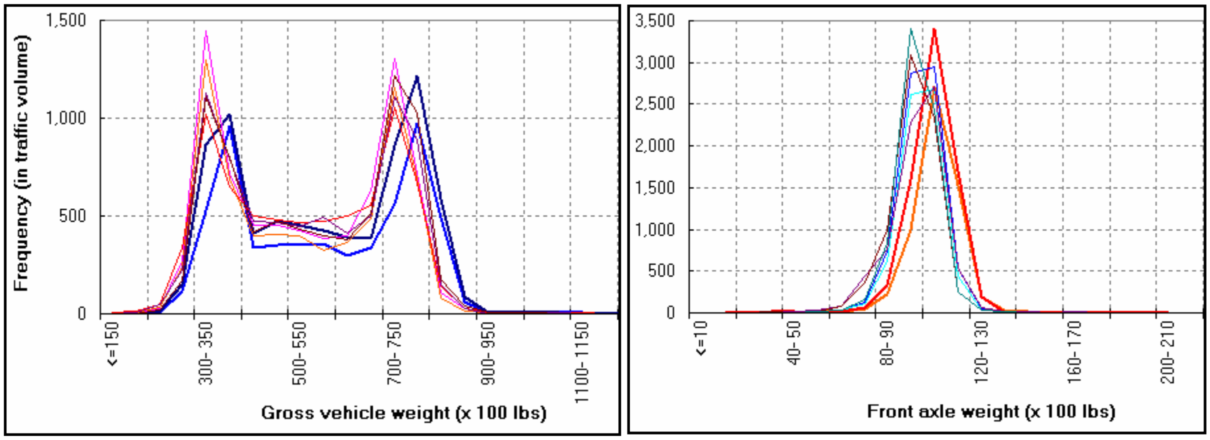

Figure 36. Weekly Distributions of Gross Weight (Left) and Front Axle Weight (Right) for the Falfurrias Site.

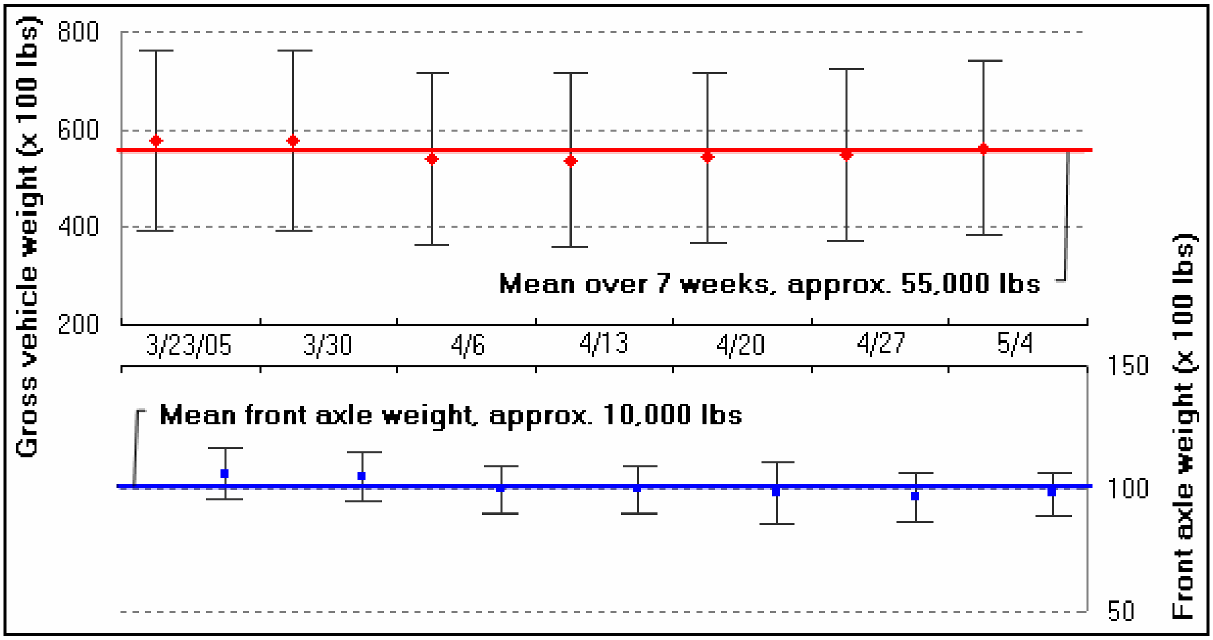

Figure 37. Weekly Averages ± 1 Standard Deviation of Gross Weight (Top) and Front Axle Weight (Bottom) for the Falfurrias Site.

6.4.2.6 Condition Survey

Researchers monitored the condition of the Quartz sensors and surrounding pavement at the Falfurrias site over time, looking for cracking in and around the sensor, loss of installation grout, and changes in sensor capacitance and resistance measured across the dielectric material (core to shield). To date, there is no distress, cracking, or grout loss observed, nor is there visible distress in the surrounding pavement. Also, there have been no significant changes in the capacitance or insulation resistance of the sensors. This good performance report is undoubtedly due in part to the short duration these sensors have been installed (6 months) and the fact that they are in Portland cement concrete.

6.4.3 Los Tomates Port of Entry

6.4.3.1 Site Description/Installation

The Los Tomates site near Brownsville is part of a truck weight/safety inspection facility operated by the Texas Department of Public Safety. TxDOT originally installed the single lane site with encapsulated piezo ceramic sensors in May of 2003, but due to the characteristics at this site, the ceramic sensors could not produce accurate weight results on a consistent basis. In July of 2004, TxDOT removed the ceramic sensors and installed Quartz sensors in the same slots under the supervision of a factory trained and certified installer.

Installers selected the sensor layout based on the typical WIM piezo sensor layout in Texas. The layout configuration consisted of two half-lane sensor strips installed 6 ft apart with a 6-ft by 8-ft loop installed between (and under) the sensors. Each half-lane strip assembly required connecting 3.28-ft and 2.46-ft sensor elements to produce a sensor strip 5.74 ft long. The loop extends beyond the sensors 1 ft. The pavement consists of reinforced Portland cement concrete with 20-ft joint spacings. Researchers did not measure longitudinal roughness, but they drove over the site at typical speeds and could not detect significant roughness from the vehicle suspension. The average speed of trucks crossing the sensors was 14.6 mph. This low speed served to minimize the potential impact of pavement roughness on truck weight measurements.

The location of the sensors at Los Tomates was not ideal for a WIM system. Trucks turn into the WIM lane 250 ft upstream from the sensors, and they make a right turn into the DPS facility 200 ft past the sensors. Some trucks accelerated over the sensors while others coasted or decelerated. These speed changes were an important reason why the piezo ceramic sensors, which rely on uniform front axle weights of Class 9 trucks (5 axle tractor-semi trailers) for self-calibration, did not perform well at this site. Also, the inspection station was open from 7:00 a.m. to 10:00 p.m. Monday through Saturday, and traffic needed by the WIM system to stay calibrated does not cross the site when the facility is closed.

6.4.3.2 Calibration

Installation of the Los Tomates site occurred in July of 2004, and installers set the WIM system to self-calibrate from installation until the calibration started the following morning. Prior to making calibration runs, field personnel turned off the self-calibration feature of the WIM electronics for the duration of the calibration process and kept it turned off for the duration of this study. They first adjusted the calibration value to correct the measured truck speed, followed by the length adjustment and then the weight. After calibrating the system, the installers ran the TxDOT calibration truck an additional 24 times at three different speeds (10, 15, and 20 mph) to analyze the repeatability and stability of the measurements and to determine the impact of vehicle speed on the measured weights.

6.4.3.3 Calibration Data Collection

After calibrating the Los Tomates WIM system, installers ran the TxDOT calibration truck an additional 24 times at three different speeds: 10 runs at 10 mph, 8 runs at 15 mph, and 6 runs at 20 mph. Table 45 summarizes the accuracy results (Group 1), which shows the number of observations in error range increments of ±2.5 percent for GVW, steering axles, and axle groups. The first column shows percent cumulative observations. These runs produced an average GVW of 57,500 lb, with a standard deviation of 2200 lb.

Thanks to the proximity of truck weight enforcement scales, researchers were able to collect additional dynamic vs. static weight comparisons at Los Tomates from mixed truck traffic. These comparisons included 5-, 6- and 7-axle trucks selected at random whose weights ranged from 60,000 to 106,000 lb. Table 45 summarizes these results (Group 2). The results from the mixed truck traffic also satisfied the ASTM Type I WIM system accuracy

Table 45. Los Tomates Truck Weight Accuracy Results.

Error Range	GVW (No. Obs.)	Steer Axle (No. Obs.)	Drive Tandem (No. Obs.)	Trailer Tandem (No. Obs.)	% Cum. Obs.
Group 1 - Los Tomates Calibration Truck Accuracy (July 26, 2004)					
±2.5%	10	2	6	5	24
±5.0%	11	5	8	11	60
±7.5%	2	4	4	5	76
±10.0%	1	10	5	2	95
±12.5%	0	2	1	0	98
±15.0%	0	1	0	1	100
Total	24	24	48		
Group 2 - Los Tomates Mixed Truck Traffic Weight Accuracy (July 26, 2004)					
±2.5%	7	3	4	3	38
±5.0%	2	0	2	5	58
±7.5%	1	3	4	2	80
±10.0%	2	4	0	0	93
±12.5%	0	0	1	0	96
±15.0%	0	1	0	1	100
Total	12	11	22		
Group 3 - Los Tomates Calibration Verification (March 29, 2005)					
±2.5%	4		1	1	38
±5.0%		3	2	2	81
±7.5%		1	1		94
±10.0%				1	100
Total	4	4	8		
Group 4 - Los Tomates Calibration Verification (June 15, 2005)					
±2.5%	1	0	0	0	5
±5.0%	4	1	2	4	60
±7.5%		2	2	1	85
±10.0%		2	1		100
Total	5	5	10		

specification for GVW, with 100 percent of all 12 comparisons occurring within ±10 percent. The results also satisfied the specifications for single axles and axle groups, with 100 percent of these comparisons falling within ±15 percent.

On March 29 and June 15, 2005, TxDOT personnel, using the TxDOT calibration truck, performed follow-up calibration verifications at Los Tomates. Table 45 presents the results of these runs (Group 3 and Group 4). For the calibration in March 2005, results of four passes of the truck indicate an average GVW of 58,500 lb and a standard deviation of 1500 lb.

In June 2005, five passes resulted in an average GVW of 57,900 lb and a standard deviation of 2000 lb. These runs demonstrate that the Quartz sensors did not require recalibration after 11 months of continuous operation. All weights produced by the system satisfy the ASTM WIM specifications for Type 1 WIM systems.

6.4.3.4 Calibration Data Analysis

Researchers analyzed the results from the July 26, 2004, calibration truck runs to evaluate speed dependency. They averaged all GVW and front axle weights for each speed range and used a simple linear regression analysis of speed versus GVW to find a dependency on speed, with an average increase in the GVW of 1600 lb for every 5 mph increase in speed. They did not evaluate this speed dependency further because higher speeds could not be achieved due to site geometry. Despite the apparent speed dependency, the results from this group of test runs satisfied the ASTM Type I WIM system accuracy specifications for all weight comparisons, with 100 percent of all 96 observations occurring within ±15 percent and 100 percent of the 24 GVW observations occurring within ±10 percent.

6.4.3.6 Condition Survey

Researchers monitored the condition of the Quartz sensors and surrounding pavement at the Los Tomates site over time, looking for cracking in and around the sensor, loss of installation grout, and changes in sensor capacitance and resistance measured across the dielectric material (core to shield). To date, there is no distress, cracking, or grout loss observed, nor is there visible distress in the surrounding pavement. Also, there have been no significant changes in the capacitance or insulation resistance of the sensors. This good performance report is undoubtedly due in part to the short duration these sensors have been installed (12 months) and the fact that they are in Portland cement concrete.

6.4.3.5 Polled Data Collection and Analysis

Data sets polled from the Los Tomates site ranged from March 27, 2003, to May 13, 2005, and pertain to 470 days, with a total traffic volume exceeding 140,000 vehicles. Figure 38 plots the monthly distributions of the measured weights, where each curve represents one of the nine consecutive months following installation of Kistler sensors on the site. It can be observed that as each curve fits to another for both gross and front axle weights, the weights measured by Kistler sensors were stable over the duration of the study. Figure 39 also shows the stability of the measured weights, which shows weekly average weights ± 1 standard deviation for all traffic data, including data collected from the piezo ceramic sensors that the Kistler sensors replaced. Note that since the Kistler sensor installation during the week of July 26, 2004, both gross and front axle weights became more stable from week to week.

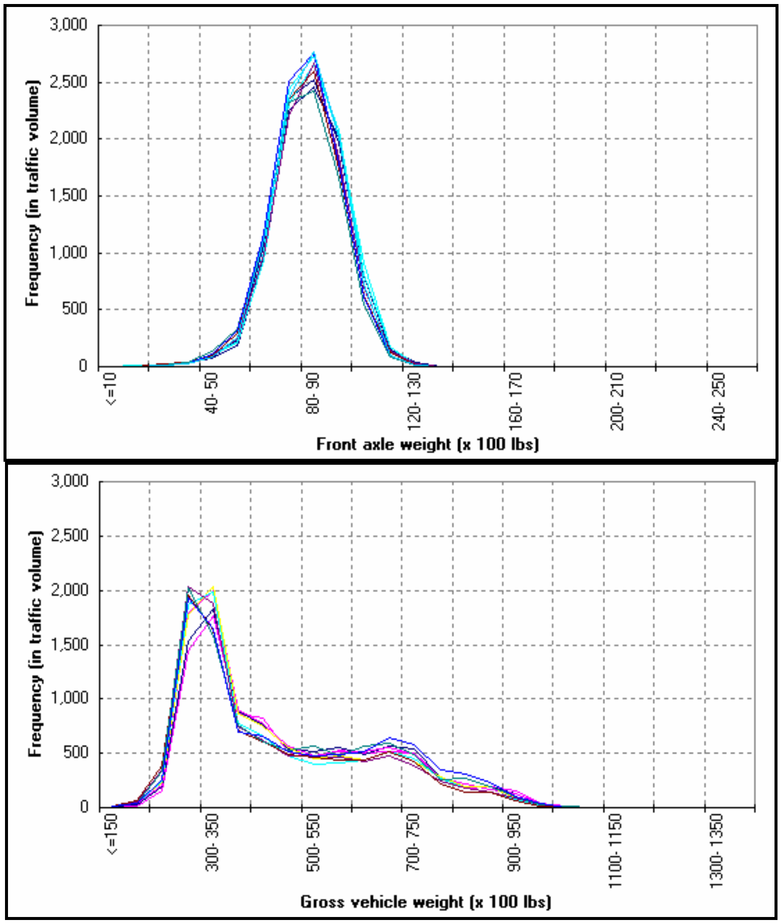

Figure 38. Monthly Distributions of Gross Weight (Top) and Front Axle Weight (Bottom) after Kistler Sensors Were Installed on the Los Tomates Site.

6.4.4 Pavement Considerations

Researchers collected sensor signals from the Quartz sensors at all sites and evaluated the quality of the signals. There are several characteristics of piezo sensor signals that make them more or less desirable for WIM applications. These characteristics include the signal to noise ratio, signal shape, and the magnitude of the negative portion of the signal. In the case of piezo ceramic sensors, the stiffness and elastic behavior of a pavement structure directly affect the performance of a WIM system. When installed properly, these sensors become a part of the pavement structure, and as the pavement deflects under load, so will the piezo sensor. Also, as the pavement rebounds or recovers from a load, so will the sensor. If the pavement deflects too much or cannot recover quickly enough from an axle load, the quality of the piezo signal (and thus the accuracy of the WIM system) will decline. Figure 40 illustrates the significance of pavement structure on the quality of a piezo ceramic sensor signal. The top pair of signals in this figure illustrates a sensor with low signal noise but a large negative signal component resulting from pavement defection under load. The third and fourth signals from the top show another pair of ceramic sensor signals in a different asphalt

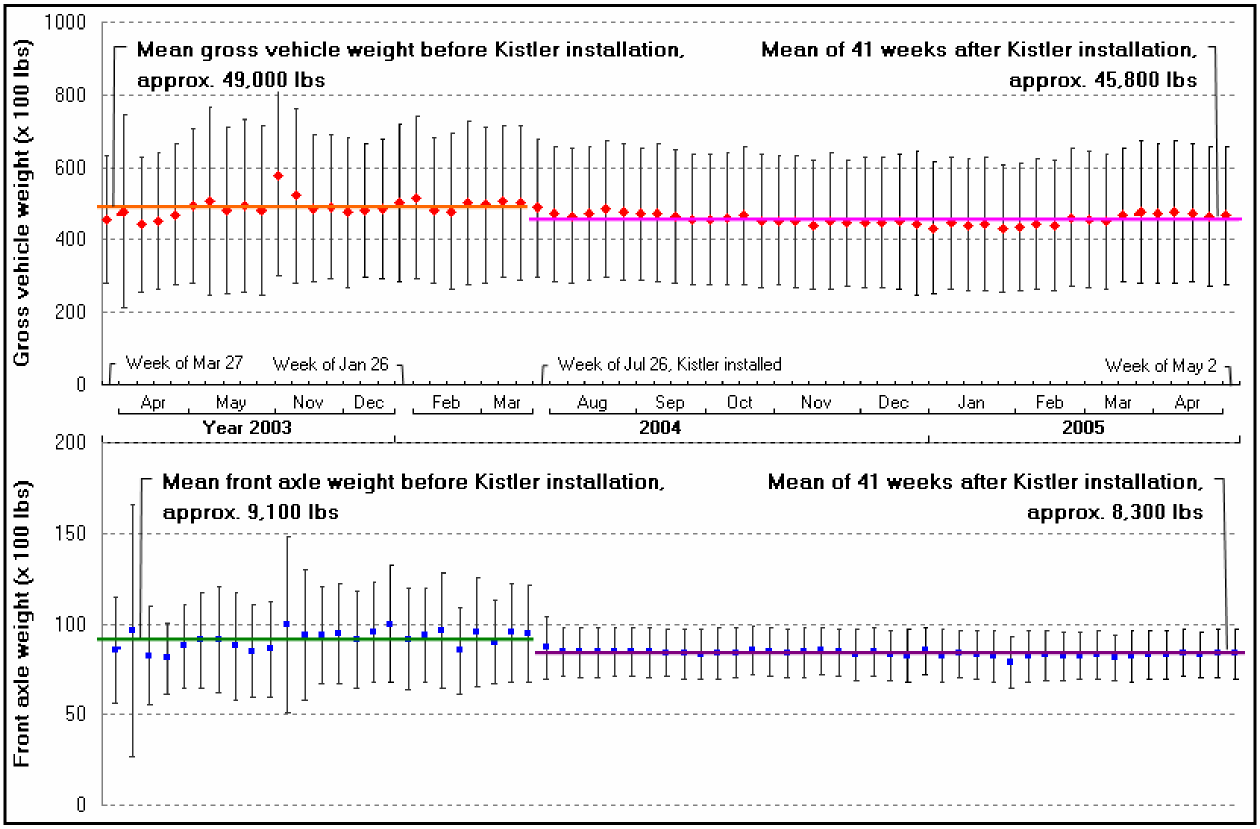

Figure 39. Weekly Averages ± 1 Standard Deviation of Gross Weight (Top) and Front Axle Weight (Bottom) for the Los Tomates Site.

pavement that does not rebound quickly from load, which causes the rounded signal and poor signal recovery between consecutive axles in a tandem group. Each of these features contributes to produce less desirable sensor signals for weigh-in-motion applications and would lower the weighing accuracy of the WIM system. The last pair in Figure 40 shows signals from the Quartz piezo sensors at Los Tomates taken as the TxDOT calibration truck crossed the sensors. This signal signature is typical of Quartz sensor output installed in PCC and asphalt pavement structures. The absence of a negative signal is due to the design and installation of the sensor, which isolates the sensing element of the sensor from the effects of pavement deflection and produces a signal that is ideal for weigh-in-motion applications.

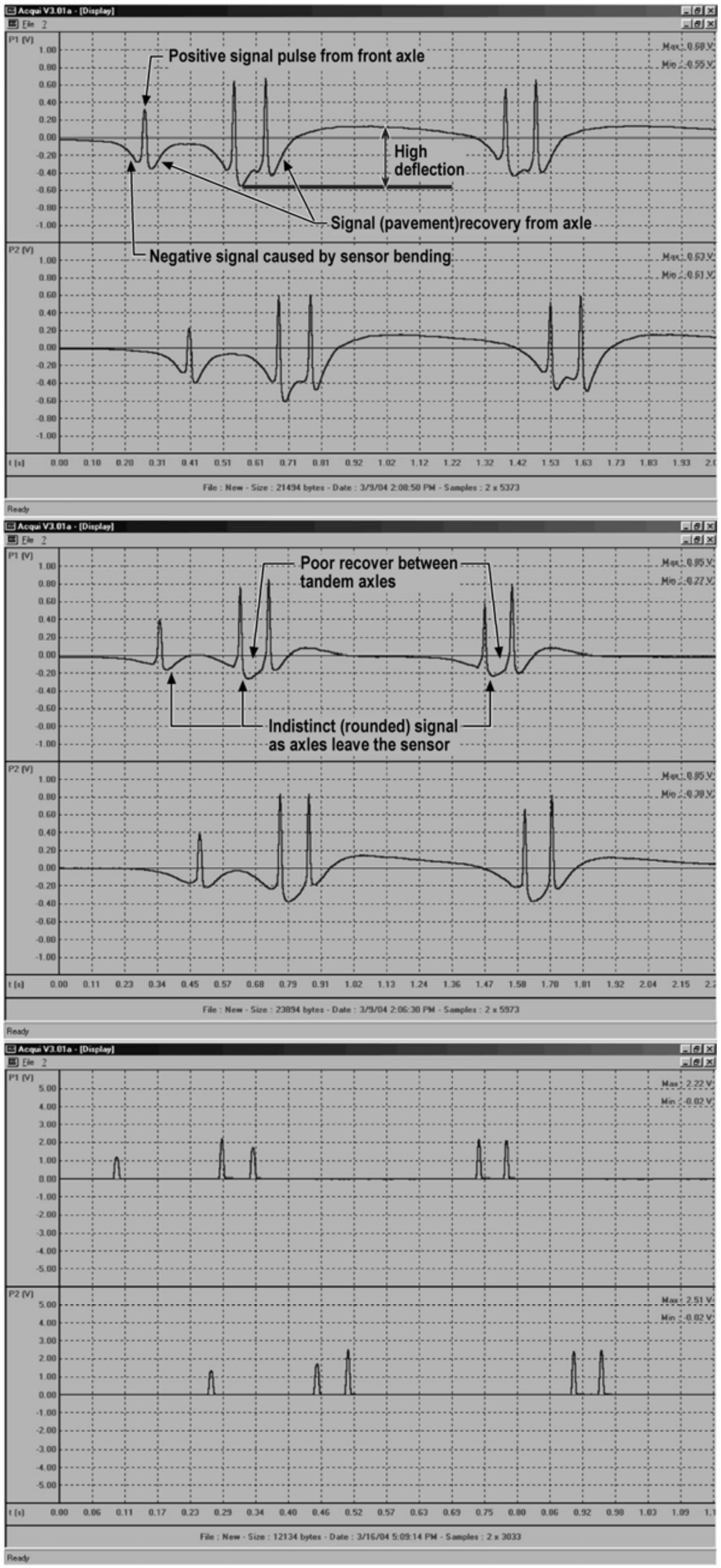

Figure 40. Examples of Piezo Ceramic and Piezo Quartz Sensor Signals.

6.4.5 Kistler Summary and Recommendations

6.4.5.1 Other States

The states contacted in this research, which plan on continuing to use Kistler Quartz sensors, are: Connecticut, Maine, Minnesota, Montana, and Ohio; Illinois will continue to use them but only in concrete pavement. Other states also expressed a concern with installing these sensors in asphalt, although some are continuing to do so. Another question pertaining to maintenance on the Kistlers was the need for calibration. Illinois calibrates the sensors three or four times per year. Maine DOT only calibrates once a year. Changes in sensor output with changes in temperature appear to be minimal. Michigan DOT believes this value to be around 2 to 3 percent over the full range of temperatures experienced in that state. The Minnesota experience seems to support this very small variation. A common theme from most states was that the installation process requires complete attention to detail to ensure the best result.

6.4.5.2 TxDOT Summary

Through careful analysis of the data, this project has reaffirmed what other users have already discovered. When properly installed in pavements that provide adequate structural support, Quartz sensors produce accurate vehicle weight measurements that remain stable over time. Furthermore, the Quartz sensors have not exhibited any signs of physical degradation such as cracks in the sensor and surrounding pavement. One can also infer from the evaluation of the average front axle weight and GVW distributions by week and the follow-up calibration verifications that there is also no significant degradation of the Quartz sensor signal.

Based on the static versus dynamic weight comparisons collected at both sites over the duration of the study using calibration trucks, and in one case mixed truck traffic selected at random, all weights collected satisfied the ASTM *(23)* GVW and axle weight accuracy specifications for Type 1 WIM systems. Tabulating the combined data from Tables 44 and 45 produced 245 static versus dynamic weight observations from measurements of GVW, steering axle, and axle group. All 245 dynamic weight measurements fell within ±15 percent of the static weight. Furthermore, 100 percent of the GVW observations satisfied the ±10 percent ASTM *(23)* criteria; 100 percent of steering axle observations satisfied the ±20 percent criteria (±15 percent was achieved); and 100 percent of all axle group observations satisfied the ±15 percent criteria.

It should be noted that calibration trucks generated 200 of these observations by making multiple controlled passes over the sensors, so the results are likely skewed somewhat in favor of the sensors. Installation conditions at the Los Tomates and Falfurrias sites were near optimum, and both used Portland cement concrete pavements. The Falfurrias site has 500 ft of Portland cement concrete that was ground smooth to satisfy the ASTM *(23)* longitudinal roughness specification. Even though installers did not measure the longitudinal roughness at Los Tomates, the relatively slow traffic speed (averaged 14.6 mph) served to minimize the impact of any roughness that did exist.

Based on the results of Kistler tests in Texas and the experience in other states, the Kistler sensors appear to have merit for continued testing in Texas. Monitoring of the Kistler sensors at the three sites reported in this document should continue, and TxDOT should install at least two or three lanes of sensors in asphalt pavement. Then, TPP can make a better decision about which WIM system applies best in each location.

CHAPTER 7.0 PAVEMENT STRUCTURAL SUPPORT CRITERIA

7.1 INTRODUCTION

TxDOT has been a leader in the development of weigh-in-motion technology through its willingness to try new WIM sensors, as well as investing in research dating back to 1968. Experience gained during numerous field installations and evaluations have revealed needed improvements to this technology. A significant effort to codify and further develop this knowledge occurred with the publication of an American Society for Testing and Materials (ASTM) specification for weigh-in-motion titled "Standard Specification for Highway Weigh-in-Motion Systems with User Requirements and Test Methods"*(3)*. This ASTM specification contributed immensely to improving WIM data collection and is widely referenced in many state procurement specifications for the purchase of WIM hardware and sensors.

Despite continuing improvements to WIM technology, one significant fact remains; there is little guidance provided in the written literature that defines the pavement foundation necessary to accommodate different types of WIM system sensors. There *are* general guidelines from various sources that address required pavement structures including:

- Installation of piezo sensors requires a minimum asphalt thickness of 4 inches.
- Installation of bending plate sensors requires ACP that is 6 inches thick or greater *(23)*.
- An unpublished LTPP specification defines a minimum pavement structure using a falling weight deflectometer (FWD) to measure maximum deflection and defection basin area *(24)*.
- Install 225 ft of 12-inch thick jointed concrete pavement for bending plate sensors *(25)*.
- Quasi-static and dynamic deflection criteria developed under COST 323 *(26)*.
- Maximum FWD variation across the location where sensors are to be installed should not exceed ± 7 percent.
- If the WIM system is to be used on a roadway that is asphalt concrete (AC) pavement, the AC pavement must be replaced with PCC pavement for a minimum distance of 50 ft before and 25 ft after the sensor.

These varied and sometimes ambiguous guidelines illustrate the significant need for basic research to define pavement structures that will improve the performance and durability of WIM sensors.

7.2 METHODOLOGY

In addition to the findings noted above, the research team requested information on minimum pavement structural support criteria from vendors and state DOTs, but little has been documented. The research team contacted a variety of "experts" who might be able to provide guidance on pavement structural support criteria. Some of the information was more useful than others. The information included in this chapter comes from a state DOT, an academician, and a representative of the major source of weigh-in-motion equipment in the U.S.

7.3 FINDINGS

7.3.1 State Practice

A representative of the Ohio Department of Transportation stated that his agency does not install sensors in any pavement that is less than 6 inches in depth. Most of the pavements that carry heavy truck volumes are thicker than that anyway, usually a minimum of 8 inches thick. In fact, many of the pavements in Ohio with significant truck volumes are 14 to 16 inches thick[1].

7.3.2 Vendor Information

A professor in the Civil and Geological Engineering Department at the University of Saskatchewan, who was once an International Road Dynamics WIM engineer, provided an opinion on the subject of pavement depth for WIM. His opinion reflects his experience, considering the amount of deflection that is sustainable at the sensor upon repeated load application. He believes that piezoelectric sensors are less susceptible to structural failure compared to bending plates to a point, and deflections of greater than 0.08 inches would probably result in failure along the piezo sensor/pavement interface over time. Use of a FWD would be one way to correlate deflections with expected loadings.

The amount of deflection that a bending plate system could sustain would be less than for piezoelectric systems due partly to the rigidity of the WIM frame. Two options exist for installing bending plate systems—direct installation in the road in a grouted frame or installation in a concrete vault. Since the latter option is more expensive, most agencies tend to install the system directly in the pavement using a frame that is grouted in. For bending plates, the pavement structure should be able to maintain less than a 0.04-inch deflection with load application. This amount of deflection would require about 6 inches of wearing surface structure to ensure that the bending plate WIM stays embedded into the top surfacing layer and does not break out the bottom of the layer[2].

The response from a second International Road Dynamics engineer provided information on pavement depth based on a "rule of thumb." Installers should not excavate asphalt pavement slots any deeper than one-quarter of the pavement thickness. There are instances when they go as deep as one-third the pavement depth, but this depth can lead to subsequent problems. As an example, a typical encapsulated piezoelectric sensor is approximately 1 inch by 1 inch, so the

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[1] Phone conversation with Mr. Steven Jessberger of Ohio DOT, September 29, 2004.

[2] Email from Professor Curtis Berthelot at the University of Saskatchewan, September 24, 2004.

sensor would require a slot approximately that size. Therefore, this sensor should not be placed in asphalt pavement that is less than 4 inches thick.

For a Kistler quartz sensor, the overall depth of the sensor is approximately 2 inches, with a slot depth of 2.25 to 2.5 inches. Using the above rule of thumb would require an asphalt pavement thickness of at least 8 inches, and preferably higher.

At this time, IRD does not recommend installing a bending plate system in asphalt, as there have been some rather dramatic failures. Even if an agency elected to install a bending plate system in asphalt, the asphalt pavement would have to be over 12 inches thick (using the same asphalt rule above).

For Portland cement pavements, IRD relaxes the depth requirement somewhat, going to a 33 percent rule. However, Portland cement pavements are usually thicker anyway. IRD does not recommend installing Quartz or bending plate systems in any Portland cement pavement less than 8 inches thick.

Again, the pavement thickness rule of thumb is only a guide. There needs to be a more comprehensive structural evaluation of a site to determine applicability of a certain pavement for WIM installation because the overall structural capacity of the pavement is the important criterion. The real issue with installing bending plate WIM in asphalt pavements is the structural strength of the pavement. IRD has some older installations in asphalt that are more than 12 years old in which the scales are still operational. These pavements were 8-inch thick asphalt pavements and should not have stood up according to IRD rules. By the same token, IRD has installed bending plates in 12-inch Portland cement concrete structures that failed. One solution is to use non-destructive testing techniques, such as FWD and ground-penetrating radar, to determine the strength of the site and develop a better standard than a simple rule of thumb approach[3].

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[3] Email from Mr. Brian Taylor of International Road Dynamics, September 30, 2004.

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APPENDIX A

Site Selection Criteria

Table 46. Final Site Selection Criteria.

Objective	Criteria	Scale	Rating			
1. Distance from TPP shop	Drive time from TPP (Min)	0 < 10	5			
		11 < 20	4			
		21 < 30	3			
		31 < 40	2			
		> 41	1			
2. Roadway geometry			Horiz. alignment (radius of curvature - ft)			
			Tangent	10,000-8000	8000-5700	< 5700
	Vert. alignment (pos. or neg. % grade)	0.0-0.5	5	4	1	1
		0.5-1.0	4	3	1	1
		1.5-2.0	2	2	1	1
		2.0+	1	1	1	0
	Cross-slope (%)	0-1	5			
		1-2	5			
		2-3	1			
		3+	1			
	Lane width (ft)	12.5-14	4			
		12.5-12	5			
		12.0-11.5	5			
		11.5-11.0	2			
		< 11.0	1			
3. Pavement structure	PCC thickness (in)	> 12	5			
		12-10	3			
		10-8	1			
		< 8	1			
	ACC thickness (in)	> 8	5			
		8-7	5			
		7-6	4			
		6-5	3			
		5-4	2			
		< 4	1			

Table 46. Final Site Selection Criteria. (Continued)

Objective	Criteria	Scale	Rating				
4. High truck volume and good mixture of truck traffic (Classes 3-13 Texas 6 Classification)			% Trucks* (4-lane facility)				
			30-20	20-15	15-10	10-5	5-2.5
	Vehicle traffic	> 40,000	5	5	4	4	3
		40,000-30,000	5	4	4	3	1
		30,000-20,000	4	4	3	2	1
		20,000-10,000	3	3	1	0	0
		10,000-5000	2	1	0	0	0
		< 5000*	1	0	0	0	0
			*minimum class 9 trucks = 500 per day in truck lane				
5. Multiple lanes		Lanes	Divided	Undivided			
		6	5	3			
		4	4	3			
		2	0	1			
6. Access to electric power & telephone service			Phone (ft. to service)				
			< 100	100-300	300-1000	1000-2000	> 2000
	Electrical (ft to service)	< 30	5	5	4	2	1
		30-100	4	4	3	2	1
		100-300	3	2	1	1	1
		300-1000	2	2	1	1	1
		> 1000	1	1	1	1	1
7. Sufficient ROW to allow for safe operations and parking for site users	Distance to safe parking (ft)	0-100	5				
		100-500	4				
		500-1000	1				
		> 1000	1				

Table 46. Final Site Selection Criteria. (Continued)

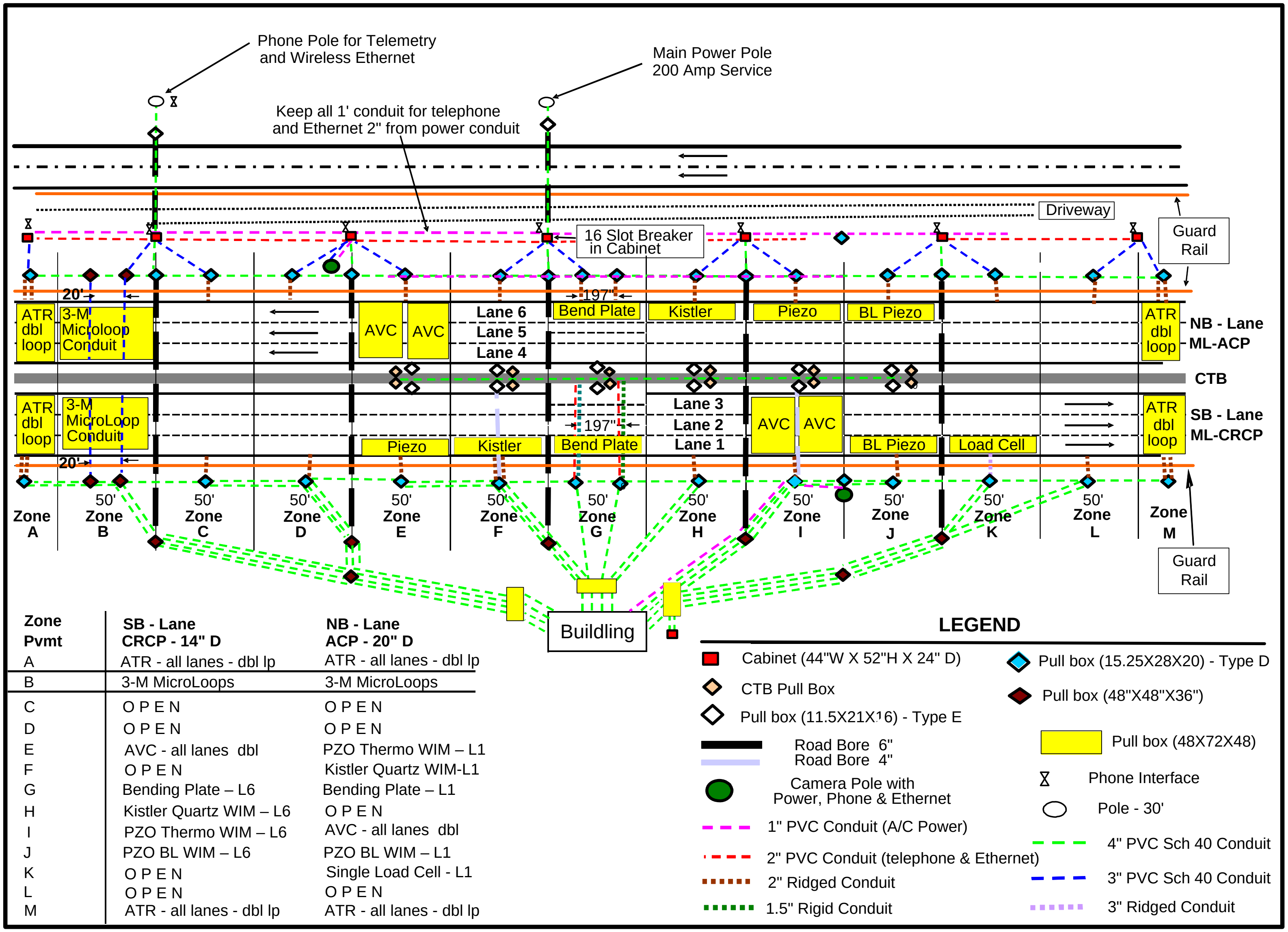
Objective	Criteria	Scale	Rating			
8. Adjacent space (walking distance) to park calibration truck		Yes	5			
		No	3			
9. Space for permanent or portable structure		Yes	5			
		No	2			
10. Sign bridge structure to mount detectors or cameras (less than 200 ft from site)		Yes	5			
		No	3			
11. Roadside mast to mount sensors (min 30 ft from edge of pvmt and 30 ft tall)		Yes	5			
		No	3			
12. Lighting		Yes	5			
		No	4			
13. Pavement condition			Cracking			
			None	Slight	Moderate	Severe
	Rutting (in)	0-1/16	5	4	2	1
		1/16-1/8	5	3	2	1
		1/8-3/16	4	3	1	1
		3/16-1/4	3	2	1	1
		1/4-5/16	2	2	1	1
		5/16-3/8	1	1	1	1
		> 3/8	1	1	1	1
	Pavement smoothness (PSR)	5	5			
		4	5			
		3	3			
		< 3	1			
14. Pavement rehabilitation programming	Rehab schedule (mo. until or since rehab)	6 mo. before	5			
		0-12 mo. after	4			
		12-24	4			
		24-36	3			
		36-48	2			
		48-60	1			
		> 60	0			

Table 46. Final Site Selection Criteria. (Continued)

Objective	Criteria	Scale	Rating
15. Turnaround time for test truck (min.)		<5	5
		5-10	5
		10-15	4
		15-20	3
		20+	1
16. Sight Distance (ft)		> 1000	5
		1000-500	4
		500-300	3
		300-200	3
		< 200	2
17. Proximity to DPS weight enforcement facility (miles upstream or downstream)		0.5-1.0	5
		1.0-2.0	4
		2.0-3.0	4
		3.0 +	3
		none	2
18. Bending plate WIM system		Existing	5
		Buildable	3
		Not buildable	1
19. Access to satellite sites (mi from site)		0-0.05	3
		> 0.05	2
20. Safety features		Mostly in place	5
(e.g., longitudinal barrier to roadside)		Requires installation	4
		Installation not possible	0
21. Congestion	Stop-and-go conditions (avg. times/week)	0	5
		1-3	2
		4+	1

APPENDIX B

General Site Layout and Cost Estimate



Zone Pvmt	SB - Lane CRCP - 14" D	NB - Lane ACP - 20" D
A	ATR - all lanes - dbl lp	ATR - all lanes - dbl lp
B	3-M MicroLoops	3-M MicroLoops
C	OPEN	OPEN
D	OPEN	OPEN
E	AVC - all lanes dbl	PZO Thermo WIM – L1
F	OPEN	Kistler Quartz WIM-L1
G	Bending Plate – L6	Bending Plate – L1
H	Kistler Quartz WIM – L6	OPEN
I	PZO Thermo WIM – L6	AVC - all lanes dbl
J	PZO BL WIM – L6	PZO BL WIM – L1
K	OPEN	Single Load Cell - L1
L	OPEN	OPEN
M	ATR - all lanes - dbl lp	ATR - all lanes - dbl lp

Figure 41. General Site Layout.

Table 47. TPP Test Facility Cost Estimate.

Description	TxDOT Spec#		Unit	Quantity	Unit cost	Total cost
6-inch crushed stone base (Type A, Grade 1) for equipment enclosure, parking and truck parking	247	857	SY	1465	$ 8.00	$ 11,720.00
Operations equipment enclosure (12 ft X 40 ft)	1461	501	EA	1	$27,000.00	$ 27,000.00
Deck with ADA ramp access			EA	1	$ 3,000.00	$ 3,000.00
8-ft chain link fence, 80 ft x 30 ft	550	568	LF	220	$ 12.95	$ 2,849.77
Vehicle gate (DOUBLE) (6 ft X 14 ft)	550	503	EA	2	$ 1,350.00	$ 2,700.00
Pedestrian gate (4 ft X 6 ft) (BARB TOP)	550	552	EA	1	$ 355.00	$ 355.00
Lightning rods and cable			EA	1	$ 250.00	$ 250.00
Hardware firewall			EA	1	$ 650.00	$ 650.00
Industrial computers			EA	4	$ 2,500.00	$ 10,000.00
Computer racks and monitors			EA	1	$ 1,500.00	$ 1,500.00
Weather station			EA	1	$ 5,000.00	$ 5,000.00
802.11 Ethernet bridge base			EA	1	$ 1,500.00	$ 1,500.00
802.11 Ethernet switch			EA	1	$ 1,500.00	$ 1,500.00
Network Ethernet hubs (high temperature)			EA	4	$ 400.00	$ 1,600.00
Direct burial Ethernet cable			LF	2000	$ 0.31	$ 620.00
BJFAS phone line (TWP) (6 PAIR) (19 AWG)	1456	501	LF	1000	$ 1.00	$ 1,000.00
CDMA modem for Internet and communications			EA	1	$ 400.00	$ 400.00
Parking spaces, 2-inch Type D asphalt concrete pavement	354	510	SY	361	$ 1.65	$ 595.77
Guardrail, metal beam gauge 10	540	509	LF	400	$ 13.84	$ 5,535.59
Roadway bore and 6-inch conduit for communications	618	543	LF	120	$ 63.00	$ 7,560.00
Roadway bore and 3-inch conduit for cabinet power			LF	120	$ 50.00	$ 6,000.00
Roadway bore and 3-inch conduit for 3-M micro-loops (2)			LF	240	$ 50.00	$ 12,000.00
6-inch conduit (PVC) (SCHD 40) roadside to trailer (w/ MaxCell)	618	515	LF	180	$ 7.43	$ 1,337.18

Table 47. TPP Test Facility Cost Estimate (Continued).

Description	TxDOT Spec#		Unit	Quantity	Unit cost	Total cost
2 ft x 4 ft pull boxes	624	508	EA	10	$ 549.93	$ 5,499.30
3 ft x 5 ft pull boxes			EA	3	$ 1,328.00	$ 3,984.00
150 amp service with pole			EA	1	$ 1,500.00	$ 1,500.00
Surge protector for power service			EA	1	$ 150.00	$ 150.00
Loop detector (TY 1) (6 ft X 6 ft)	6505	503	EA	24	$ 870.00	$ 20,880.00
Loop lead-in cable IMSA Spec 50-2		684	LF	4000	$ 0.24	$ 960.00
Piezo quartz WIM sensor			LN	4	$ 8,000.00	$ 32,000.00
Piezo ceramic WIM sensors	1211	501	EA	12	$ 1,200.00	$ 14,400.00
Bending plate WIM			EA	1	$50,000.00	$ 50,000.00
Microwave vehicle presence detector	8993	501	EA	1	$15,000.00	$ 15,000.00
RTMS radar vehicle detector	8912	501	EA	1	$ 4,000.00	$ 4,000.00
Color PTZ camera with associated hardware			EA	2	$ 5,000.00	$ 10,000.00
Pole structure 40 ft to mount camera/traffic sensors	1484	501	EA	3	$18,090.00	$ 54,270.00
3/4-inch PVC Conduit (for loop lead-in from roadway)			LF	200	$ 3.10	$ 620.00
3/4-inch PVC Conduit (for phone line)			LF	2000	$ 3.10	$ 6,200.00
2-inch schedule 40 PVC for pull box interconnections, power, coaxial, fiber optic cable runs as needed			LF	2000	$ 3.40	$ 6,800.00
Equipment cabinets, communication cabinet (TY 2)	1484	502	EA	5	$ 2,520.00	$ 12,600.00
Cabinet foundation			EA	5	$ 2,000.00	$ 10,000.00
Construction management (15%)						$ 53,030.49
Subtotal						**$406,567.10**
Contingency (10%)						$ 40,656.71
Grand Total						**$447,223.81**

APPENDIX C

Justification for Continuing Project

Introduction

At the outset of this project, TxDOT intended to have a “go” or “no-go” decision at the end of six months of work. However, this decision assumed that the remaining work would rely on having a test site available to conduct the research. Researchers proposed ways to make the remaining tasks productive even without the proposed test site. The following sections discuss the tasks that remained after the initial decision period of about six months and ways to accomplish them without the new test facility.

Evaluate Lineas Quartz WIM Sensors (Task 6)

The research team will contact the state DOTs in Ohio, Connecticut, Maine, Minnesota, and Illinois to examine their experiences with the Kistler Quartz sensors. If information is available, the project team proposes to use telephone interviews to determine: number of sensors installed, number of failures by type, accuracy data compared to baseline at available time intervals, truck and total traffic volume, installation details such as sensor and inductive loop layout, type of epoxy used, pavement type, weather factors, and any other documented information. Phone interviewers will ask each DOT representative whether that state plans on continuing the use of the Kistlers and the exact application. The result will be a summary of sensor information gathered from each state and appropriate comparisons regarding pavement type and observed equipment performance. The performance of these sensors in ACC will be of particular interest.

Establish Pavement Structural Support Criteria (Task 7)

In this task, the research team will establish minimum pavement structural support criteria to ensure suitable traffic data collection using permanent in-road sensors. Researchers will request information from vendors and as many as five state DOTs based on the failures in Texas. To best replicate Texas conditions, researchers will first gather information from TPP(T) regarding the failures that have occurred in Texas. This might include any information specifically pertaining to a sensor type or manufacturer, pavement type, sensor life, failure mode, truck and non-truck volume, axle weight or other site-specific loading characteristics, and level of enforcement activities.

Establish Optimum Techniques for Bending Plate WIM Systems on Three Plus Lanes (Task 8)

At one of the early project meetings, the project director indicated to researchers that this task would no longer be needed because TPP(T) personnel had apparently already found the solution through other means.

Evaluate East Texas Sensor Failure Mode (Task 9)

The research team proposed two possible means of accomplishing this task: 1) by conducting forensic investigations on failed sensors, and 2) by contacting another agency that might have similar conditions to ask for their input. The first option would require collecting data and other available pertinent information to investigate failure modes of permanently installed sensors in East Texas. If the pertinent information exists, the team will perform a forensic evaluation of the failure mode of these sensors on selected installations in East Texas. The information that project staff will request at each selected site would include: date installed, truck and non-truck volume, historical weather data, and pavement parameters (rutting, cracking, or other distress information). There also would be an examination of failed sensors.

If TxDOT does not have sufficient documentation to perform a forensic evaluation, researchers proposed contacting other states that either have conducted a scientifically based investigation or have enough data for project research staff to do so. For sensor data to be transferable to Texas, the research will have to locate a state with similar sensor type and installation techniques, weather, pavement, traffic, and soil types. Some equipment vendors might be helpful in this process as well.