Bridge Weigh-in-Motion (B-WIM) System Testing and Evaluation

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16. Abstract

The expansion in freight shipments on the nation's highways has led to a substantial increase in road traffic congestion. Of particular concern is the increase in the number, size, and weight of heavy commercial vehicles. Because of the limited resources available to enforcement agencies, an effective program of highway maintenance and safety could benefit substantially from an affordable traffic sampling and enforcement program that is not manpower intensive. A reliable, accurate, and portable dynamic sampling system capable of delivering measurements of moving vehicle type, size, and weight would be attractive. The continued advancement and acceptance in Europe of bridge weigh-in-motion (B-WIM) technology as a tool for highway maintenance, safety, and enforcement has established an interest for field demonstrations of the technology and potential applications in the United States. In this project, a team of researchers from the University of Alabama at Birmingham (UAB), University of Alabama (UA), and University of Alabama in Huntsville (UAH) was initiated to evaluate the potential use of B-WIM systems in Alabama. Over the course of eighteen months, the team consulted with experienced researchers and practitioners in Europe and the United States. A commercial B-WIM system developed in Slovenia was purchased for testing. System installation and calibration was conducted at two remote sites. A short, in-service field test at the second site resulted in accuracy classifications of C(15) for gross vehicle weight and lower accuracy for single axles and group of axles. After work at the two test sites was completed, an international one-day B-WIM workshop was held to discuss practical applications for B-WIM technology in heavy truck freight operations. The report concludes with recommendations for bridge selection, system installation, calibration techniques, and operational methods.

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Executive Summary

Under UTCA Project #07212 a team of researchers from the University of Alabama at Birmingham (UAB), the University of Alabama (UA), and the University of Alabama in Huntsville (UAH) was selected to evaluate the potential use of commercially available bridge weigh-in-motion (B-WIM) technology on selected bridges in Alabama. During the eighteen-month project the team worked in close collaboration with ALDOT representatives, worldwide technology experts, AASHTO, FHWA, and TRB WIM task-force members to demonstrate the field application of a commercial B-WIM system. The system selected for field testing was the SiWIM FAD24/0 portable version developed by CESTEL, a Slovenian company.

Two interstate highway bridges were selected for instrumentation installation, calibration, and in-service testing. The first bridge experience revealed several problems unique to the environment associated with a remote bridge in Alabama. The bridge itself consisted of nine simply supported spans, each 35 feet in length. There were two lanes. The flexibility of the bridge girders coupled with the rough surface of the bridge and the simultaneous presence of multiple vehicles on the bridge resulted in erratic measurements from the system. After overcoming difficulties associated with the solar panel and battery configuration, in-service data collection was successful. Problems were also encountered with the cellular communications because of the weakness of the cellular-telephone signal in the vicinity of the bridge.

The second bridge selected was on a four-lane interstate highway south of Birmingham. Lessons learned from the first installation were applied, resulting in greater success in the calibration and in-service data-collection efforts. While the SiWIM system gathered data for many of the trucks crossing the bridge, a large number of vehicles crossed either undetected or with their measurements masked. The reason for the missed or useless (masked) measurements was largely due to the problems associated with identifying a single vehicle when multiple vehicles traveling at high speeds are on the bridge at the same time. During the second installation the modified power-supply installation worked well and the cellular connection performance was good.

This project demonstrated the SiWIM system on typical bridges in the Alabama highway inventory. The report documents the installation, calibration, and in-service experiences in detail. Recommendations for bridge-selection criteria for SiWIM instrumentation in Alabama and conclusions about the accuracy of the system are presented.

Section 1.0
Introduction

The expansion in freight shipments on the nation's highways has led to not only a substantial increase in traffic congestion but also an increase in the number, size, and weight of heavy commercial vehicles. Overweight vehicles can severely reduce the life of structural pavement and bridges, and oversized vehicles can be detrimental to the safety of other vehicles on the road. A reliable, accurate, and portable dynamic sampling system capable of accurately measuring a moving vehicle's type, size, and weight would be an attractive tool for heavy freight traffic enforcement, transportation-infrastructure maintenance, and future design planning. The simple objective of bridge weigh-in-motion (B-WIM) technology is to provide portable instrumentation technology capable of transforming a highway bridge into a temporary weigh station capable of detecting overweight vehicles traveling at freeway speeds. The continued advancement in Europe of B-WIM technology has established an interest in demonstrating the technology in the field in the United States, as evidenced by the January 16, 2007, UTCA B-WIM Request for Proposals (RFP). Under UTCA Project #07212, a team of researchers from the University of Alabama at Birmingham (UAB), University of Alabama (UA), and University of Alabama in Huntsville (UAH) was selected to evaluate the potential use of commercially available B-WIM technology on selected bridges in Alabama. During the 18-month project, the Team worked closely with ALDOT representatives, worldwide technology experts, AASHTO, FHWA and TRB WIM task force members.

Project Objectives

This project was in response to the UTCA RFP dated January 16, 2007. It had three primary objectives:

1) Identify the potential benefits of using B-WIM technology in Alabama.
2) Perform a pilot B-WIM field test in Alabama to evaluate potential for deployment.
3) Use the results from the technical research and field testing as both an educational tool and a foundation for further discussion on a national level.

Work Tasks

The State of Alabama is a leader in providing an opportunity for researchers and the Alabama Department of Transportation (ALDOT) to test a state-of-the art commercially available B-WIM system designed and constructed in Slovenia by a firm named *CESTEL*. The proprietary system, called *SiWIM*, is a portable B-WIM system that can be installed on a bridge in less than a day.

The majority of SiWIM experience has been in Europe. In fact, when the project kicked off, only one other SiWIM had been purchased for installation and testing in North America (in Ontario, Canada). The project team organized the work plan into the following sequential tasks:

1. **Appraisal of Applicability of Bridge Weigh-in-Motion Technology and Selection of Equipment.** This task had two deliverables: a review of B-WIM technology evolution and a commercial B-WIM system for testing, purchased in coordination with ALDOT.

   Since this would be the first installation of commercially available B-WIM technology in the United States, the team set out to conduct an overall review of B-WIM technology development since the 1980s to identify special considerations for employing the B-WIM system in Alabama. The effort involved a comprehensive literature review, e-mail correspondence and telephone conversations with B-WIM users and developers, and visits to selected users and developers of B-WIM systems. Two members of the research team traveled to Paris in May 2007 to participate in the International WIM Symposium.

   During the research-proposal period, the decision was made to purchase a SiWIM system from Cestel/ZAG, a Slovenian company, for the pilot-testing program. The research team collaborated with Cestel/ZAG to gain a preliminary understanding of the current system design and experiential data available. The system was ordered by ALDOT, hoping for system delivery in early September 2007.

2. **Suitability of B-WIM System Deployment in Alabama.** The WIM concept uses the principle that a concentrated load moving across a bridge will create strains proportional to the product of the influence value and the magnitude of the load. In theory, any type of bridge structure—including concrete slab, pre-stressed beam, truss, and skewed girder—could be used for portable WIM-system installations. A preliminary review of European data suggests the most accurate results are obtained from a single-span beam-slab bridge with neither skew nor a culvert.

   The aim of this task was to create a preliminary list of candidate bridges in Alabama. The selection of potential sites for expanded field testing would take into consideration important issues associated with size and weight enforcement for commercial traffic, such as the location of existing static weigh stations; logical bypass routes in the vicinity of the weigh stations; and bridge attributes identified in *Task 1*, such as traffic patterns, load rating, and construction material. These efforts were coordinated with ALDOT representatives.

   The primary source of information was ALDOT's inventory of bridges. Specific objectives to be accomplished include identification of:

   - Current static weight stations.
   - Suitable bridge types/structures for B-WIM.
   - Proximity of candidate bridges to enforcement locations.
   - Potential avoidance routes with suitable bridges for instrumentation.

The expected deliverables from this task were a list of suitable bridges for the expanded portable B-WIM evaluation in Alabama and a summary report of the work performed during this task. The summary report would be presented at the B-WIM symposium (Task 5) and included in the final project report.

While the full array of potential bridges and recommended priorities for instrumentation would not be known until the project approached completion and perhaps beyond, the identification of recommended bridges for the initial field testing was important for planning and equipment-procurement purposes. After consulting ALDOT representatives, the research team proposed the following bridges for initial field testing:

- I-59 (north of Birmingham): Bridge Identification Number 007239
- I-459 bridge in Birmingham: Bridge Identification Number 012296

These Birmingham bridges were selected with the hope that they would be an excellent exhibit for visitors during the symposium planned for Birmingham in 2008.

3. **Delivery of a Portable B-WIM System.** Based on collaboration with key stakeholders, ALDOT decided to purchase a B-WIM system designed and built in Slovenia by CESTEL. The characteristics of the CESTEL SiWIM system follow:
    - System is easily moved to other locations
    - Installation in one work day
    - Video system
    - Installation without damage to pavement or stoppage of traffic
    - Installation is not visible to traffic
    - Calibration can be done with pre-weighed vehicles

    The researchers coordinated with ALDOT and CESTEL with hopes of assuring that the technology package and support would be adequate for the planned tests. They hoped the system would be delivered at least one month before field installation so they could check it out, but the system was not fully cleared through customs and delivered until a few days before the planned field installation.

4. **Field Testing and Data Analysis.** The field test was the core task of this research project. The field test was designed to gain field-installation, calibration, and data-acquisition experience. Data would be gathered and evaluated for the range of capabilities of the purchased SiWIM system. Task 4 was initially planned to include the following steps:
    - Controlled laboratory-scale demonstrations of the B-WIM components and software before the field installation. A crucial requirement of this task is to establish a reliable system-calibration methodology.
    - A detailed equipment-installation methodology would be confirmed and the data-collection and transmission equipment setup tested and finalized.

- A detailed field-testing plan for the selected field test would be developed and coordinated with ALDOT and other stakeholders.
- Field-system calibration and testing would be accomplished using the selected bridges. A typical site layout is shown in Figure 1-1. A minimum of two trucks would be used for testing. The trucks would first be weighed on a static scale and then driven multiple times over the test bridge, which is instrumented with the B-WIM system. The software calibration algorithms built into the B-WIM system by the equipment vendor would be evaluated.

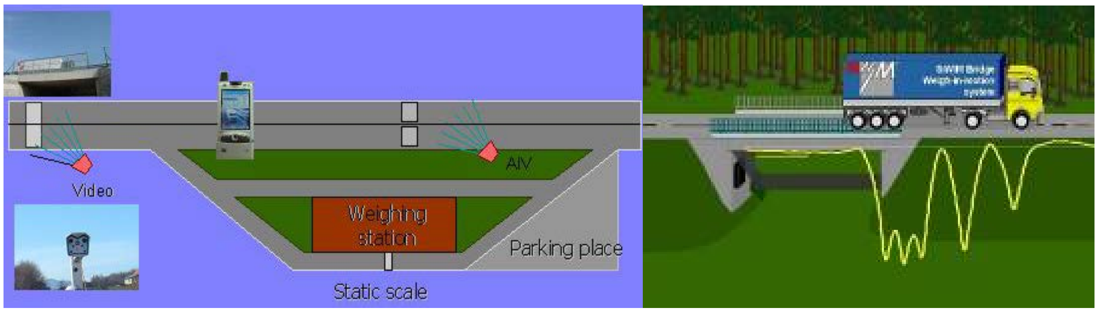

Figure 1-1. Example field implementation of B-WIM system developed in Slovenia

- Advanced WIM-calibration technologies, such as calibration by axle rank, would also be investigated.
- Several trucks of unknown axle weight would be measured with the B-WIM system then weighed on static truck scales.
- Analysis of results for the tested bridge's structural configuration and recommendations for application to different types of bridges.

Because the equipment arrived nearly a month later than hoped, the first two equipment "shakedown" tasks were not accomplished. Thus the final deliverables for this task include the accomplishment of the other steps and a detailed report of the work performed. A summary of the findings was presented at the B-WIM symposium (Task 5) and is included in the final project report.

5. **International B-WIM Symposium.** An international B-WIM symposium was organized and held toward the end of this project. The objective of the symposium was twofold: 1) bring together leading engineers and researchers from the US and Europe to exchange ideas and information concerning the state of practice and research of WIM systems and techniques and 2) develop an agenda for future research and deployment. Participants included representatives from ALDOT, AASHTO, the trucking industry, equipment vendors, and technology experts from around the world.

   The symposium preparation, execution and technology exchange consisted of six steps:

   1. ***Announcement:*** A brochure describing the symposium was prepared and mailed to individuals interested in B-WIM technology.

2. ***Formal Invitation:*** A few expert delegates were invited and asked to send a PowerPoint presentation.
3. ***Administration and Coordination:*** The PIs worked closely with the guests to arrange hotel reservations, coordinate local transportation, obtain audiovisual equipment, and complete other necessary support tasks.
4. ***Recording:*** The symposium was recorded. However, the quality of the audio was disappointing and the editors determined that it was impractical to splice the portions that did have acceptable quality. Consequently, recorded proceedings are not available.
5. ***Task Report:*** A task report was developed addressing the symposium outcomes and recommendations. The contents of the report are included in the body of this final report.
6. ***Presentations at Technical Meetings:*** The initial reporting of the project occurred at the TRB Issues in Freight Transportation Conference, Washington, D.C., October 22-23, 2007. At the conference a poster display was presented to outline the project plan and expectations. On May 27-31, The 10th International Conference on Application of Advanced Technologies in Transportation (AATT) was held in Athens, Greece. Virginia Sisiopiku presented a paper entitled "The U.S. Experience with New Generation Weigh-In-Motion Systems."

In addition to the symposium itself, another important deliverable was a summary documenting future research needs for implementation and a plan for follow-up discussions and activities. The summary results of this report provide this information.

6. **Final Report: Summary, Conclusions, and Recommendations.** The project tasks were fully documented and shared with ALDOT stakeholders and expert consultants and formed the basis of recommendations for future field testing. The final report brings together product reports from co-PIs, input from the Advisory Group, and the symposium results. Because this work is a cooperative effort between government, academia, and the private sector, the participants were mindful that some of the technology was patent protected, and therefore care was taken to insure that proprietary information was respected and properly handled.

Section 2.0
B-WIM Technology Overview

2.1 B-WIM Technology Advancement

Bridge weigh-in-motion (B-WIM) is a process by which axle weights and gross vehicle weights can be determined for trucks traveling at highway speeds over instrumented bridges. The original B-WIM model was developed in the late 1970s by Fred Moses (Tierney, *et al.* 1996) and funded by the Federal Highway Association (FHWA). Moses observed what could be done with WIM by using it as two different tools: a weighing mechanism and an instrument to determine the stresses on the bridge due to overloaded commercial vehicles. B-WIM systems involve attaching strain transducers to the bridge soffit, which provide the behavior of the bridge under the moving vehicle, and placing sensors on the pavement to provide information on vehicle type, velocity, axle spacing, and position. The latter information can also be obtained by placing additional strain transducers under the bridge instead of detecting sensors; this kind of system is called the *nothing-on-road (NOR)* or *free-of-axle detector (FAD) B-WIM system* (European Weigh in Motion Pages, 2007). Because the measurements are taken while the whole vehicle is passing over the structure, dynamic effects have less influence on the system. B-WIM systems also provide information about impact factors, lateral distribution factors, and strain records, which are used for further bridge analysis.

In Europe, extensive research was underway in the late 1990s as part of the WAVE (Weigh-in-motion of Axles and Vehicles for Europe) project. Work on the development of B-WIM focused primarily on improving accuracy on typical bridges, extending B-WIM to other types of bridges, conducting dynamic analysis of typical bridges, and improving calibration procedures. During the EC 4th Framework project WAVE, held in the 1990s, Slovenia's National Building and Civil Engineering Institute (ZAG) developed a prototype of a new-generation B-WIM system known as *SiWIM*. To commercialize the SiWIM system, ZAG and Cestel began to cooperate in 1999.

2.1.1 The Slovenian SiWIM System

SiWIM was developed by Slovenia's National Building and Civil Engineering Institute (ZAG) for the following purposes:

- Maintenance planning based on captured traffic-loading data.
- Pre-selection or automated enforcement based on captured weight data.
- Structural bridge analysis based on captured weigh and volume data.

The deployment of the Slovenian SiWIM technology targeted short-deck (5–10 meter) orthotropic bridges. Five SiWIM devices were used to collect data for one-week periods at thirty locations twice a year. Because it eliminates the need to disrupt traffic and minimizes worker risk when installing traditional roadway telemetry, B-WIM possessed major benefits. Weight instrumentation is applied to the under deck of the structure. Multiple sensors are used to monitor travel lanes, and a data hub draws readings from the individual sensors and composites the deck loading readings. Axle weights, gross vehicle weights (GVW), axle spacing, vehicle speed, and vehicle class are captured through this approach.

The SiWIM system operates as follows: As a vehicle passes over the bridge, a series of strain transducers, positioned below the bridge and unnoticeable to the vehicle driver, measure the vehicle's weight as a voltage output from the transducer. This voltage measurement is not transformed to strain-measurement units. The signals from each sensor (typically 16 sensors per two lanes of traffic) are amplified and converted from analog to digital. All data are accumulated in a file and used to support the system calculation of axle loads, axle spacing, gross vehicle weight, etc. The strain transducers compensate for temperature to enhance accuracy. In addition, the system uses input for up to five thermocouples to evaluate the temperature of the structure and calculate applicable correction factors. The system can be set up with a camera to capture a video image of each vehicle crossing the bridge. The video image and weight data can be communicated to enforcement officers in support at a downstream enforcement site.

2.1.2 B-WIM Applications in France

France has implemented the Slovenian SiWIM system on three bridges. The last bridge that was documented for testing in France was the Autreville deck bridge, an orthotropic steel bridge, in June 2006. Orthotropic-structure behavior is independent of span length, unlike concrete-bridge behavior. The Autreville deck bridge is 232 meters long and has three spans. It is supported by two main girders and is composed of cross beams, longitudinal trapezoidal stiffeners, and a plate 12 centimeters thick and asphalt pavement 8 centimeters thick. It has two lanes of traffic in each direction, and an average of 10,000 trucks cross it in each direction per day.

There were difficulties in installing the SiWIM system at the Autrevill bridge. The strain transducers did not effectively adhere to steel, so special glue had to be used. Other possible solutions included securing the transducers to metal plates using screws, which would then be attached to the metal structure, or using strain gauges. The bridge was instrumented with 14 transducers affixed to the bottom of the longitudinal stiffeners of a bridge section, under two traffic southbound lanes, halfway between two cross beams, near the south side of the river. Two transducers were affixed to a section located 4.62 m upstream to identify axles and measure vehicle speed. Fourteen trucks were stopped and weighed in Lesmesnil (the static-weighing area located 15 kilometers upstream) and released. Most of these trucks were overloaded because they were selected by a road-sensor WIM system upstream of the weighing area. Of the fourteen trucks, seven didn't cross the bridge because police stopped them. Four were not recognized by the SiWIM system. The accuracy class obtained for each axle category was D+(20). The verified data omitted one of the 14 trucks tested. That last truck was, however, found by the system once the system was set to allow 5-axle trucks. The final trial included only three trucks, which was not enough to review the accuracy of the WIM system. The bridge was also subjected to incessant traffic vibrations.

The other two bridges in France that are documented as using the Slovenian SiWIM technology were tested in 2005. The RN4 at Rozay-en-Brie had two lanes running eastbound with a static-weighing area two kilometers upstream. It had a span 8 meters long and 13 meters wide and was skewed 10.6 degrees with the concrete slab measuring 60 centimeters thick. The road profile and the pavement near and on the bridge are in good condition. The traffic is on the heavy side, with about 2000 trucks crossing every day. The RN19 at Noget-sur-Seine consisted of two lanes running westbound, with a static-weighing area located three kilometers upstream. It had a span 10 meters long and 11 meters wide and was made of reinforced concrete slab 60 centimeters thick. The road profile before and on the bridge was also in good condition with 1500 trucks crossing each day.

Both bridges had 16 strain transducers: 12 located mid-span measure the bending strains used for axle and vehicle weighing and 4 detect axles and provide vehicle velocity. Two trucks were used for calibration: a two-axle rigid truck (Deflectometer) and a tractor with a semi-trailer with tridem axles. The accuracy assessment used the pre-weighed trucks. In accordance with the European Cost 323 Specifications weight results are reported in four categories: gross weight, group of axles, single axle, and axle of group. With B-WIM systems, the axles of group were weighed with less accuracy: class C(15). It is important to note that the European Weigh-in-Motion Specifications recommend not considering this criterion in the accuracy assessment. The accuracy for the other three criteria were rather consistent: B(10) to C(15) at Rozay, where the pavement is a bit rough, and B+(7) to B(10) at Nogent, where the pavement is smoother.

2.1.3 B-WIM Applications in Alabama

In October 2007, the University of Alabama in Birmingham (UAB), the University of Alabama (UA), the University of Alabama at Huntsville (UAH), and the Alabama Department of Transportation (ALDOT) worked on the first CESTEL SiWIM installation in the US. Installation, together with training, was performed on bridge BIN 007239 on I-59, with preparations for an installation on bridge BIN 012296 on I-459. Initial calibration was done using traffic vehicles, and there were preparations for more in-depth calibration for the next installation. Bridge 007239 lay on Highway I-59 near exit 166 over Muckleroy Creek in St. Clair County, Alabama. The bridge is a nine-span simply supported T-beam bridge with 306 ft (9 x 36 ft) span. The second bridge is located on Highway I-459 over Sulphur Springs Road in Hoover, Alabama. It is near the I-459 and SR-150 interchange.

2.1.4 Conclusion

B-WIM is gaining popularity and is a well-established WIM technology used in many countries. B-WIM has several advantages:

- Full portability. All equipment can be detached from one site and installed at another site within hours.
- Accurate results. The long weighing platform (entire length of the bridge) proves beneficial in dealing with dynamic vehicle loading.

- Swift installation and maintenance. No need to stop traffic and no direct contact with pavement.
- Price efficiency.

2.2 Selection of CESTEL SiWIM Technology

There are two types of SiWIM systems available: SiWIM M and SiWIM P. The SiWIM M is larger and heavier and has the capability to detect and record more axles than the SiWIM P system. Options available on both types include (1) free-of axle detector installation; (2) battery power; (3) solar power; and (4) optional video monitoring (SiWIM-C) using a handheld computer, dual-lens camera, and WiFi/GPRS/UMTS connectivity.

2.2.1 SiWIM Instrumentation

Figure 2-1 shows a schematic of the SiWIM instrumentation. SiWIM uses ST-500 strain transducers on the bottom flange of the bridge and, if necessary, axle detectors on the surface of the pavement. ST-500 (Figure 2-2) is a steel strain transducer based on strain-gauge technology. To connect the strain transducer and data-acquisition system, a distributor-collector is available for the ST-500 sensor, as shown in Figure 2-3.

2.2.2 SiWIM M System

The SiWIM M has the following characteristics:

- mobile
- capable of handling 24 ST-500 strain transducers
- capable of handling 8 axle detectors
- accurate to B+(7)
- capabable of handling 4 lanes of traffic
- GSM module
- Third-party axle-detector connectivity
- WiFi (for remote control), camera, palmtop compatibility
- power 12V DC, 25VA
- 36-hour backup
- 60x80x30 cm (w×h×d)
- weight: 57 kg

Figures 2-1, 2-2, 2-3, and 2-4 show the components of a SiWIM system.

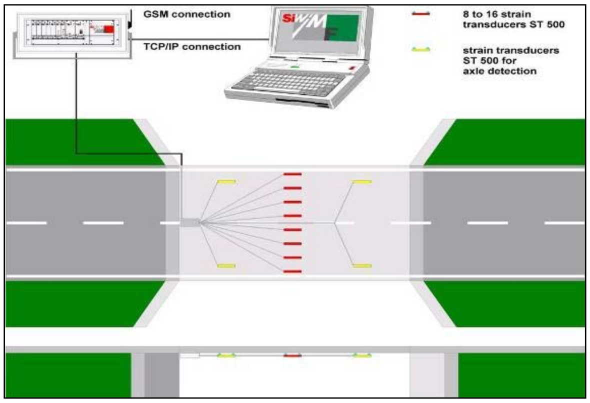

Figure 2-1. SiWIM instrumentation

Figure 2-2. ST-500 strain transducer

Figure 2-3. Distributor/collector for eight ST-500 sensors

Figure 2-4. SiWIM M processor housing

2.2.3 SiWIM P System

Compared to SiWIM M, SiWIM P is smaller (54x43x24 cm) and lighter (29 kg). SiWIM P can handle up to six axle detectors instead of the SiWIM M's eight. Figure 2-5 shows a picture of the SiWIM P processor housing.

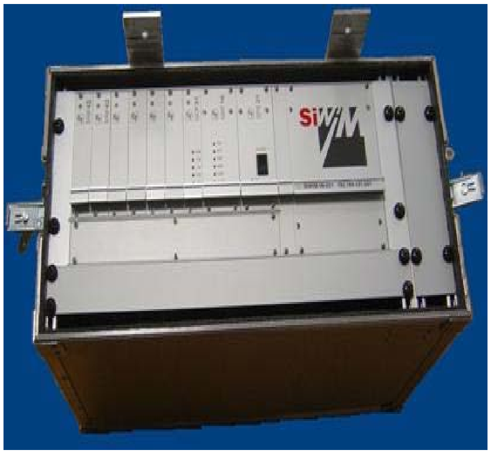

Figure 2-5. SiWIM P processor housing

Section 3.0
B-WIM Installation Testing Program

3.1 General

The purpose of the field test was to demonstrate the SiWIM system and to compare the performance of the SiWIM system with portable static-weight equipment. This section of the report further explains the SiWIM system, presents the field installation and measurement procedures, gives the results of the calibration exercises, compares SiWIM and static weighing of random vehicles pulled from the traffic, and gives the SiWIM measurement results for the selected test period and the evaluation and analysis of these results.

Weigh-in-motion (WIM) techniques have been traditionally used for measuring vehicles' weights while traveling at highway speeds. WIM systems provide detailed data on gross vehicle weights, individual axle loads, vehicle velocities, and axle spacing for most of the vehicles passing over the system. Bridge WIM (B-WIM) is a special type of WIM technology where bridges are instrumented to become high-speed weighing scales. The original B-WIM algorithm, developed by Moses in the late 1970s, requires information from strain sensors attached to the soffit of the structure and from the axle detectors attached to or built into the pavement (Moses 1979). Several systems using similar principles were introduced in 1980s, but none of the B-WIM systems was incorporated into the WIM-equipment inventory in the United States. While B-WIM technology in the United States stagnated, development continued in Europe. By the late 1990s, considerable improvements were achieved as a result of the WAVE project ("Weigh-in-motion of Axles and Vehicles for Europe"), a research project from the EU 4th Framework Programme. The main focus of this work improved accuracy, user friendliness, portability, and durability of commercial systems.

All B-WIM systems work essentially the same in that the instrumentation is applied to existing bridges or culverts, as illustrated in Figure 3-1. Parts of the structure are instrumented, and strains are measured to collect information about bridge behavior under moving vehicles. Strains are recorded during the full duration of the vehicle pass over the structure. This complete data stream provides useful information when trying to account for the influence of dynamic effects on vehicle-bridge interaction. These additional data are an undeniable advantage of the SiWIM system over in-pavement WIM systems where measurement of an axle lasts only a few milliseconds. Until recently, all B-WIM systems required axle or vehicle detectors on the pavement close to or on the bridge to provide vehicle type, velocity, and axle spacing. This requirement has been eliminated in the new-generation SiWIM system.

3.1.1 SiWIM Measurements

The development of the SiWIM system commenced during the WAVE project, and by the end of the project, a working prototype had been developed. To transform the system from an experimental prototype to a commercial system, cooperation with the CESTEL Company from Ljubljana, Slovenia, was established soon after WAVE. CESTEL developed and deployed SiWIM systems, initially in Europe. The SiWIM FAD24/0 (SiWIM M model) portable version used in Alabama is from the new generation of SiWIM systems. The configuration of the system with noted changes from the last generation follows:

- 24 strain transducers attached to the bottom of the superstructure. Strain transducers are used to provide information about the behavior of the bridge under the moving vehicle.
- 2 additional strain transducers per measured traffic lane to detect vehicle speed and axle spacing.
- Signal-conditioning unit, composed of signal amplifiers, pneumatic sensor electronics, and other electronics for conditioning the measured signals.
- Power supply, battery, and cabling.
- Computer processor running Windows XP.
- Mobile HSDPA/UMTS/GPRS connection with a remote supervising computer via a virtual private network (VPN).
- Casing with electronics (Figure 3-2).
- SiWIM software, version 4.0.2.

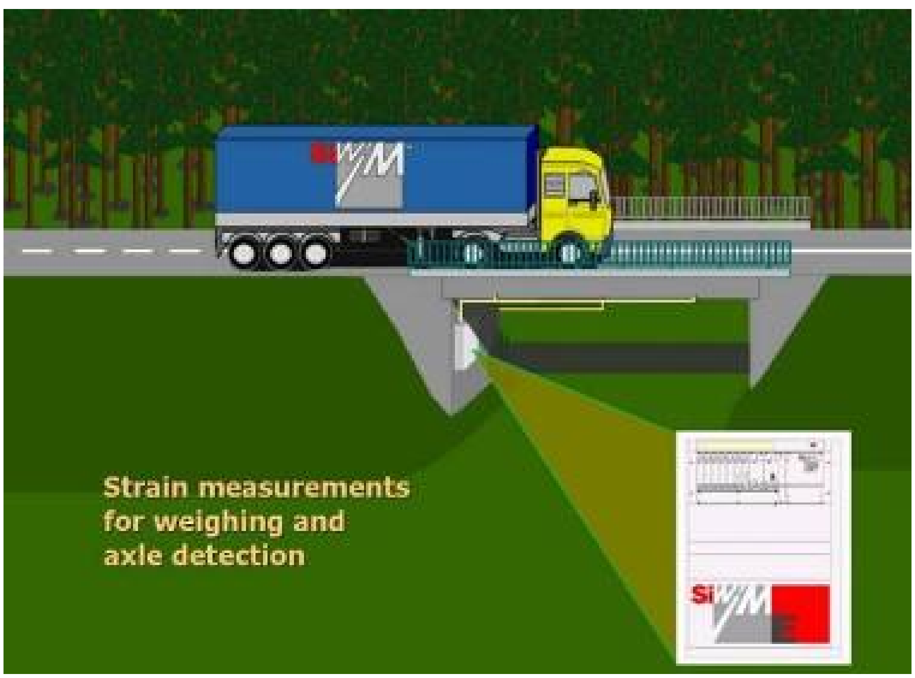

Figure 3-1. B-WIM instrumentation

Figure 3-2. SiWIM M Model electronics

3.1.2 SiWIM Software

The SiWIM software is a multi-threaded (i.e. several processes running at the same time) program running in the 32-bit Microsoft Windows environment. To prevent the system from losing data, the data-acquisition thread has highest priority, followed by the data-evaluation (weighing) thread and the lower-level threads, such as display of the results. SiWIM has been developed on a Windows NT 4.0 platform and has also been tested under Windows 95/98/2000/XP. Even for more than 30,000 vehicles/day, the current version of the program is capable of processing up to 16 input channels with real-time filtering and processing when run on a 233-MHz Pentium® II computer with 128 MB of RAM. The system employed in Alabama has a 300-MHz Celeron® processor and 256 MB of RAM.

Due to its complexity, SiWIM contains several software maintenance tools that permanently monitor the condition of the weighing process and can, if necessary, restart individual components of the program or even restart the computer. The SiWIM system can be controlled remotely through a mobile WiFi connection. In the case of problems or questionable results, a short text message is sent to the mobile phone of the person(s) monitoring the system. Figure 3-3 demonstrates a typical SiWIM window. In this figure the raw strain-transducer data are displayed. Other windows display tables of results and parameters that control the weighing procedure.

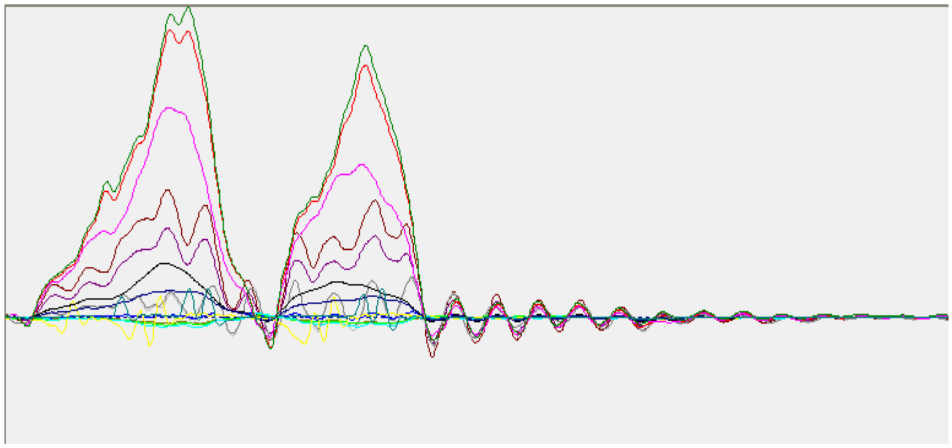

Figure 3-3. Raw signals from strain transducers 1 to 16 for a 5-axle vehicle

3.1.3 Data Collection

The SiWIM system stores data in a text format (NSWD files) that contains the following information about each vehicle:

- Road section
- Number (ID) of the instrumented bridge
- Date
- Hour, minute, and second of the passing vehicle
- Vehicle category according to specified classification based on axle spacing (unlimited number of categories)
- Axle loads
- Gross vehicle weight
- Axle spacing
- Length from the first axle to the last axle
- Temperature from 2 sensors
- ESAL value of the vehicle

NSWD files are post-processed with the SiWIM-D package which accomplishes the following data analyses:

- searches for doubtful results
- reclassifies vehicles, if necessary
- counts single, double, triple, and more axles
- calculates ESAL values for single, double, and triple axles
- adds the ESAL value of the vehicle into the SWD file
- calculates overloading for single, double, and triple axles
- calculates histograms of single, double, and triple axles
- calculates histograms of gross vehicle weights based on vehicle category
- calculates time histograms based on vehicle category
- simulates expected maximum load effects on short-span bridges, etc.

Results can be presented in either US or metric units.

3.1.4 Classification of Vehicles

The SiWIM system classifies vehicles primarily based on axle spacing. There are no limits for the number of classifications that can be used. For some types of vehicles with similar axle spacing, such as 2-axle trucks and vans, the classification is fine-tuned based on gross vehicle weight and axle load. For practical purposes it is convenient to merge vehicle classifications into categories.

3.1.5 Accuracy of SiWIM results

SiWIM accuracy depends on the type of structure and particularly on the evenness and smoothness of the pavement. Rating accuracy in accordance with the European specifications for WIM (Cost 323 1999) was accomplished by comparing SiWIM measurements to the values obtained from a more accurate static scale.

The European specifications define accuracy classes with a letter followed by a number in the parentheses. Class A(5) is the most accurate class followed by classes B+(7), B(10), C(15), D+(20), D(25), and E(30). The number in parentheses is the confidence interval δ (expressed as error %) for a given confidence level π. The exact confidence level depends on the number of test vehicles, the type of check (initial calibration or subsequent validation), and the test's environmental conditions. The European system is explained in more detail in Section 3.3 of this report.

3.1.6 Data Transfer and Remote Control

A SiWIM system is connected to the outside world by an encrypted GSM/GPRS/UMTS/HSDPA connection (Figure 3-4). The system uses a proprietary VPN server to establish a VPN-protected connection between the SiWIM system under the bridge and a PDA (or PDAs) at a remote location (or remote locations). All transfers are encrypted, and photos taken on site can be viewed on-the-fly. Data can be accessed only thru a VPN connection or directly thru the ethernet/WiFi connection. To access the raw data, custom software is needed because the format of the stored data is neither widely known nor widely employed.

3.2 Site Selection

3.2.1 Site-Selection Requirements for the SiWIM System

B-WIM systems are installed on existing bridges or culverts. Selected structure and superstructure members are instrumented underneath the bridge, and strains are measured to determine how the bridge behaves under moving vehicles. One of the main advantages of a SiWIM system over an in-pavement WIM system is that a SiWIM system is not visible to vehicle drivers. In addition, for many bridge configurations, SiWIM is easy to install and maintain, and working conditions are safe.

Strains are recorded during the entire vehicle pass over the structure. The collection of data over this extended time window provides useful information when the influence of dynamic effects due to vehicle-bridge interaction must be accounted for. This feature of SiWIM is another undeniable advantage over in-pavement WIM systems where measurement of an axle lasts only a few milliseconds. While most current B-WIM systems require axle or vehicle detectors installed on the pavement to provide vehicle silhouette and velocity, the SiWIM model does not.

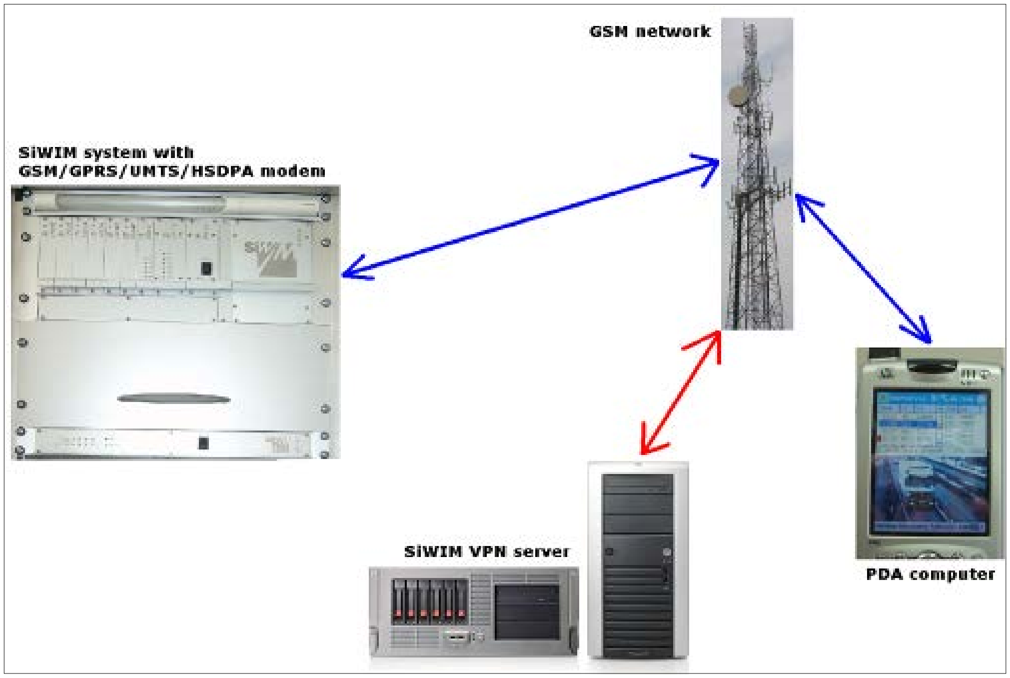

Figure 3-4. Encrypted communication

The performance of a SiWIM system is greatly influenced by site conditions. Every feature of a roadway potentially impacts the performance of the system. Therefore, many factors should be considered in selecting proper sites for the effective installation of a SiWIM system. Important considerations include road geometry and pavement characteristics, with particular emphasis on longitudinal evenness and road-surface deterioration (such as rutting and deformation).

The geometric features of the proposed site are vital for SiWIM installation because they greatly influence the accuracy of the dynamic and static load measurements. It is important that vehicles approaching the weighing system are not subjected to a condition that will result in acceleration or deceleration because results are better if the vehicle crosses the bridge at a uniform speed. The geometric design requirements for each type of WIM installation system have been specified in the ASTM standards (Center 1997). The major environmental concern is the climate. For example, the temperature must be between -20°C and +60°C to operate properly (COST 323 1999).

There are a few general rules recommended for selecting appropriate bridges for SiWIM measurements: (1) It is important to understand the quality of results (accuracy and percentage of weighed vehicles) needed. Less demanding applications, such as a collection of traffic load statistics, requires lower accuracy and thus broadens the set of appropriate structures; (2) The bridge should be located on an open road with fluid traffic; (3) Bridges with smooth approach ramps and deck surfaces will yield more accurate results; (4) Fixed-support structures are favored over simply supported structures; (5) The length of the spans should be between 5 and 12 meters for single-span bridges and any length up to 12 meters for multiple-span bridges for most NOR (Nothing On Surface) installations; (6) To minimize the effect of 'multiple presence' events, it is recommended to use shorter span bridges if vehicle traffic is heavy because SiWIM systems measure the effect of all axles at the same time, since the research illustrates that on roads with fewer than 1000 heavy vehicles per day and span lengths shorter than 10 meters, less than 1% of measurements are expected to come from multiple vehicles (ZAG 2003); (7) Older or deteriorated structures require special attention during installation. For example, care should be taken to avoid installing strain transducers near cracks in the concrete. Table 3-1 lists comments as to the suitability of bridge configurations for a SiWIM installation.

For the Alabama B-WIM testing described in this report, the following general criteria were established for choosing the test bridges: (1) easy underneath access, (2) limited longitudinal and lateral slopes (< 2–3%), (3) straight road section or long radius of curvature (> 1000 m), (4) no crossing or entrance/exit close to the bridge, and (5) representative of ALDOT bridges.

Traffic conditions and on-site facilities and equipment should be considered as well. B-WIM accuracy is strongly related to the number of trucks (axles) that might influence the structure while a truck of interest is being measured (COST 323 1999). Therefore, it is not surprising that one truck crossing the bridge at a time gives the best results. Therefore, the length of the structure and traffic density should be considered. The denser the traffic, the shorter is the optimal length of the structure if interference from other vehicles is to be minimized.

If the influence value is used in the weight-assessment algorithm, an influence value based on strain readings can improve the accuracy of calculation. This is particularly important when a continuous bridge is instrumented. With this type of structure it is also essential that all the spans that considerably influence the behavior of the instrumented span (where the strains of the superstructure are measured) are taken into account (COST 1999). Table 3-2 outlines the criteria for B-WIM bridge selection.

In summary, since the most accurate results are obtained with one truck crossing the influence area at a time, the density of traffic should be monitored before installing SiWIM, particularly when the bridge has a long span or multiple spans. In addition, vehicle braking and accelerating should be avoided close to the influence area to achieve more accurate weight results. Approaches to the bridge and the bridge deck surface itself should be even and smooth. For best results the bridge configuration should fall within the following constraints: (1) a span length between 1 m and 30 m; (2) a span length of 3 m to 15 m for Free of Axle Detector (FAD) B-WIM systems on a simply supported bridge; (3) a span length of 6 m to 12 m is best if the end

Table 3-1. Suitability of bridge configurations for SiWIM Installation

	Bridge span	Thickness of the superstructure	Boundary conditions	Advantages and disadvantages
Slab bridge	1 to 15 m can be used for B-WIM instrumentation. Optimal span length is between 5 and 10 meters.	With 30 to 60 cm in depth the superstructure (slab) is usually thin compared to the minimum axle spacing of a freight vehicle. This provides good resolution of individual axle load effects.	Fixed-support bridge is the preferred type of bridge.	Short-slab bridges are the most favorable type of structure for SiWIM instrumentation: 1. Being short and narrow, they enable more accurate measurements of single axles and group of axles, which generally improves overall accuracy. 2. They are easy to instrument and maintain. 3. In many countries they are the predominant type of the bridge, comprising over 60% of all bridges.
Girder/deck bridge	Modern girder/deck structures are longer, with spans over 15 meters. Steel girders or prestressed beams (I or box shaped) are often 30 to 50 m long. Spans up to 30 meters can provide accurate results if traffic density is reasonable and if the main priority is vehicle gross weight.	Girder/deck bridges can be well over 1 meter thick.	With the exception of very short older structures, which are similar to slab bridges, the first and the last supports of girder/ deck bridges are usually simply supported, with an extension joint in the pavement.	Their main advantages over slab bridges are: 1. They more accurately weigh gross weights because they are longer (measuring time is longer, which is used to filter out the dynamic effects more efficiently). 2. The stresses due to traffic loading are longitudinally concentrated in beams/girders; strains are therefore easier to measure than on slab bridges, where stresses are distributed longitudinally and laterally. Their disadvantages compared to slab bridges are: 1. There are fewer girder/deck bridges than slab bridges and thus they are more difficult to find. 2. Their spans are generally longer, which results in a higher probability of multiple-presence events. 3. superstructures are deeper (height of girders/beams plus thickness of the slab), which results in lower axle load accuracy if only the girders/beams are instrumented, 4. spans with length over 30 m can exhibit considerable dynamic excitations due to bridge/vehicle interaction
Long span bridge	The conventional B-WIM approach with strain transducers around the mid-span cannot be successfully applied on bridges with spans well over 30 to 40 meters. However, on some longer bridges measurements can be taken on their 'substructures', i.e. on parts of the spans that connect structural elements in the lateral direction, such as stiffeners. Typically such structures are steel box girders or steel orthotropic deck bridges. B-WIM measurements on orthotropic deck bridges have important characteristics that differ from conventional B-WIM installations: - Short secondary spans between cross stiffeners and thin steel deck provide sharp peaks in the strain responses due to a crossing axle. These signals are useful for axle detection. - As orthotropic decks are sensitive in the lateral direction, more strain detectors are needed in the transverse direction. This makes it possible to calculate other truck parameters not normally calculated on slab or beam/deck bridges, i.e. the transverse position of trucks in lanes. - The strain measurements can be used for fatigue calculation of the structural elements.			

Table 3-1 (continued). Suitability of bridge configurations for SiWIM Installation

	Bridge span	Thickness of the superstructure	Boundary conditions	Advantages and disadvantages
Skewness of the bridge	For properly instrumented and evaluated bridges, the skewness of the bridge has a minor effect on the accuracy of results. Experience shows that after checking the calibration and test data, angles up to 60° are acceptable (with 90° being completely straight). Skewed bridges, however, require additional attention during installation and calibration.			
Single- vs. multiple-span bridges	There is no theoretical limitation to instrument single- or multiple-span bridges for measurement. If both types of bridges are available, then the following factors should be considered: - multiple-span bridges are generally longer, which will likely provide better gross weigh results, but the probability of multiple presence events is higher; - bridges with 2 or more shorter spans (up to 12 meters) allow for efficient 2-line free of axle detector installation, with one plane of strain transducers in each span			

Table 3-2. Bridge-selection criteria (COST 323 1999)

Criteria	Optimal	Acceptable
Bridge type	Steel girders, pre-stressed concrete girders, reinforced concrete girders, culverts, steel orthotropic decks (1)	Concrete slab
Span length (m) (2) (3)	5-15	8-35
Traffic density	Free traffic – no congestion (traffic jam)	
Evenness of the pavement before and on the bridge	Class I or II	Class III
Skew (º)	≤10	≤25 ≤45 (*)

(1) Expected to be optimal, research work in progress in "WAVE."

(2) This criterion applies to the length of the bridge that influences the instrumentation

(3) Except culverts.

(*) After inspection of calibration data.

supports are fixed (rigid); and (4) the thickness of the superstructure should be between 30 cm and 60 cm. Based on the test results in Alabama, the preferred type of structure is a fixed-support span with the desired span range.

3.2.2 Bridge Site Selection for SiWIM Installations in Alabama

Based on the recommended site-selection criteria, two sites were selected for calibration and traffic testing of the SiWIM system in Alabama. The two selected bridges were on Highways I-59 and I-459. Table 3-3 summarizes selected bridge information for the I-59 and I-459 bridges and contrasts bridge characteristics with the criteria recommended for SiWIM installation.

Table 3-3. Ideal and acceptable criteria for some of the basic bridge characteristics (COST 323 1999)

Criteria	Ideal	Acceptable	Bridge on I-59	Bridge on I-459
Structural material	Reinforced concrete, prestressed concrete, steel	Concrete, Masonry, Stone	Reinforced concrete	Prestressed concrete
Superstructure or bridge type	Slab, beam/deck systems, culvert, steel orthotropic decks	Arches	Slab, beam systems	Slab, beam systems
Traffic density	Free traffic – no congestion	Free traffic – no congestion	Free traffic – no congestion	Free traffic – no congestion
Span	1 or 2 spans	More than 2 spans	9 spans	3 spans
Span length	length 16 to 32 ft 6 to 16 ft for AD only	Length 3 to 16 ft Length 15 to 50 ft	length 34ft =10.36m	length 46'4" =14.122m
Skewness	0° to 20°	20° to 45°	0°	0°
Supports	Fixed (integral bridge)	Simply supported*	Simply supported	Simply supported
Vibration	<10% of static values	<30% of static values**	<10% of static values	<10% of static values
Pavement	Smooth, no bumps	Small bump*	Smooth on the center of the bridge, pavement on the approach to the bridge is uneven.	Smooth on the center of the bridge, pavement on the approach to the bridge is even.

* pure simply supported bridges are rare: the exact degree of fixity can usually be determined only after the initial (test) strain measurements.

** based on experience or after test strain measurements

3.3 Calibration Procedure

Calibration is a crucial part of the SiWIM installation process. Dynamic results are obtained and compared with the accurate static weight to calibrate the SiWIM system. The system will be accurate only if the SiWIM system is correctly calibrated.

The appropriate calibration test is mainly based on the desired level of accuracy and the desired confidence in the results. The higher the desired accuracy and confidence, the more elaborate, time consuming, and expensive the calibration must be. However, there are diminishing returns because the accuracy and confidence of any B-WIM system is largely influenced by multiple factors, as discussed in the previous section of this report.

SiWIM accuracy depends on (1) the type of bridge, (2) the installation and calibration procedure, (3) the selection of the influence line and fine tuning of the weight parameters, (4) the accuracy of the static weighing procedure use for comparing dynamic results with static weight results, and above all (5) the smoothness of the bridge approach and surface pavement.

In accuracy tables, two levels of confidence are provided:

- π_0, which is the confidence level for the achieved confidence interval δ, and
- π, which is the confidence level for the attained accuracy class. π is generally greater than π_0.

Four test conditions and three environmental conditions are used. The four test conditions follow:

- full repeatability (one vehicle under the same traffic conditions)
- limited repeatability (one vehicle with different loads under changing traffic conditions)
- limited reproducibility (2 to 10 different trucks under changing traffic conditions)
- full reproducibility (more than ten vehicles form the traffic)

The environmental conditions follow:

- environmental repeatability (short measurements in mostly constant environmental conditions - weather)
- environmental limited reproducibility (short measurements in changing environmental conditions - weather)
- environmental full reproducibility (long-term measurements in changing environmental conditions - weather)

For example, accuracy class B(10) means that approximately 95% of the gross weight estimates will fall within 10% of the true static value. Estimates of single-axle loads will tend to fall within 15%, and estimates of group axles will tend to fall within 12%. Accuracy classes achievable with bridge WIM systems range from an excellent B+(7) on very good structures with smooth pavement to an acceptable D(25) on less-than-ideal bridges with very rough pavement. Typically B(10) or C(15) can be expected.

COST 323 specifies the WIM requirements for performance and environmental conditions, site criteria, calibration procedure, and accuracy class. In COST 323, four test conditions and three environmental conditions are used. The test conditions are (1) *full repeatability* (r1), (2) *limited repeatability* (r2), (3) *limited reproducibility* (R1), and (4) *full reproducibility* (R2). For test conditions (1) and (2), only one vehicle is needed in repeated runs; the difference is that in the first the vehicle runs under the same loading and traffic conditions, but in the second it runs under different conditions. Condition (3) needs 2 to 10 trucks driven over the bridge several times under changing traffic conditions. Condition (4) uses more than ten vehicles from the traffic. The environmental conditions are (1) *environmental repeatability* (I), representing short measurements in mostly constant environmental conditions (weather); (2) *environmental limited reproducibility* (II), representing short measurements in changing environmental conditions (weather); and (3) *environmental full reproducibility* (III), representing long-term measurements in changing environmental conditions (weather) (Zag 2003).

European Weigh-in-Motion Specifications define an accuracy class with a letter and a number in the parentheses. Class A(5) is the most accurate class, followed by B+(7), B(10), C(15), D+(20), D(25), and E(30). On average, about 95% of the measurements will fall within δ percent of the vehicle's true weight, where δ is the number in parentheses. The exact level of confidence depends on the number of test vehicles, on the type of check (initial calibration or subsequent in-service validation), and on test and environmental conditions. Table 3-4 shows values for environmental repeatability conditions (short measurements in mostly constant environmental conditions). In other words, to be sure that 90% to 95% of results will fall within ±δ percent around the true (static weighed) value, it is necessary to have ten to several hundred valid measurement results, depending on the test and environmental conditions.

Table 3-4. Minimum confidence level π_0
(of the centered confidence intervals in %) - under environmental repeatability

Sample size (*n*) / **Test conditions**	**10**	**20**	**30**	**60**	**120**	**∞**
Full repeatability (r1)	95.0	97.2	97.9	98.4	98.7	99.2
Limited repeatability (r2)	90.0	94.1	95.3	96.4	97.1	98.2
Limited reproducibility (R1)	85.0	90.8	92.5	94.2	95.2	97.0
Full reproducibility (R2)	80.0	87.4	89.6	91.8	93.1	95.4

π_0, which is the confidence level for the achieved confidence interval δ, and π, which is the confidence level for the attained accuracy class and is generally higher than π_0.
Source: COST (1999)

Figure 3-5 demonstrates the minimum confidence level π_0 by the number of data points. The European specification is mainly focused on two cases: R1, which stands for the initial calibration, and R2, which represents an in-service check. The environmental conditions of both cases are *environmental repeatability.*

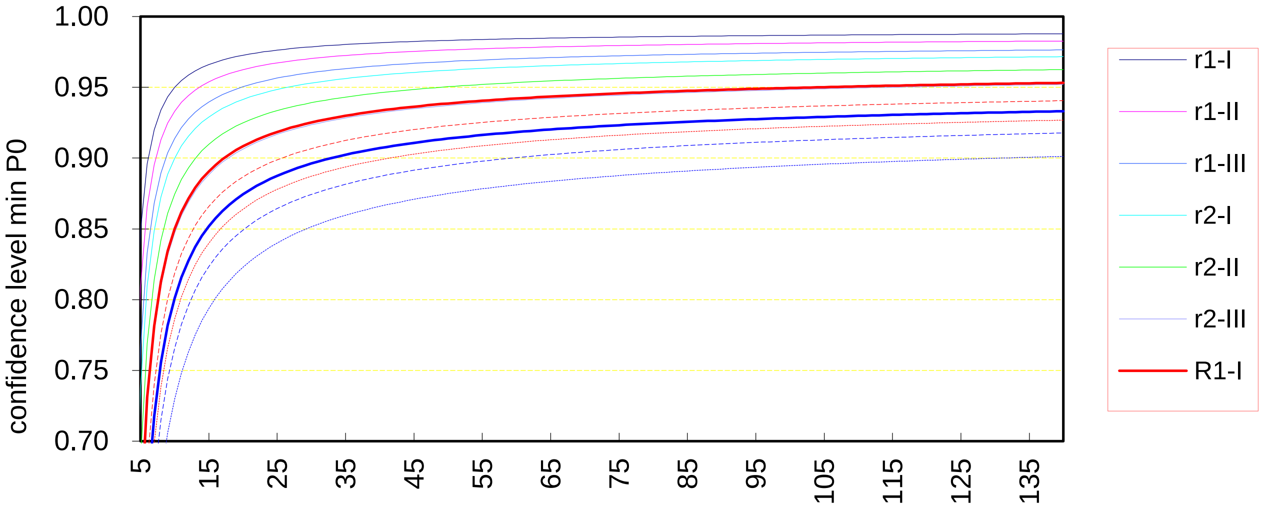

Figure 3-5. Minimum confidence level π_0 by number of data points

Table 3-5 illustrates tolerances of the accuracy classes of gross weight, group of axles, single axle, and axle of a group respectively at the confidence interval δ. Accuracy class B(10) for example means that approximately 95% of the gross weight results (Table 3-5) can be expected between ±10% from the true static value. Single axle loads can be expected in the interval ±15% and group axles in the interval ±13%. Accuracy classes achievable with SiWIM systems range from the excellent class A(5) on ideal sites with very smooth pavement and after detailed calibration to still acceptable class D(25) on less ideal bridges with very rough pavement or with a bump on the entrance ramp to the bridge.

Table 3-5. Accuracy class tolerance (confidence interval δ in %)

Criteria (type of measurement)	Accuracy Classes: Confidence interval width in each direction of the true value δ (%)											
Accuracy Class	**A (5)**	**B+ (7)**	**B (10)**	**C (15)**	**D+(20)**	**D (25)**	**E(30)**	**E(35)**	**E(40)**	**E(45)**	**E(50)**	**etc.**
Gross weight (>3.5t)	5	7	10	15	20	25	30	35	40	45	50	…
Group of axles	7	10	13	18	23	28	33	39	44	49	55	…
Single axle (>2.0t)	8	11	15	20	25	30	36	42	48	54	60	…
Axle of a group	10	14	20	25	30	35	41	47	53	59	65	…

Source: COST 323 (1999)

3.3.1 Initial Calibration

For a newly installed SiWIM system, to obtain confidence level π_0=95%, the European specification requires the truck configurations, weights, and speeds shown in Table 3-6.

Table 3-6. Calibration plan with two pre-weighed test trucks (number of runs in each direction)

Test vehicle	Speed (km/h)[1]	Loading and number of runs		
		Fully loaded	**Half loaded**	**Empty**
2-axle rigid truck	$1.2V_m$	8 runs	5 runs	-
	V_m	14 runs	10 runs	-
	$0.8V_m$	8 runs	5 runs	-
5-axle semi-trailer	$1.2V_m$	8 runs	5 runs	2 runs
	V_m	14 runs	10 runs	6 runs
	$0.8V_m$	8 runs	5 runs	2 runs
Total runs=110 runs				

1. V_m: mean truck speed in the traffic. It is better for 1.2Vm does not exceed the speed limit.
Source: COST 323 (COST 1999)

For the initial calibration, the confidence intervals given in Table 3-5 are modified as [-0.8δ, 0.8δ] for each relevant accuracy class and criterion.

3.3.2 In-service Verification

After the initial calibration (in limited reproducibility [R1]), the accuracy of the system can be verified in more realistic full reproducibility conditions (R2) based on the European WIM Specifications. With the help of the Department of Public Safety, trucks can be pre-weighed on a static scale, ideally within the 5 km before the bridge. To obtain a minimum 80% confidence level, there need to be more than 10 valid truck passes over the bridge during the in-service check. During the course of the project, researchers learned that the most efficient way to approach the in-service verification is to capture trucks and statically weigh them after they cross the bridge. This way only trucks measured by the SiWIM system are stopped.

3.4 First Installation

The first SiWIM installation took place between October 16 and 26, 2007, on a two-lane bridge located north of Birmingham, AL on I-59S (Figure 3-6). During the calibration process, gross weights and axle loads of vehicles pulled from the traffic were statically weighed by an axle static scale. These results were compared to the weight estimates obtained from the SiWIM.

The equipment was left installed on the bridge for fourth months for further testing and data recording.

3.4.1 Selection of the Bridge

The initial process for bridge selection consisted of first finding a highway section where SiWIM measurements would be useful for heavy freight weight enforcement followed by a detailed inspection of the bridge types along that section of highway (with exact measurements, comments about approach to the bridge, smoothness of the approach, bridge geometry, type of superstructure, etc.). The I-59 bridge was selected as a suitable candidate.

The approach ramp to the bridge is bumpy, and the pavement on the bridge had some cracks (Figure 3-7). It turns out that these surface imperfections induced dynamic effect on the vehicles and substantially influenced the accuracy of the results.

3.4.2 Bridge Description

Bridge B007239 lies on Highway I-59 near exit 166 over Muckleroy Creek in St. Clair County, Alabama. The bridge is a simply supported T-beam bridge with nine 34-ft spans. Figures 3-8, 3-9, and 3-10 show the elevation, plan, and cross section of the bridge.

Figure 3-6. Side view of the I-59S bridge

Figure 3-7. The pavement

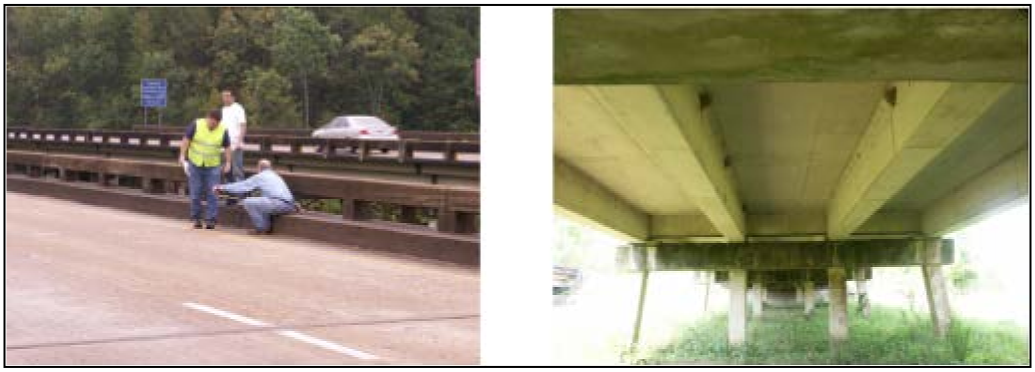

Figure 3-8. View of bridge on Highway I-59S

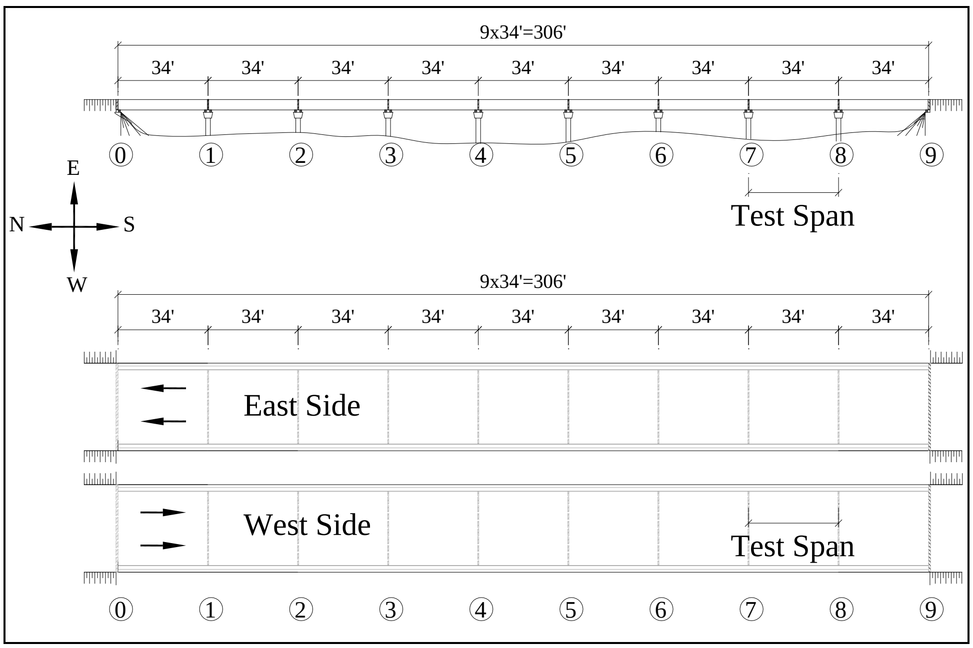

Figure 3-9. Elevation and plan of the bridge

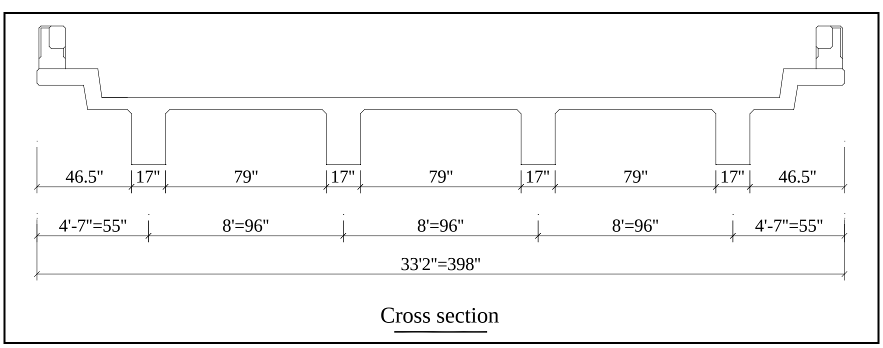

Figure 3-10. Cross section of B007239 bridge

3.4.3 Bridge Instrumentation

Each bridge span consists of four beams with free vertical clearance between 10 ft and 18 ft. The highway has four lanes, two in each direction. Only one side was instrumented.

Exact measurements were performed before drilling and installing the sensors, distributor/collectors, cabinet, cables, etc. For this SiWIM instrumentation, eight strain transducers (weighing sensors) were mounted on the soffit of the beam at the 8th span (the southernmost span on the traffic lanes headed south). To detect axles and speed, four strain transducers were installed (FAD sensors) 12 ft apart just beneath the slab (left lane: Nos. 3 and 8; right lane: Nos. 8 and 7). Additionally, four strain transducers were mounted on the slab to detect the axles. The position of the FAD sensors and weighing sensors is illustrated in Figure 3-11. Cables were connected to all the sensors, with the SiWIM electronics located in the cabinet. The cabinet was attached to the bridge abutment.

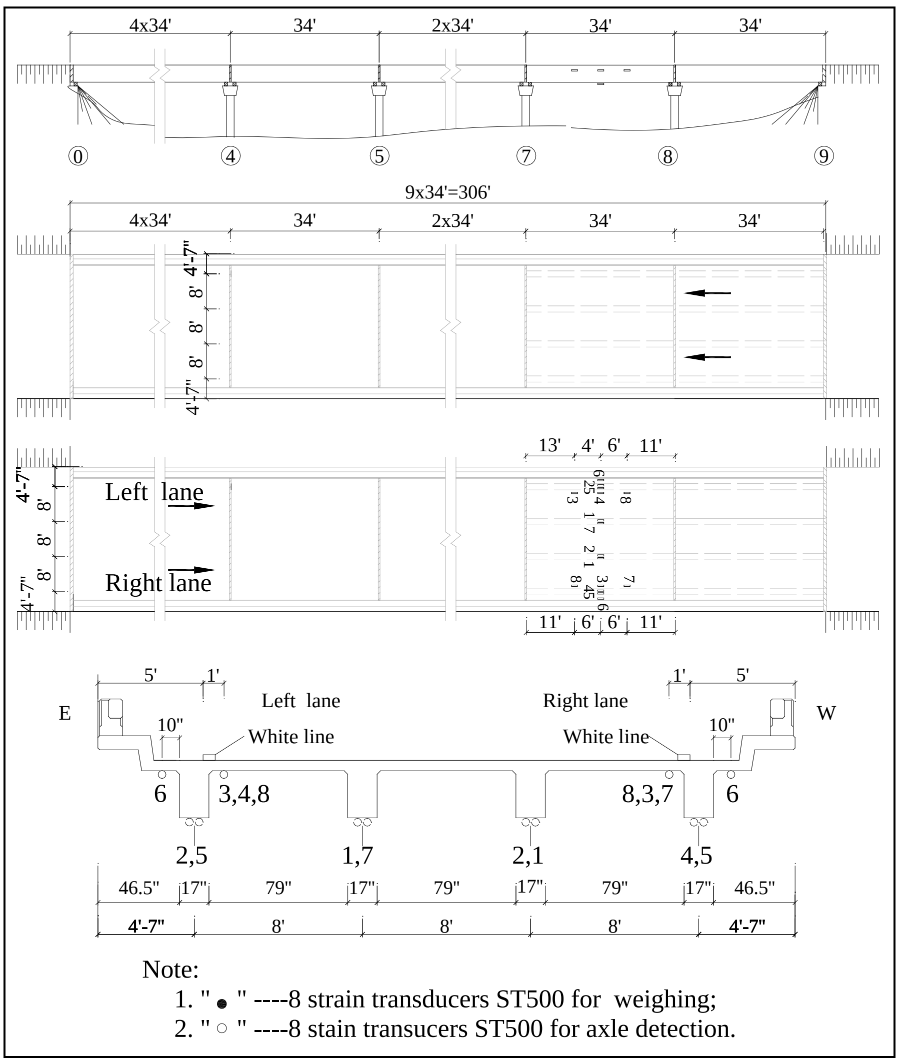

Figure 3-11. The position of the weighing and FAD sensors

3.4.4 Installation Procedure of Sensors

Sensor installation included the following steps (Figure 3-12):

- Mark the sensor location and drill.
- Place an anchor in the drilled hole and hammer it.
- Bolt the strain transducer in its proper place. The bolts should be tight to get accurate measurements.
- Once the transducers are in location, install the spider and begin to connect the data cables.
- Make sure the extra cable lengths are wrapped together.

Figure 3-12. Sensor installation procedure

3.4.5 Installation of Camera

The camera or cameras must be installed so that they capture a clear shot of the vehicles as they cross the bridge:

- Camera installation and adjustment is the last step in hardware installation.
- Make sure the camera is adjusted to see the targeted traffic lanes (Figure 3-13).
- Tighten the camera screws to ensure the camera stays in place.
- Connect the camera cable to the system.

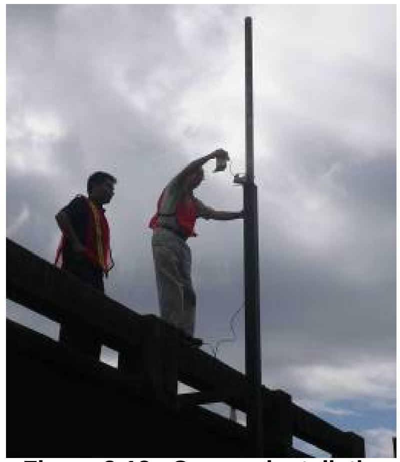

Figure 3-13. Camera installation

3.4.6 System Setup and Configuration

A proprietary access key is required to use the software contained in the SiWIM-F system. With a PC notebook connected to the SiWIM system, basic parameters were entered. After the default influence line was created from the parameters, vehicles were detected with the system and raw data was used to construct influence lines using real traffic on the bridge. After that, final tuning (parameters settings) was performed. This was accomplished with the help of experienced CESTEL personnel.

3.4.7 Bridge Calibration

Bridge B007239 was calibrated according to limited reproducibility (R1) under environmental repeatability (I), which requires 2 to 10 trucks. The calibration test involved collecting short measurements in mostly constant environmental conditions.

On October 23, 2007, the initial calibration attempt used two rigid pre-weighed ALDOT vehicles (Figure 3-14). The ALDOT trucks crossed the bridge several times. Unfortunately, the ALDOT test trucks were not identified by SIWIM system; therefore, these trucks were unsuitable for calibrating the SiWIM system. The lack of detection surprised all concerned, so a secondary plan was implemented.

It was determined that calibration could be accomplished using trucks drawn from traffic. The trucks would first be weighed by a portable static-weigh system and then released to cross the bridge. Department of Public Safety patrolmen stopped 11 semi-trailer trucks and sent them to a weighing area at a rest stop north of the bridge. At the rest area, each truck was weighed and released. Of the 11 trucks, SiWIM captured measurements and photos for only three of the trucks (Figure 3-15). The other pre-weighed trucks were either not identified by the system or they passed over the bridge at the same time as other trucks. Therefore, the first calibration was based on three trucks. Summary information of the trucks is shown in Table 3-7.

Figure 3-14. Initial calibration truck for the bridge on Highway I-59S

Figure 3-15. Trucks captured during in-service check for the bridge on Highway I-59S

Table 3-7. Comparison of calibration vehicles

	Vehicle 1			Vehicle 2*			Vehicle 3		
	Static	SIWIM	(%)	Static	SIWIM	(%)	Static	SIWIM	(%)
1st Axle	8250	7931	-3.87	10350	11190	8.12	9700	9263	-4.51
2nd Axle	15300	12346	-19.31	10100	10260	1.58	6150	6268	1.92
3rd Axle	13300	15089	13.45	10150	8780	-13.50	6150	7117	15.72
4th Axle	17300	15162	-12.36	7000	6525	-6.79	6600	6148	-6.85
5th Axle	16100	18532	15.11	7050	7975	13.12	6400	7514	17.41
Total	70250	69061	-1.69	44650	44730	0.18	35000	36312	3.75
Group 1	28600	27435	-4.07	20250	19040	-5.98	12300	13385	8.82
Group 2	33400	33694	0.88	14050	14500	3.20	13000	13662	5.09

* Actual data form SIWIM are not available, the data was derived.

The accuracy assessment for the bridge was made using the sample of pre-weighed trucks identified by the system. The COST 323 conditions of full reproducibility (R2) and environmental repeatability (I) were employed. Table 3-8 gives the results according to the *European Weigh-in-Motion Specifications* under environmental repeatability and general reproducibility (in-service check). As mentioned earlier, typically the group of axles are weighed with less accuracy than the other criteria and the Cost 323 Specification recommends that this criteria not be used in accuracy assessment. However in this case, the group of axles result was class C(15) and the single axles result was D+(20). The "Accepted Class" is the accuracy classification based on the most restrictive class of the three criteria calculated. In this case the single axle result of D+(20) dictates the accepted class.

Table 3-8. Accuracy result for the bridge on I-59S

Criteria	n	Mean (%)	St. dev. (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	$\pi_{criteria}$ (%)	π_{class}	π (%)	π_c (%)	Accepted Class
Gross weight	3	0.73	2.26	-25.8	B(10)	10.0	8.6	8.6	10	/	80.0	
Group of axles	6	1.32	5.11	73.1	C(15)	18.0	16.6	13.6	15	/	94.1	D+(20)
Single axles	3	-0.10	5.78	-25.8	D+(20)	25.0	21.1	16.1	20	/	79.3	

Since only three calibration vehicles were identified by the SiWIM system during the initial calibration test, the experts from CESTEL decided to manually check all the vehicles captured by the system over a four-hour timeframe. They manually checked over 400 vehicles and found an additional three calibration vehicles without photos. These results were then combined with the three trucks reported above. Table 3-9 gives the weights and axle distances for the combined calibration vehicles, and Table 3-10 gives the adjusted accuracy results.

Table 3-9. Weights and axle distances for calibration vehicles

Vehicle	Tag No.	Weight (lb)						Spacing (in)			
		GVW	1st axle	2nd axle	3rd axle	4th axle	5th axle	A1-A2	A2-A3	A3-A4	A4-A5
1	Y58-42A	34400	11000	6750	5850	5700	5100	197	53	365	52
2	31X-8535	70250	8250	16300	14300	16300	15100	147	54	188	53
3	2AD-399	46650	10350	12100	11150	6500	5550	197	54	439	53
4	43538H2	35000	9700	7150	6750	6300	5100	152	54	264	52
5	IR-9766	73650	11800	16950	16750	16550	11600	234	54	398	53
6	AE-95905	74450	11800	17600	15900	13750	15400	216	54	408	52

Note: Vehicles 2, 3, and 4 are the vehicles for which the SiWIM captured photos.

Table 3-10. Modified accuracy result for bridge on I-59S

Criteria	n	Mean (%)	St. dev. (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	$\delta_{criteria}$ (%)	δ_{class}	π (%)	π_c (%)	Accepted Class
Gross weight	6	0	1.98	73.1	B(10)	10	8	8	10	97	99	
Group of axles	12	-0.6	2.64	87.1	B(10)	13	13	10	10	99.9	99.9	C(15)
Single axles	6	0	4.68	73.1	C(15)	20	16	11	15	93.6	97.7	

3.5 Second Installation

3.5.1 Bridge Description

The second bridge tested was on I-459 near exit 10, about 15 miles southwest of Birmingham, AL. The bridge is identified as BIN number 012296 and was built in 1980. The bridge is located on Highway I-459 over Sulphur Springs Road in Hoover, Alabama (see Figure 3-16). The bridge has four lanes with a total ADT of 31,980. Trucks comprise 17% of the traffic. The bridge consists of three simply supported spans, each 35 ft long. Each span consists of 10 prestressed concrete girders. The bridge has no skew angle with the abutments or piers. The pavement over the bridge and the approach slabs are smooth with little cracking. The girders are AASHTO type II girders. Dimensions of the bridge and girder spacing are given in Figure 3-17, which shows a cross-sectional view of the bridge. The figure also shows the lane positions with reference to the nearest girders.

Since the bridge has four lanes, 24 strain transducers were placed at the middle of the third span. Calibration was performed over two days using four calibration trucks provided by ALDOT: a rigid truck (three-axle) at maximum legal load (80 kips), another with half the maximum load, a semi-rigid (five-axle) fully loaded, and another semi-rigid with a half load. The plan was for each truck to run on each lane ten times. It turned out this number of repetitions was difficult to attain, so fewer runs with the half-loaded trucks were performed. In addition, screening of regular truck traffic was performed over two additional days.

Figure 3-16. Elevation view of the bridge

3.5.2 Bridge Instrumentation

Installing the system hardware involved the placing the transducer sensors, running and connecting the cables, fixing the cameras to steel poles, and bolting the SiWIM data logger to the abutment. The installation process required substantial pre-planning to set the number of sensor locations. The SiWIM system sensors only go underneath the bridge's superstructure, thereby avoiding traffic interruption during installation.

Each group of B-WIM transducers had a particular function. The first set of sensors placed on the girders weigh the vehicles as they travel over the bridge at normal speeds, and the second set detects the axle spacing and velocity of those vehicles. One weighing sensor was placed midspan of each girder. Two axle detector sensors, also known as Free-of-Axle Detectors (FAD), were placed on the slab for each lane along the traveling path of the vehicle. The FAD sensors were placed 4.16 m apart, measuring 2.08 m on each side from the weighing sensors. To summarize, the sensors used:

- 10 strain transducers attached to the bottom side of the superstructure (on each beam)
- 8 strain transducers, with 2 per measured traffic lane to detect speed and axle spacing
- 6 strain transducers on the diaphragms for testing purposes
- 24 strain transducers were used in total, the maximum number that can be used

Due to the slope of the abutment, a platform scaffolding truck provided by ALDOT was required to reach the bridge soffit (Figure 3-18) to install the sensors. A bucket truck was used as shown in Figure 3-18 when it was necessary to relocate some of the sensors. Figure 3-19 shows the bridge after installing all the sensors, wires, and spiders. A spider is a hub that collects wires from eight sensors and is connected with the main B-WIM data logger.

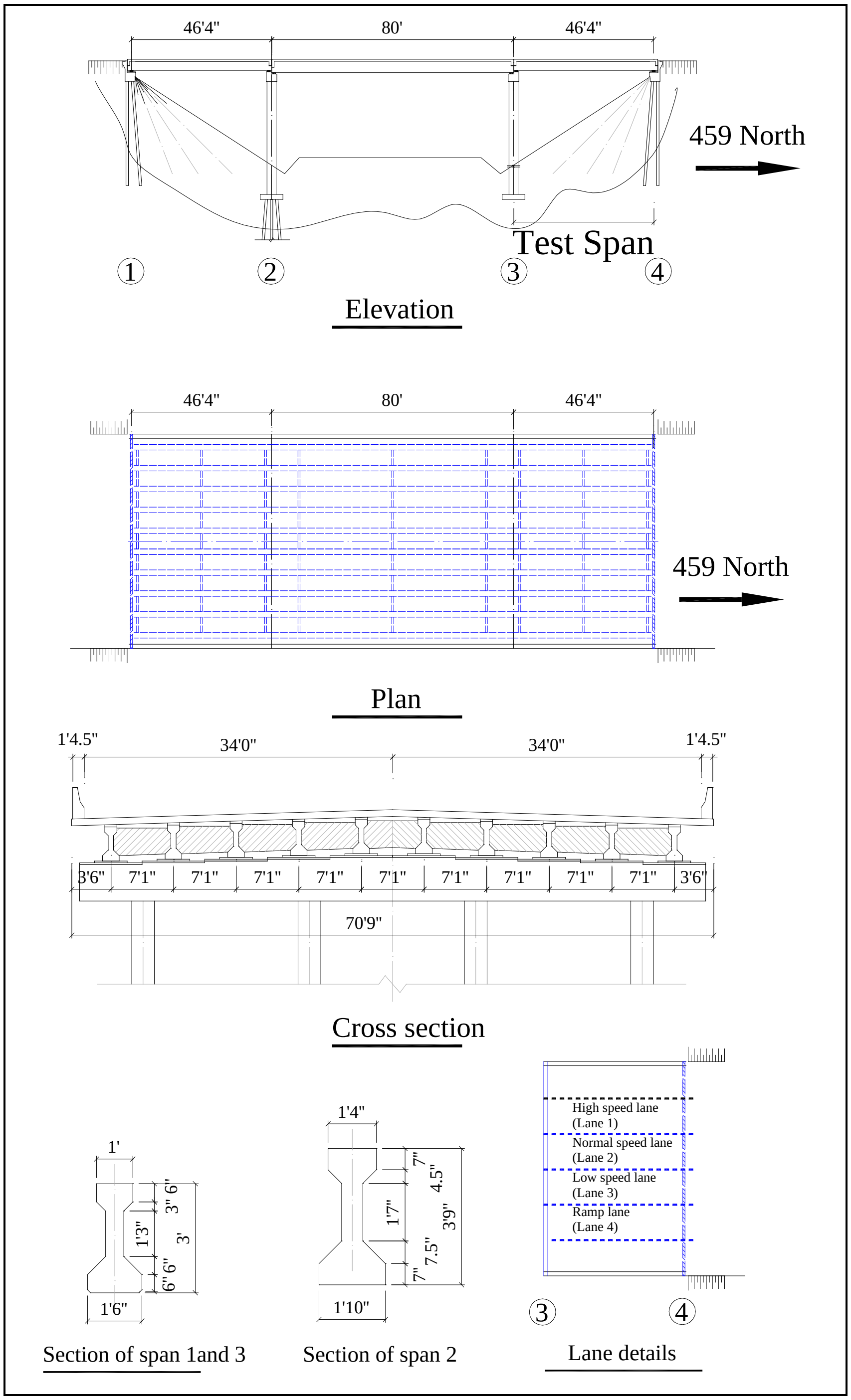

Figure 3-17. Elevation, plan, and cross section of the bridge

Figure 3-18. UAB team on the scaffolding marking sensor locations

Figure 3-20 shows the camera installation on a pole fabricated by ALDOT. The camera adjustment was then performed to make sure that it was capturing the required lane. The camera parameters were then set to enable the system to decide the number of pictures captured for each truck, as well as the best camera angle and distance. Night illuminators can be used with the camera for night pictures. Figure 3-21 shows a lockable box containing the batteries needed to power the system. The locked battery box was necessary after the battery was stolen at the I-59S site. The system wiring was finished in a cooperative effort between UAB and ALDOT.

As is the case for many bridges on Alabama highways, a local AC power supply was not available to power the system. ALDOT uses solar cells for other installations requiring power, and it was necessary to find the right configuration of solar panels and battery storage to power the system. After several configuration attempts, a sufficient power system was configured to operate the cameras and processor and to transmit information. The final power configuration was composed of three solar panels charging six deep-cycle 12-volt batteries placed in two boxes. These six batteries were connected in parallel, which would provide power to the system for at least four to five days with minimal solar input, such as on cloudy or rainy days, provided the camera is turned off when not in use.

The 10 weighing sensors were mounted on the girders on Span No. 3 one foot off center because of the diaphragm. For vehicle detection and speed calculation, eight ADMP (Axle Detector Measuring Point) sensors (also called FAD sensors) were mounted under the tire tracks for each lane (there are three driving lanes and one additional lane, coming from Exit 10). The remaining six sensors were installed to determine if vehicles could be detected on the diaphragms. They were installed on diaphragms, 90° rotated according to the driving direction and positioned between girders 2 and 8, one between each two girders.

Initially, the ADMP sensors were placed under the right tire track for the two right lanes and under left tire track for the two left lanes. During the sensor check before the calibration test, it was discovered that the ADMP sensors were not effective in detecting axles. Upon further investigation, it was determined that the ADMP sensors were in the negative moment range. The system software does not recognize negative strain input, which is why the ADMP sensors did not work. This software limitation was not known to the testing team, but CESTEL experts were able to recognize the problem and explain the limitation. The ADMP sensors were then moved farther from the girder (20 inches from the girder). The details are illustrated in Figure 3-22.

Figure 3-19. Sensors installed and wired

Figure 3-20. Camera installation

Figure 3-21. The power box with batteries inside

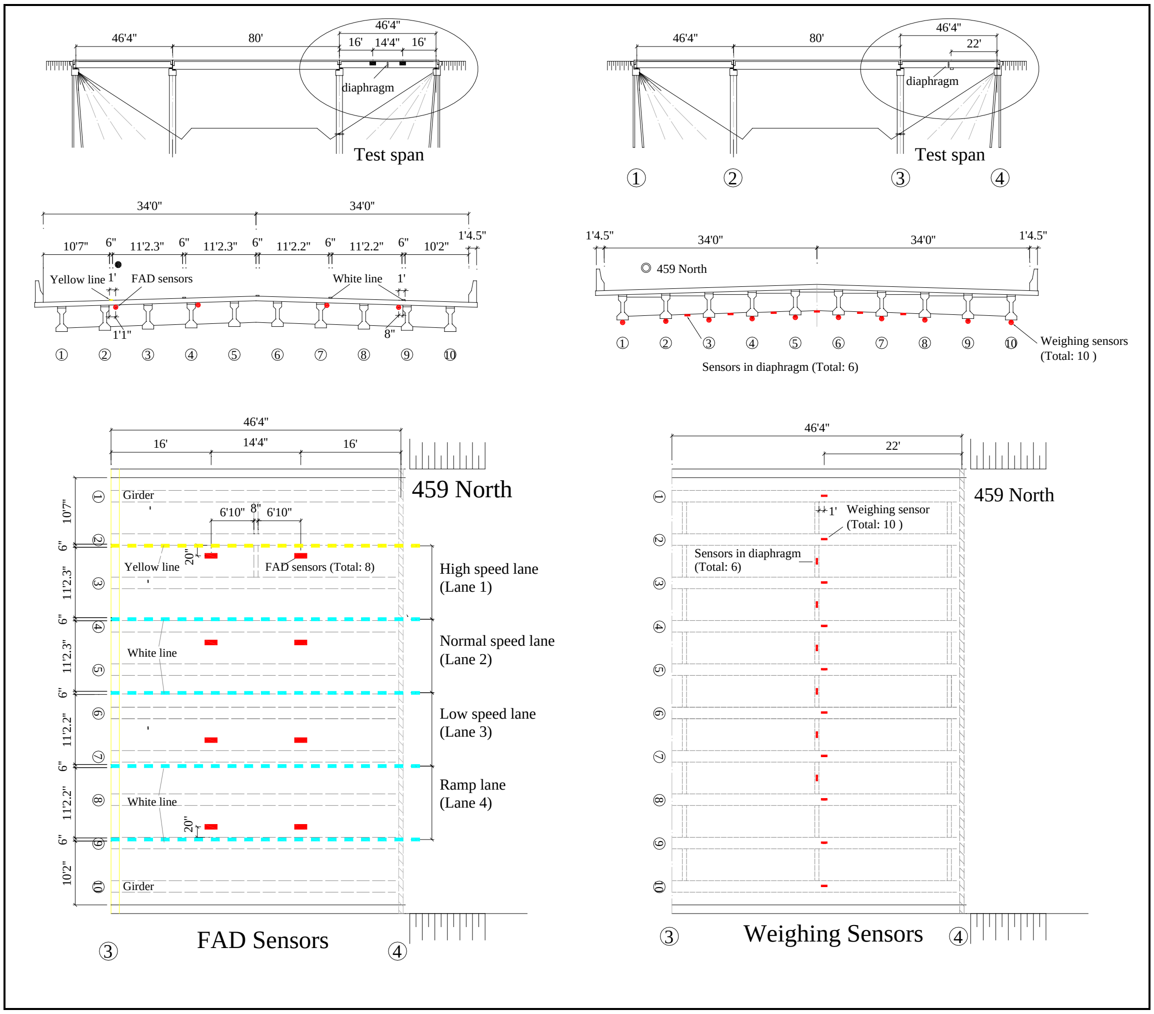

Figure 3-22. Weighing and ADMP (FAD) sensors

3.5.3 Calibration and In-service Check Test Plan

Calibration Plan: The calibration test plan was based on the European specification COST 323. As this was the first SiWIM system installation in the United States, researchers hoped to achieve a high classification confidence level of 95%. For the initial calibration, limited reproducibility (R1) was employed, which means 2 to 10 trucks must be driven over the bridge several times each under changing traffic conditions. The environmental condition was environmental repeatability (I), meaning short measurements in mostly constant environmental conditions (weather).

According to Table 3-4 and Figure 3-5, to achieve a 95% confidence level under limited reproducibility (R1), a total of 110 valid runs would be necessary. Therefore, the initial calibration plan called for four ALDOT calibration truck configurations: a rigid truck (three-axle) at maximum legal load (80 kips), another at half maximum legal load, a semi-rigid (five-axle) fully loaded, and a semi-rigid half loaded.

The calibration process would be accomplished by running the pre-weighed and premeasured (axle spacing) trucks on all the testing lanes. The collected truck data would then be processed by the SiWIM software, and a calibration factor established. The software is programmed to classify truck type based on the axle spacing and weight of each passing truck. That was the main reason behind planning the use of two truck types—rigid and semi-rigid—for the calibration runs. The software develops two calibration factors for each lane: one for semi-rigid trucks and one for rigid trucks.

Figure 3-23. Fully loaded semi-rigid calibration 18-wheeler

Figure 3-24. Half-loaded semi-rigid calibration 18-wheeler

Figure 3-25. Fully loaded rigid dump truck

Figure 3-26. Half-loaded rigid dump truck

In-Service Check Plan: For the in-service check plan, full reproducibility (R2) and environmental repeatability conditions (I) were desired, which means at least 10 vehicles from the traffic flow would be required. The other consideration in determining the number of vehicles weighed in this test is the desired confidence level of the results. According to COST 323, at least 10 trucks are required for a 80% confidence level, 33 trucks for a 90% confidence level, and about 2000 trucks for a 95% confidence level. If a near 90% minimum confidence level is targeted, then at least 30 vehicles should be selected from the traffic and successfully weighed by the SiWIM system. The team initially planned a goal of 50 trucks to be pulled from the traffic flow. Why were 50 trucks established as the goal for the test plan? An important obstacle for using random traffic for calibration verification and enhancement is that the procedure requires a large number of trucks to be weighed to achieve an acceptable confidence level because the SiWIM system will not likely capture all of the trucks pulled from the traffic flow. For example, according to one experience in Slovenia, over three days 82 trucks from traffic were weighed on the static scale, and 77 of them were identified when passing the SiWIM site (Zag 2003). However, in France, over three days 29 trucks were stopped and weighed in static scale before crossing the bridge, and only 11 trucks gave useful data (Bouteldja, *et al.* 2008). To attempt to achieve a high confidence level (i.e. near 90%) researchers wanted to record at least 30 useful truck data runs. The 50-truck goal was therefore established to meet this objective.

Another reason for scheduling such an intensive in-service check over two days rather than multiple days or weeks has to do with the response of the commercial truck drivers to an spot-check of load weight. Once weighing operations begin and random trucks are pulled from the traffic stream, it is a given that the number of trucks passing this location will decrease quickly as word spreads between drivers by CB radio and other communications means. This possibility will remain a problem for future research efforts, and more importantly, future deployment operations by ALDOT and the Department of Public Safety.

3.5.4 The Actual Calibration Vehicles and Runs

The calibration runs took place on March 18 and 19, 2008. The calibration vehicles, the number of runs, and the speeds measured are listed in Table 3-11. The detailed calibration weight information of the test trucks is detailed in Table 3-12. Figure 3-23 shows the fully loaded semi-rigid calibration 18-wheeler passing on lane one. Figure 3-24 shows the half-loaded semi-rigid calibration 18-wheeler passing on lane three. Figure 3-25 shows the fully loaded rigid calibration truck passing on lane two. Figure 3-26 shows the half-loaded rigid calibration truck passing on lane one. All the calibration trucks pictures were captured using the B-WIM system camera. The initial calibration procedure took two days. This was mainly due to the large number of runs planned and the fact that four lanes were being tested. During the calibration test, four trucks made repeated runs at different speeds on different lanes. In total there were 128 runs. Most of the runs (90%) were on lanes 2 and 3 because of the traffic flow tendencies on the bridge. This experience clearly established that, for future SiWIM installation and testing on bridges with more than two lanes, the number of truck runs necessary for calibration could be greatly reduced. This can be achieved by being selective on which lanes to test. The lane determination can be achieved during the pre-analysis phase coupled with field investigation to determine which lanes the trucks use the most. In addition, the half-loaded trucks developed more significant dynamics on the bridge, generally leading to a higher error rate. As a result, the researchers concluded that half-loaded trucks should be omitted in future calibration processes.

Table 3-11. Initial calibration used in UAB

Test vehicle	Speed (km/h)	Loading and number of runs		
		Fully loaded	Half loaded	Empty
3-axle rigid truck	$1.2V_m$=110km/h V_m=90km/h $0.8V_m$=70km/h	8 runs 16 runs 8 runs	8 runs 16 runs 8 runs	- - -
5-axle semi-trailer	$1.2V_m$=110km/h V_m=90km/h $0.8V_m$=70km/h	8 runs 16 runs 8 runs	8 runs 16 runs 8 runs	- - -
Total runs=128 runs				

Table 3-12. Calibration vehicle information

Vehicle number	Axle weight (lb)						Axle distance (in)			
	GVW	1st axle	2nd axle	3rd axle	4th axle	5th axle	A1-A2	A2-A3	A3-A4	A4-A5
1	79800	10500	15400	16400	18600	18900	170.5	52.0	434.6	50.4
2	41100	10700	7800	7700	7400	7500	170.5	52.0	445.0	49.2
3	80100	21500	29700	28900	/	/	166.0	57.4	/	/
4	41100	20000	10800	10300	/	/	166.0	57.4	/	/

3.5.5 The Actual In-service Check Runs

The ALDOT support team coordinated with the Department of Public Service troopers to stop commercial trucks to be statically weighed, axle spacing measured, and released to traffic for weight measurement by the SiWIM system. The truck data collected was written on a "vehicle weight report" that was then compared against the recorded SiWIM system data focusing primarily on weight and axle distances. Further analysis of the strain data was performed using finite element modeling techniques by the team researchers in the office. Recall the research team hoped to obtain thirty good SiWIM readings during the exercise. The test goal was to stop and weigh twenty-five trucks each of two consecutive days for a total of 50 trucks in the hopes of realizing at least 30 good results.

The in-service SiWIM check was conducted on March 20 and 21, 2008. Time and traffic conditions resulted in only 24 vehicles being pulled from traffic, weighed, and released to cross the bridge. Figure 3-27 shows the axle spacing of one of the trucks being measured after being pulled over by Department of Public Service troopers. Figure 3-28 shows the static weighing of the one of the truck's axles. The trucks was then released to the traffic to be weighed by the SiWIM crew, who knew which trucks to weigh because the static weigh crew sent them license plate data via a radio link. Figure 3-29 shows the pictures captured by the SiWIM system camera as the truck crossed the bridge.

Figure 3-27. Measuring axle distance for truck 7

Figure 3-28. Static weighing truck 7

Figure 3-29. Truck 7 passing the bridge

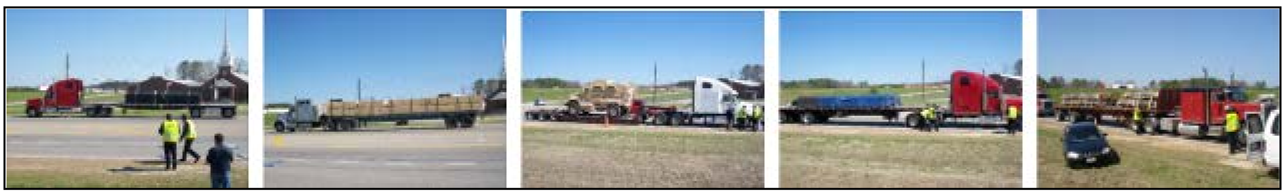

Figure 3-30. Vehicles for in-service check

Of the 24 vehicles pulled out of the traffic during the in-service check, 15 vehicles were captured by SiWIM system. Table 3-13 summarizes the single axle and gross vehicle weight results for the 15 in-service check vehicles captured by the SiWIM system, and Table 3-14 shows a comparison of GVW, single-axle load, and group of axles.

Table 3-13. Captured vehicles for the in-service check

	Vehicle 1			Vehicle 2			Vehicle 3			Vehicle 4		
	Static	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**
SA 1	11650	7664	-34.2%	11300	10139	-10.3%	11350	10026	-11.7%	10700	13077	22.2%
SA 2	15500	13806	-10.9%	17400	15479	-11.0%	15600	16479	5.6%	16800	13789	-17.9%
SA 3	15200	13901	-8.5%	16900	18919	11.9%	15200	13482	-11.3%	16300	16854	3.4%
SA 4	17050	10211	-40.1%	19050	16514	-13.3%	16450	12163	-26.1%	17750	15223	-14.2%
SA 5	16700	16378	-1.9%	16150	20183	25.0%	16700	16571	-0.8%	17350	18606	7.2%
GVW	76100	61960	-18.6%	80800	81235	0.5%	75300	68722	-8.7%	78900	77548	-1.7%
	Vehicle 5			**Vehicle 6**			**Vehicle 7**			**Vehicle 8**		
	Static	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**
SA 1	12000	3012	-74.9%	10450	10145	-2.9%	11150	4730	-57.6%	11150	11911	6.8%
SA 2	17000	12170	-28.4%	18200	17027	-6.4%	16350	13614	-16.7%	14700	12998	-11.6%
SA 3	15300	9958	-34.9%	17450	18977	8.8%	14800	11138	-24.7%	14400	15886	10.3%
SA 4	18200	22828	25.4%	15650	13374	-14.5%	17550	15762	-10.2%	16850	14054	-16.6%
SA 5	16400	12795	-22.0%	15850	16346	3.1%	17450	11636	-33.3%	15800	20080	27.1%
GVW	78900	60763	-23.0%	77600	75870	-2.2%	77300	56880	-26.4%	72900	74930	2.8%

Table 3-13 (cont.). Captured vehicles for the in-service check

	Vehicle 9			Vehicle 10			Vehicle 11			Vehicle 12		
	Static	SIWIM	%	Static	SIWIM	%	Static	SIWIM	%	Static	SIWIM	%
SA 1	10450	12387	18.5	11700	13950	19.2%	10700	9712	-9.2%	10350	7820	-24.4%
SA 2	18700	16908	-9.6	16050	14617	-8.9%	15200	13097	-13.8%	16550	15942	-3.7%
SA 3	18200	20251	11.3%	14100	17865	26.7%	15200	16007	5.3%	15650	18278	16.8%
SA 4	18900	17514	-7.3%	15850	15185	-4.2%	17050	13207	-22.5%	11950	10099	-15.5%
SA 5	19700	21406	8.7%	16850	23007	36.5%	17300	23356	35.0%	12400	11221	-9.5%
SA 6										12150	12344	1.6%
GVW	85950	88465	2.9%	74550	84624	13.5%	75450	75380	-0.1%	79050	75704	-4.2%
	Vehicle 13			**Vehicle 14**			**Vehicle 15**					
	Static	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**			
SA 1	10400	10570	1.6%	11400	9648	-15.4%	9850	8090	-17.9%			
SA 2	15500	14218	-8.3%	15800	13862	-12.3%	16850	18246	8.3%			
SA 3	15300	17378	13.6%	15450	14911	-3.5%	16850	14928	-11.4%			
SA 4	16850	13821	-18.0%	18000	13892	-22.8%	16250	14945	-8.0%			
SA 5	17100	23145	35.4%	16100	28968	79.9%	17550	17163	-2.2%			
GVW	75150	79133	5.3%	76750	81281	5.9%	77350	73373	-5.1%			

Table 3-14. Comparison of GVW, single axle load, group of axles

	Vehicle 1			Vehicle 2			Vehicle 3			Vehicle 4		
	Static	SIWIM	%	Static	SIWIM	%	Static	SIWIM	%	Static	SIWIM	%
SA	11650	7664	-34.2%	11300	10139	-10.3%	11350	10026	-11.7%	10700	13077	22.2%
GOA	30700	27707	-9.7%	34300	34398	0.3%	30800	29961	-2.7%	33100	30643	-7.4%
GOA	33750	26589	-21.2%	35200	36697	4.3%	33150	28734	-13.3%	35100	33829	-3.6%
GVW	76100	61960	-18.6%	80800	81235	0.5%	75300	68722	-8.7%	78900	77548	-1.7%
	Vehicle 5			**Vehicle 6**			**Vehicle 7**			**Vehicle 8**		
	Static	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**
SA	12000	3012	-74.9%	10450	10145	-2.9%	11150	4730	-57.6%	11150	11911	6.8%
GOA	32300	22128	-31.5%	35650	36004	1.0%	31150	24752	-20.5%	29100	28884	-0.7%
GOA	34600	35623	3.0%	31500	29720	-5.7%	35000	27398	-21.7%	32650	34134	4.5%
GVW	78900	60763	-23.0%	77600	75870	-2.2%	77300	56880	-26.4%	72900	74930	2.8%
	Vehicle 9			**Vehicle 10**			**Vehicle 11**			**Vehicle 12**		
	Static	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**
SA	10450	12387	18.5%	11700	13950	19.2%	10700	9712	-9.2%	10350	7820	-24.4%
GOA	36900	37159	0.7%	30150	32482	7.7%	30400	29104	-4.3%	32200	34220	6.3%
GOA	38600	38920	0.8%	32700	38192	16.8%	34350	36563	6.4%	36500	33664	-7.8%
GVW	85950	88465	2.9%	74550	84624	13.5%	75450	75380	-0.1%	79050	75704	-4.2%
	Vehicle 13			**Vehicle 14**			**Vehicle 15**					
	Static	**SIWIM**	**%**	**Static**	**SIWIM**	**%**	**Static**	**SIWIM**	**%**			
SA	10400	10570	1.6%	11400	9648	-15.4%	9850	8090	-17.9%			
GOA	30800	31596	2.6%	31250	28773	-7.9%	33700	33174	-1.6%			
GOA	33950	36966	8.9%	34100	42860	25.7%	33800	32108	-5.0%			
GVW	75150	79133	5.3%	76750	81281	5.9%	77350	73373	-5.1%			

Note: SA = single axle; GOA = group of axles; GVW = gross vehicle weight.

Based on the data shown in Table 3-14, 12 of the vehicles were deemed acceptable for accuracy assessment for in-service check. Vehicles 1, 5, and 7 were deemed outliers and therefore excluded. The error for the outlier readings is largely due to multiple presence of vehicles on the bridge. The likelihood of multiple presence is substantially increased with four active lanes in the same direction.

3.5.6 Summary of Accuracy Classification Results of the I-459 Bridge Test

During the calibration test, a calibration factor was established for each lane by truck type. An accuracy analysis was conducted on each lane. The accuracy analyses for lanes 2 and 3 are shown in Tables 3-15 and 3-16 respectively, showing GVW accuracy of C(15) for lane 2 and D20+ for lane 3. Lanes 1 and 4 only captured two vehicles and one vehicle respectively, which is not enough to perform an accuracy analysis for these two lanes. Table 3-17 gives the results of the in-service check.

Table 3-15. Accuracy results for the bridge on I-459 (Lane 2)

Criteria	n	Mean (%)	St. dev. (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	$\delta_{criteria}$ (%)	δ_{class}	π (%)	π_c (%)	Accepted Class
Gross weight	27	1.41	4.95	92.1	**C(15)**	14.4	11.4	14.3	15	**92.3**	97.8	**E(35)**
Group of axles	42	2.96	6.38	93.5	**D+(20)**	18.4	15.3	16.1	20	**93.7**	97.7	
Single axles	27	-3.53	12.93	92.1	**E(35)**	33.6	29.6	32.0	35	**92.2**	95.8	

Table 3-16. Accuracy results for the bridge on I-459 (Lane 3)

Criteria	n	Mean (%)	St. dev. (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	$\delta_{criteria}$ (%)	δ_{class}	π (%)	π_c (%)	Accepted Class
Gross weight	15	3.04	4.98	89.1	**D+(20)**	18.4	12.6	15.8	20	**89.3**	98.7	**E(30)**
Group of axles	20	4.73	8.14	90.8	**D(25)**	22.4	20.3	22.4	25	**90.9**	94.3	
Single axles	15	2.23	11.17	89.1	**E(30)**	28.8	25.7	27.1	30	**89.2**	93.4	

Table 3-17. Accuracy results for the bridge on I-459 (in-service check)

Criteria	n	Mean (%)	St. dev. (%)	π_o (%)	Class	δ (%)	δ_{min} (%)	$\delta_{criteria}$ (%)	δ_{class}	π (%)	π_c (%)	Accepted Class
Gross weight	12	0.74	5.90	82.8	**C(15)**	18.0	12.5	12.5	15	**83.1**	96.5	**E(30)**
Group of axles	24	1.08	8.40	88.5	**C(15)**	18.0	17.5	14.5	15	**88.7**	89.9	
Single axles	12	-1.96	15.70	82.8	**E(30)**	36.0	33.2	28.2	30	**83.0**	87.2	

3.6 Proposed B-WIM Calibration and Testing Method

If each instrumented bridge required the COST 323 calibration procedure, installation would be time consuming and costly. Both conditions could deter the wide application of the SiWIM system in Alabama and perhaps elsewhere. However, it is believed that such rigor is not required to establish a workable calibration of the system, provided the bridge selection and traffic are suitable. Based on the accuracy analysis from the bridge on I-459, the following proposed calibration procedure was devised.

3.6.1 Calibration Data Analysis for the Bridge on I-459

Figure 3-31 shows the total runs, captured runs, and effective runs for the four calibration trucks. Figure 3-32 illustrates the accuracy calculations for the four trucks. Figures 3-33 and 3-34 show accuracy calculations for the semi-trailer with full loads only and for the rigid truck with full loads only. Tables 3-18, 3-19, and 3-20 lists the calibration data for the four vehicles together, semi-trailer with full loads, and rigid truck with full loads respectively.

As shown in Figure 3-31, a total of 128 trucks runs crossed the bridge during the initial calibration. However, owing to the presence of multiple trucks on the bridge, observation and communication problems, etc., only 74 runs were recorded by the SiWIM system in the initial calibration. Of these 74, there were 45 runs acceptable for the calibration accuracy assessment. There was substantial scatter in the data. Even the measurement of calibration vehicles varied from run to run, suggesting the presence of multiple vehicles on the bridge was a problem. During calibration, the outliers were removed as were the captured data for the semi-trailer with a half load, which were erratic.

For three cases—day 1, day 2, and days 1 and 2 together—three accuracy assessments were completed. Based on the results summarized in Figures 3-31, 3-32, and 3-33, researchers concluded that two days of data did not show significantly better results than one day alone.

3.6.2 Proposed Procedure for SiWIM Specification for Calibration

The initial calibration and the in-service check were time consuming and labor intensive. The initial calibration required four trucks and two days (two trucks with different loads), and the in-service check required one-and-a-half days. A more streamlined procedure would be required for general use of the SiWIM system. Otherwise, it would be difficult to use this system widely. Ideally a simplified calibration procedure would achieve almost the same accuracy as the rigorous procedure described in previous sections. The test results from the I-459 bridge did provide enough information to recommend a calibration procedure for similar installations in Alabama.

Based on the previous analysis, the researchers recommend the following procedure: For the initial calibration, two fully loaded semi-trailers should be used. Each semi-trailer would make 20 runs across the bridge. With this approach, the minimum confidence level would be 92.5%. The estimated time to complete the calibration should be half a day. For the in-service check, it is recommended that 10 typical trucks be pulled from traffic for static weighing. The in-service check should also take about half a day. The proposed procedure could be verified using FEM modeling and other analytical calculations.

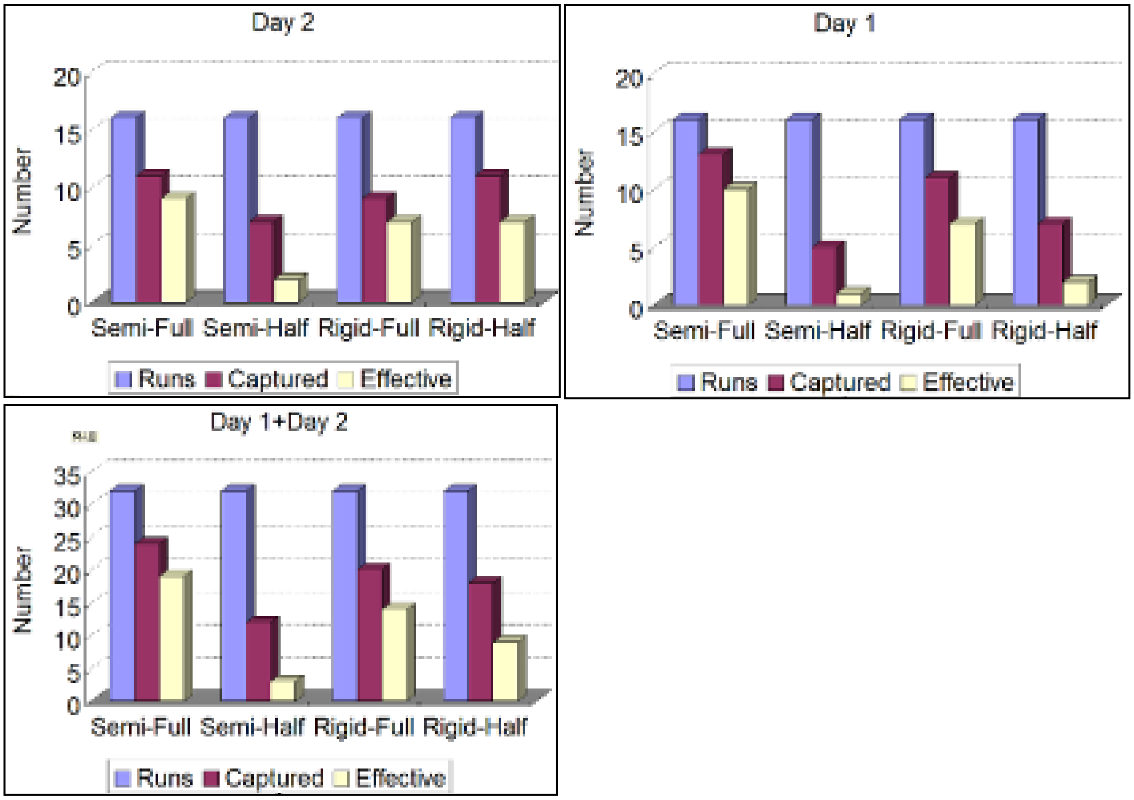

Figure 3-31. Comparison of total runs, captured runs, and effective runs for all four trucks

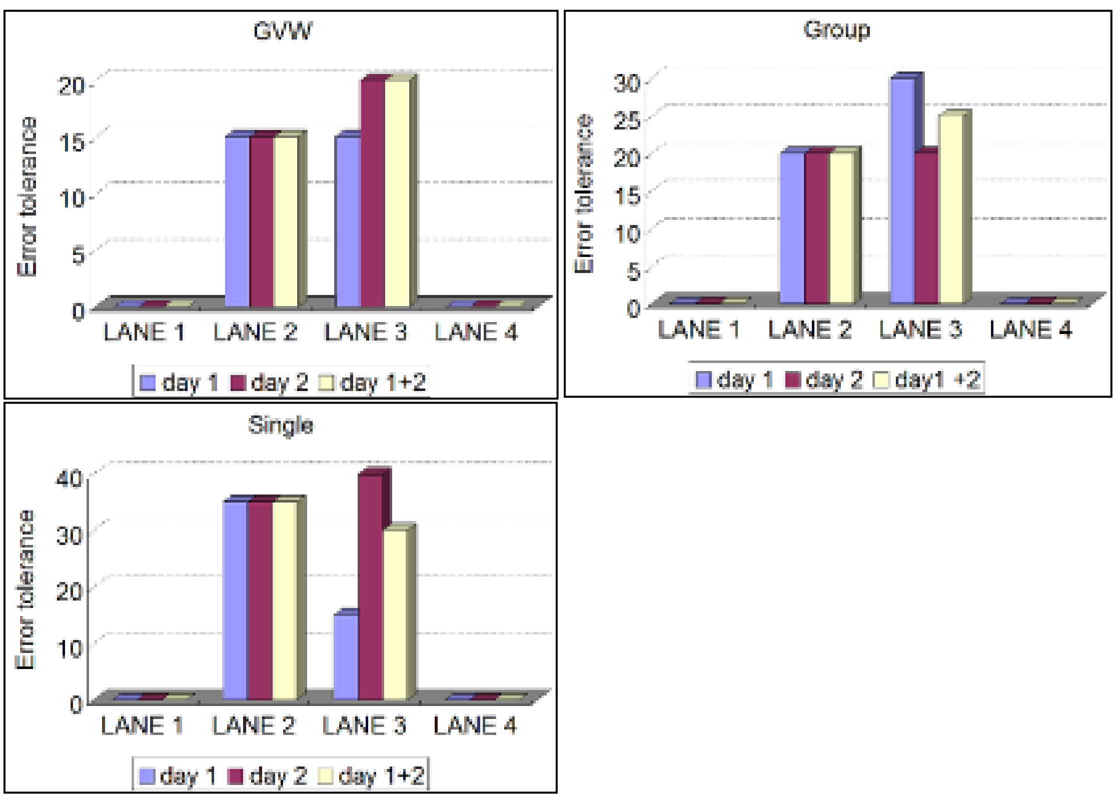

Figure 3-32. Accuracy calculation for all four trucks

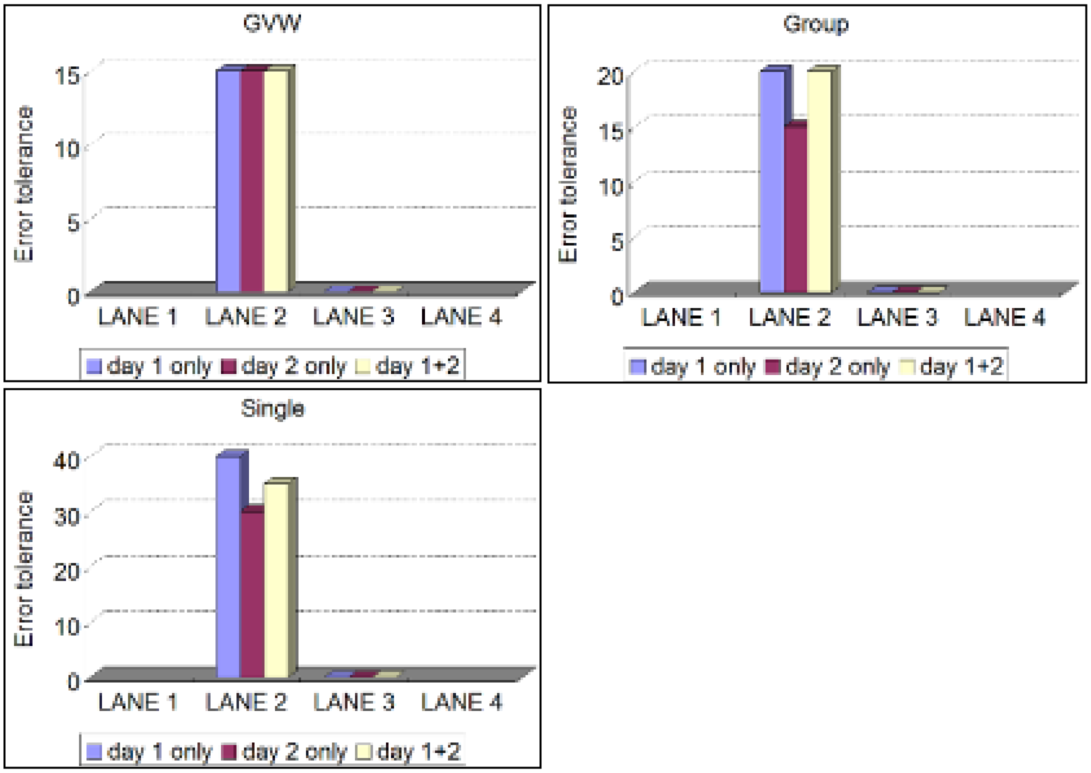

Figure 3-33. Accuracy calculation for semi-trailer with full loads

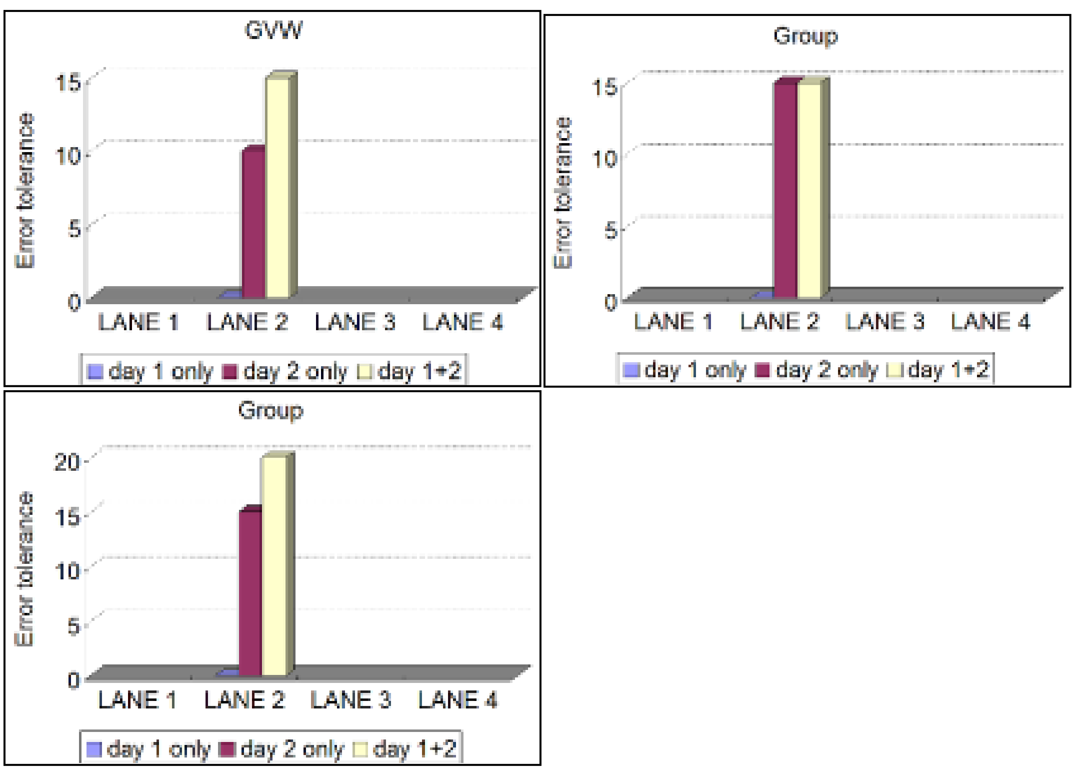

Figure 3-34. Accuracy calculation for rigid truck with full loads

Table 3-18. Calibration data for all four vehicles

	Lane 2				Lane 3				
		number	Mean (%)	Std dev (%)			number	Mean (%)	Std dev (%)
Day1 + Day2	GVW	27	-3.53%	12.93%	Day1 + Day2	GVW	15	2.23%	11.17%
	Group	42	2.96%	6.38%		Group	20	4.73%	8.14%
	Single	27	1.41%	4.95%		Single	15	3.04%	4.98%
Day 1	GVW	10	-2.48%	13.74%	Day 1	GVW	7	-0.37%	5.46%
	Group	17	4.06%	6.34%		Group	9	6.98%	9.95%
	Single	10	3.52%	4.05%		Single	7	4.00%	3.93%
Day 2	GVW	17	-4.15%	12.82%	Day 2	GVW	8	4.51%	14.53%
	Group	25	2.21%	6.42%		Group	11	2.89%	6.20%
	Single	17	0.18%	5.12%		Single	8	2.20%	5.88%

Table 3-19. Calibration data for semi-rigid with full load

	Lane 2				Lane 3				
		number	Mean (%)	Std dev (%)			number	Mean (%)	Std dev (%)
Day1 + Day2	GVW	14	-7.36%	11.40%	Day1 + Day2	GVW	1	/	/
	Group	28	3.02%	6.38%		Group	2	/	/
	Single	14	1.64%	4.01%		Single	1	/	/
Day 1	GVW	7	-7.13%	13.56%	Day 1	GVW	2	/	/
	Group	14	3.61%	6.91%		Group	4	/	/
	Single	7	2.13%	4.11%		Single	2	/	/
Day 2	GVW	7	-7.59%	9.87%	Day 2	GVW	3	11.13%	12.02%
	Group	14	2.44%	6.00%		Group	6	4.73%	11.07%
	Single	7	1.14%	4.17%		Single	3	6.13%	5.69%

Table 3-20. Calibration data for rigid with full load

	Lane 2				Lane 3				
		number	Mean (%)	Std dev (%)			number	Mean (%)	Std dev (%)
Day1 + Day2	GVW	8	9.15%	4.29%	Day1 + Day2	GVW	3	2.60%	5.41%
	Group	8	1.09%	5.95%		Group	3	2.00%	3.73%
	Single	8	3.26%	3.89%		Single	3	2.17%	2.00%
Day 1	GVW	3	8.37%	6.79%	Day 1	GVW	2	/	/
	Group	3	6.17%	1.86%		Group	2	/	/
	Single	3	6.77%	0.84%		Single	2	/	/
Day 2	GVW	5	9.62%	2.91%	Day 2	GVW	5	8.10%	10.26%
	Group	5	-1.96%	5.41%		Group	5	1.58%	3.21%
	Single	5	1.16%	3.37%		Single	5	3.34%	2.16%

3.7 Summary of Issues Impacting SIWIM Use in Alabama from the I-59S and I-459 Bridge Installations

3.7.1 Installation

Based on experience from the bridge on I-59S, researchers found that the flexibility of long bridge spans coupled with an uneven deck surface caused strong bridge dynamics. In many cases the strain readings were masked. In addition, it was determined early in the testing that the system's default strain voltage setting was too low to detect axles. This situation occurred because the strains on the I-59S bridge girders exceeded prior experience on shorter-span bridges in Europe. Another factor that impacted the quality of measurements was the cracking present on the surface of beams in the vicinity of the sensors. As a result, there were sensors that registered excessive strain beyond the limits of the system and thus rendered the data useless. Some of the sensors were relocated to alleviate the problem.

The bridge field test on I-459 demonstrated that if the FAD sensors lay in the negative moment area, it is impossible for the FAD sensors to detect the axles because the default voltage setting is only applicable for positive moment areas. This experience revealed that it is essential that a feasibility analysis using simplified FEM modeling calculations be performed before any field test to avoid the possibility of placing sensors in a negative moment location. In addition, during the calibration on I-459, the six sensors attached to the soffits of the diaphragms proved ineffective.

Other important issues encountered in initial testing are described in the following sections.

3.7.2 Software Issues

The overall results from the installation tests on the two bridges showed that the current version of SiWIM is not fully adaptable to two bridges selected from ALDOT's inventory. The high sensitivity of the signals to the transverse wheel location for these bridges and application of negative strain for FAD detection should be addressed by the software along with the issues created by the presence of multiple vehicles on the bridge. Having said that, it is possible by analyzing adjacent transducer signal amplitudes for one vehicle to estimate its lateral location, but this function is not yet implemented in the SiWIM.

A finite element analysis performed at UAB confirmed that for a typical ALDOT bridge the influence surface has to be taken into account (instead of influence line for slab bridges) so that an influence line can be linked to each transducer. Additional research is needed to address the presence of PMDF, which is prevalent on most of the post-1990 ALDOT bridge slabs. The SiWIM system seemed to be slow to capture data, and it missed vehicles, as evidenced by the amount of truck data missed during calibration.

To insure that the SiWIM system is installed effectively, a feasibility study should be carried out before the installation. It is critical that the location of each transducer is carefully chosen and measured because the sensor locations govern the shape and amplitude of the influence line used in the axle load calculation.

3.7.3 Power Issues

Experience at the I-59S installation: From the experience on bridge I-59S, researchers learned that the initial power configuration (two batteries with two solar panels) could not perform perfectly, leading the SiWIM system to shut down. SiWIM configuration files are easy to corrupt, and when the SiWIM engine could not start due to power failures, not only were data lost; it was also impossible to communicate with the system remotely. During the trouble-shooting process, the hard drive in the operating system was replaced because there was a belief that a hard-drive failure was the problem. That was a lesson learned: a continuous source of power is crucial to system performance!

Experience at the I-459 installation: Initially the power system configuration used on the I-459 bridge consisted of three batteries with three solar panels. Unfortunately, with the system's full power requirements, particularly from the cameras, three batteries were insufficient. On overcast days the batteries would not recharge sufficiently, resulting in rapid power drainage and ultimately system shutdown. If this scenario were repeated a few times, the hard drive could stop working. The system was expanded to a configuration of three solar panels and six 12-volt deep-cycle batteries.

Figure 3-35 illustrates the maximum voltage achieved, the dropped voltage, and the safety margin for combinations of batteries and solar panels. Figure 3-36 shows the types of days on which the power system properly functions. Figure 3-37 depicts the power system's charging current over time.

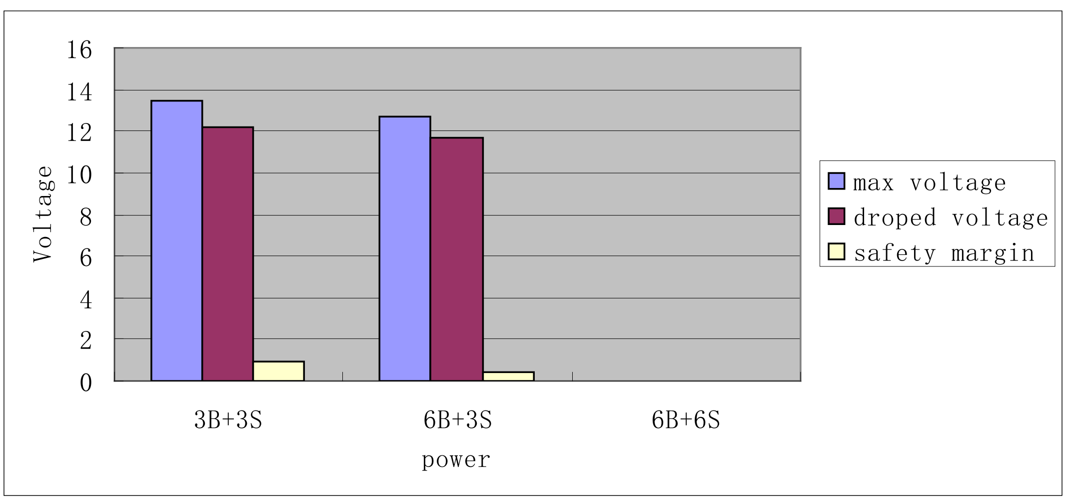

Figure 3-35. Voltage for batteries and solar panels (B=battery, S=solar panel)

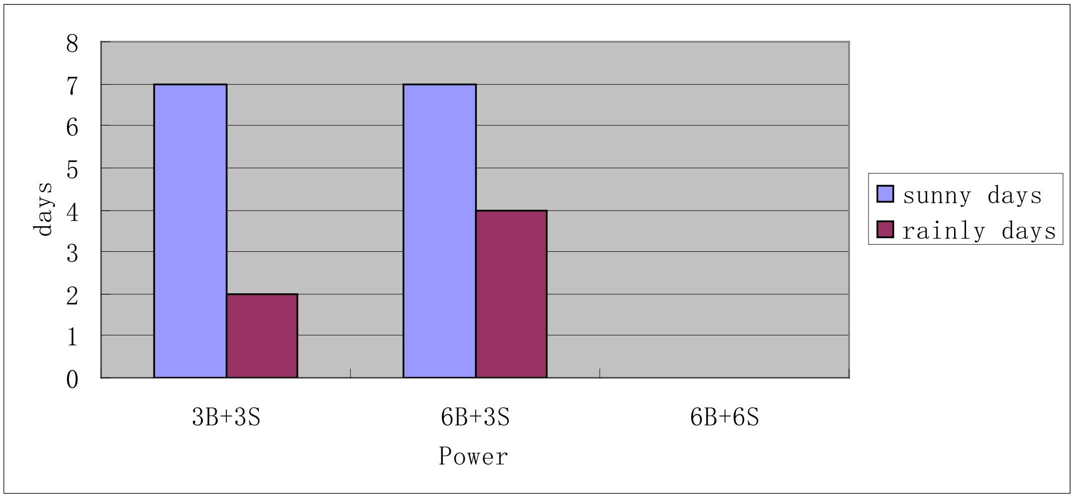

Figure 3-36. Power system charging history

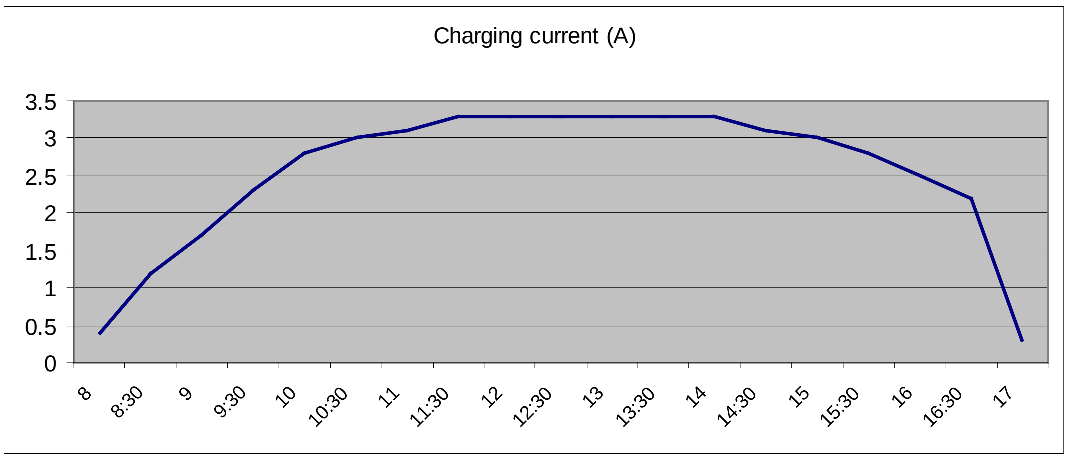

Figure 3-37. Power system's charging current over time

3.7.4 Progress Meeting with ALDOT

After the I-59S and I-459 tests, the research team met with ALDOT to discuss the results and plan the next installation. Based on the discussion between the B-WIM team and ALDOT, the following decisions were made concerning the next comprehensive SiWIM system test:

1. One bridge will be selected for live enforcement. There was general agreement that the next bridge installation would include the following parameters:
    - The roadway will be a maximum of two lanes.
    - A bridge will not be skewed.
    - Calibration and in-service testing will be completed in one day each.
2. A feasibility analysis will be performed on the selected bridge using a UAB-recommended procedure to choose sensor locations.
3. Calibration will use a UAB-recommended procedure that employ fully loaded semitrailers making fewer runs.

4. The pre-selection process, which uses a PDA to identify trucks for weighing, will be used downstream from the bridge for enforcement purposes during in-service testing.
5. A cell-phone amplifier will be used for the VPN connection.
6. Six solar panels, six batteries, and an automatic camera-shutoff switch will be used for the power supply.

3.7.5 Summary

There were issues faced on the I-59S bridge:

- The rigid trucks chosen for the calibration process were not detected by the system.
- The alternative approach to calibration required pulling semi-rigid trucks from the traffic. Only three of the trucks pulled from traffic were successfully captured by the SiWIM system. Three trucks was a small sample to use for calibration.
- Data were collected for two weeks, then problems occurred for several reasons:
    - The power supply was insufficient to meet total demand.
    - The SiWIM system software froze.
    - The cellular-telephone signal to the site was erratic.
    - The system was pulled from the site for investigation and repair.

There were new issues encountered at the I-459 bridge:

- FAD positioning problems revealed the importance of placing sensors where positive moments will occur.
- Half-full vehicles were not useful for calibration and should be avoided in the future.
- Pre-selection trucks were accurately detected on lanes 1 and 2 but not on lane 3.
- Data were collected continuously.

Lessons Learned for Next Installation:

- Excellent experience has been established for concrete girder bridges.
- A bridge with two lanes or fewer will reduce the number of sensors required and limit to some extent the impact of multiple vehicle presence on the bridge.
- Select a bridge with no skew.
- Fewer calibration runs will be adequate, as described in the report's recommendations.
- Use fully loaded test vehicles.
- Conduct in-service checks after the pre-selected vehicles cross the bridge.
- Use a cell phone amplifier for the VPN connection.
- Install an automatic camera "off" switch to preserve power when the camera is not in use.

Section 4.0
B-WIM International Workshop

4.1 Workshop Objectives

As part of the project team's commitment to outreach and advancement of the technical knowledge of B-WIM, the University of Alabama at Birmingham (UAB) hosted an international B-WIM workshop at the UAB campus on August 11 and 12, 2008. The 2008 B-WIM Workshop was co-sponsored by the University Transportation Center for Alabama, the International Society for Weigh-in-Motion (ISWIM), the Alabama Department of Transportation, and the US Department of Transportation. There were three objectives of the workshop:

1. Review the state of practice for WIM technology.
2. Discuss the benefits and challenges related to the implementation of B-WIM systems.
3. Identify future research, collaboration, and deployment opportunities.

The workshop agenda also included the presentation of preliminary findings from this UAB-led project and a field demonstration of the system.

4.2 Workshop Development Approach

Originally, an international symposium was planned for April 2008. However, the project team, in collaboration with ALDOT and FHWA partners, agreed that a less-formal one-day workshop was more appropriate to meet the project's technology-transfer objectives and to give an update on the progress of the implementation. A decision was made to hold the workshop in August 2008.

In a conference call with ALDOT and FHWA representatives, it was agreed that four B-WIM leaders from Europe would be invited to present at the workshop. The four experts invited were Bernard Jacob (France), Eugene O'Brien (Ireland), Ales Znidaric (Slovenia), and Hans van Loo (Netherlands). All four have a proven record of expertise in this area and had interacted with team members and other European B-WIM experts during the 5th International Conference on Weigh-in-Motion, held in Paris in May 2008. All four gentlemen accepted the invitation to join Richard Christenson of the University of Connecticut and B-WIM project team researchers at the workshop.

Invitations were sent to state transportation departments across the country, and preparations commenced for organizing the event and finalizing the agenda, a copy of which is available in Figure 4-1. Randy Woolley of the CalTrans Division of Research and Innovation (and also a 2007 scan tour participant) agreed to present an overview of weigh-in-motion experience in the United States the evening prior to the workshop at the Double Tree Hotel. Randy was joined by

Bernard Jacob from the *Laboratoire Central des Ponts et Chaussées* in Paris. Bernard presented an overview of weigh-in-motion in Europe. The evening meeting was well attended. The workshop started the following morning.

A total of 48 participants attended the workshop, including personnel from ALDOT, the Mississippi Department of Transportation, and FHWA. Professors and students from all three University of Alabama campuses attended (Figure 4-2).

4.3 Summary of Presentations

The agenda for the workshop, including presentation titles, speakers, and speaker affiliations, is shown in Figure 4-1. A brief summary of salient points from the workshop is provided.

- Fred Moses, while at Case Western Reserve in Cleveland, calculated axle and gross vehicle weights by minimizing the error between the theoretical and measured bridge strains in 1979. Weigh-in-motion technology, including B-WIM, was advanced in Europe during the late 1990s as part of two European projects: COST 323, Weigh-in-Motion of Road Vehicles; and WAVE, Weighing of Axles and Vehicles for Europe. The SiWIM system developed from these projects.
- The SiWIM system, purchased by ALDOT and studied in this research project, has many improvements over Fred Moses's original bridge weigh-in-motion system. It offers better installation, calibration, and operation than earlier B-WIM equipment. The SiWIM system can operate unmanned and will notify a downstream DOT weigh crew of a potentially overweight vehicle. The PDA displays a photo of the vehicle as well as the axle and gross vehicle weights.
- The SiWIM system has been used successfully at many bridge sites in Europe. The best axle-weight accuracy has been achieved on short-span concrete slab bridges with integral (monolithic) abutments, which are common in Europe. For shorter-span bridges, not all of the axles are on the span at the same time. For longer spans, axle-weight accuracy will decrease but gross-weight accuracy will be high. One idea for accurately measuring axle weights on long spans is to instrument short-span components, for example stringers or lateral stiffeners.
- The B-WIM instrumentation attaches to the underside of the bridge, giving B-WIM systems several advantages over pavement-based WIM systems:
  - The installation does not disrupt traffic.
  - Truck drivers cannot see the WIM equipment and therefore do not know they are being weighed.
  - The instrumentation is protected from tire impact and weather, improving durability.
- In a B-WIM installation, the bridge is part of the load-measuring instrument. This leads to several disadvantages over pavement-based WIM systems:
  - Each strain sensor is affected by all loads on the bridge. Long spans may be loaded with multiple axles from the same vehicle, and multi-lane bridges may have multiple vehicles on them at the same time ("multiple-presence event").
  - The lateral position of the vehicle within the lane can affect the strain measurement on orthotropic steel deck bridges and for girder bridges.

- Techniques have been proposed to address the disadvantages discussed above. The axle weights of closely spaced axles can be calculated more accurately using a technique called *Tikhonov regularization* (Rowley 2008). Construction of a two-dimensional influence line for a bridge (an influence surface) will help resolve multiple-presence events and improve accuracy for vehicles not centered in the lane. Such an influence surface would need to be calibrated with trucks at different (and known) lateral positions (Quilligan 2002).

4.4 Results and Recommendations

The event was a great success and drew the attention of local media, including Channel 13 NBC News and *The Birmingham News*. Workshop participants found the workshop worthwhile. In a post-workshop survey, respondents overwhelmingly agreed that the workshop was balanced, informative, and valuable. Table 4-1 summarizes the survey responses of workshop attendees, and Table 4-2 provides information on their affiliations. Anecdotal comments provided by the workshop attendees are available in Table 4-3.

Table 4-1. 2008 B-WIM workshop summary evaluation

	Number of Replies	YES	MAYBE	NO
Satisfied with selection of speakers and topics	25	23	2	0
Presentations were informative	25	22	3	0
Had opportunity to interact with experts	25	25	0	0
Workshop improved my knowledge	25	23	2	0
Overall the workshop was valuable	25	24	1	0
Was pleased with facilities and hospitality	25	24	0	0
Increased my knowledge on the issues	25	24	1	0
Workshop was of appropriate length	23	21	Short: 2	

Table 4-2. Professional affiliations for survey respondents

	Number of Replies
State DOT	11
FHWA/DOT/DOE	1
Industry/Vendor	4
Academia	5
Student	2
Other	2
Total	25

2008 B-WIM WORKSHOP AGENDA

August 11, Double Tree Hotel, 808 20th Street South, Birmingham

6:00 p.m. - 6:45 p.m.	Light Dinner and Discussion	University Room
7:00 p.m. – 7:45 p.m.	Overview of WIM in the United States, *Randy Woolley,* CalTrans	Arlington Room
7:45 p.m. – 8:00 p.m.	Break	Arlington Room
8:00 p.m. – 8:45 p.m.	Overview of WIM in Europe, *Bernard Jacob*, Laboratoire Central des Ponts et Chaussées	Arlington Room

August 12, Business and Engineering Complex (BEC), UAB

8:00 a.m. – 12:00 p.m.	Registration	BEC 109
8:30 a.m. – 9:00 a.m.	**Breakfast**	BEC 106
9:00 a.m. – 10:15 a.m.	**Plenary Session I: B-WIM State of the Art**, Moderator*: Virginia Sisiopiku*, UAB	BEC 109
9:00 a.m. – 9:15 a.m.	Welcome and Introduction, *Wilbur Hitchcock*, UAB	
9:15 a.m. – 9:45 a.m.	B-WIM Systems in Europe: Recent Developments, *Bernard Jacob*, Laboratoire Central des Ponts et Chaussées, Paris	
9:45 a.m. – 10:15 a.m.	Bridge Weigh-in-Motion—Latest Developments and Applications Worldwide, *Eugene Obrien*, University College Dublin	
10:15 a.m. – 10:30 a.m.	**Refreshment Break**	BEC 106
10:30 a.m. – 12:00 p.m.	**Plenary Session II: B-WIM State of Practice**, Moderator: *Houssam Toutanji*, UAH	BEC 109
10:30 a.m. – 10:40 a.m.	Si-WIM System and Latest Developments, Robert Brozovič, **CESTEL** d.o.o, **Slovenia**	
10:40 a.m. – 11:05 a.m.	Implementation of B-WIM on Different Types of Bridges, *Aleš Žnidarič*, Slovenian National Building and Civil Engineering Institute	
11:05 a.m. – 11:30 a.m.	Experiences with Bridge Weigh-in-Motion, *Hans Van Loo*, Kalibra Intl., The Netherlands	
11:30 a.m. – 12:00 p.m.	Leveraging Long-Term Bridge Monitoring for Bridge Weight-In Motion, *Richard Christenson*, University of Connecticut	
12:00 p.m. – 1:00 p.m.	**Lunch**	BEC 106
1:00 p.m. – 2:15 p.m.	**Plenary Session III: Alabama B-WIM Project**, Moderator: *Jim Richardson*, UA	BEC 109
1:00 p.m. – 1:30 p.m.	Alabama DOT Weight Enforcement Program, *Randy Braden*, ALDOT	
1:30 p.m. – 2:15 p.m.	Alabama B-WIM Project: Description, Results and Conclusions, *Nasim Uddin and Talat Salama*, UAB	
2:15 p.m. – 2:30 p.m.	**Refreshment Break**	BEC 106
2:30 p.m. – 4:00 p.m.	**Panel Discussion**, Moderators: *Wilbur Hitchcock* and *Dan Turner* (UA) Expert Panel: *George Conner* (ALDOT), *John Nicholas* (FHWA), Bernard *Jacob*, *Eugene Obrien*, *Aleš Žnidarič*, *Hans van Loo*	BEC 109
4:00 p.m.	**Closing Remarks**, *Wilbur Hitchcock*	BEC 109

Organized by the University of Alabama at Birmingham(UAB), the University of Alabama in Huntsville(UAH), and the University of Alabama in Tuscaloosa(UA) in collaboration with the University Transportation Center for Alabama (UTCA) and the Alabama Department of Transportation (ALDOT)

Figure 4-1. Agenda for August 11-12 B-WIM workshop

Figure 4-2. B-WIM workshop participants

Table 4-3. Workshop evaluation survey – anecdotal comments

What were the strengths of this workshop? What did you value the most?

- Knowledgeable experts
- Brought the industry experts together for presentations and interaction
- Getting people from Europe is really outstanding. Having only 40 people is a good idea, instead of 200.
- Alabama's presentation
- Excellent expertise of speakers; strong program, good discussion, nice planning
- Wide variety of experiences presented
- Excellent presentations by the experts in the field
- Practical applications
- International experts
- I was glad to have the opportunity to learn about different types of WIM systems. It was also nice to get perspective from vendors and users of the systems
- The choice of participants
- Small, focused
- Number of experts in this area
- Good variety of presenters. Made for some lively discussions. Very knowledgeable groups of individuals. Enjoyed the availability of healthy food options

***Were there any major weaknesses? Please explain*.**

- Too much mathematical detail
- Too short
- Wish it was longer
- Too much focus on CESTEL system
- Nassim's presentation was too long
- None

How do you plan to use the information that you obtained from the workshop?

- California plans to install a B-WIM as part of a larger WIM testbed site for our first installation
- In classroom to further knowledge of students and ALDOT
- Planning for the future
- Conduct research on B-WIM and potential use for enforcement
- Great research potentials
- Further research
- Working with ALDOT
- I will use the information to better understand the B-WIM system
- Collaborate with others present
- Make further contacts for collaboration or partnership in this area
- In conjunction with our existing WIM program, B-WIM could be an effective additional tool. May consider participation in upcoming pool fund study

Any additional comments or recommendations for the organizing committee?

- Would like to see several follow-on webinars to discuss various topics. Suggestions:

More about bridges/bridge types; accuracy/reliability; data; sensor placement; influence lines (calculation/measurements)

- Need to have some of them at the practitioner/user level rather than academic with calculus!
- Great food!
- Didn't receive updated agenda
- Well done!
- Very good
- Good job Ms. Gilmer and all professors from UAB, UAH, and UA

Section 5.0
Conclusions and Recommendations

5.1 Conclusions

The research project was designed to establish a baseline understanding of the potential for using a commercial B-WIM system to support heavy freight traffic monitoring and enforcement in Alabama. The SiWIM system developed by CESTEL was selected for testing. Over a nine-month period, the system was installed on two interstate-highway bridges. The experience gained and recommendations are summarized below.

5.1.1 Field Testing of the SiWIM System

The conclusions from the first two field installations of the SiWIM system are summarized as follows:

- The installation of the SiWIM system can be accomplished in a day.
- Installation crews should be trained by experienced SiWIM users to understand how to place the sensors and what kinds of problems to look for, such as cracks on the girder surface.
- All sensors must be placed where positive moments will occur in the selected structural members.
- A preliminary finite element analysis of the bridge will help planners understand where to place the sensors.
- Calibration can be accomplished in one day using 10 good runs per lane. It is best to use fully loaded semi-rigid trucks for the initial calibration.
- For the in-service check, the most efficient way to pull trucks from the traffic is to capture them first with SiWIM as they cross the bridge then pull them from the traffic.
- The complexity of the traffic directly affects the ability of the SiWIM system to 1) capture vehicles at all and 2) accurately determine axle weight and total weight.
- A maximum of two traffic lanes on a bridge, coupled with a steady traffic velocity, significantly improves the chances for successful vehicle capture and the collection of meaningful data.
- Multiple-span bridges and lengthy spans result is a substantial increase in dynamic interaction of multiple vehicles on the bridge.
- The condition of the bridge-deck surface and the smoothness of the ramp onto the bridge significantly impact the dynamic behavior of the vehicles on the bridge and consequently the quality of the SiWIM weight estimates.
- The cellular signal strength can vary during the day at a remote locations. The use of a signal amplifier should be considered if there is a concern.

- A continuously running camera requires a lot of energy. This can be a problem if a solar cell and battery pack are used.
- The power-supply components and processor should be securely locked in cabinets to discourage theft and vandalism.

5.1.2 International B-WIM Workshop

The one-day workshop was a success and demonstrated the level of interest in WIM and B-WIM. Conclusions from the workshop include the following:

- A workshop of this nature should last at least two days.
- Attendees to a conference of this nature will have a wide range of interests, from practical field application to advanced technology research.
- On-site equipment demonstrations add to understanding and increase the value of the conference experience.

5.2 Recommendations

5.2.1 Field installation of the SiWIM system

- Excellent experience has been established for concrete girder bridges. Therefore, select this type of bridge when it makes sense.
- Using a bridge with two lanes or fewer will reduce the number of sensors required and limit to some extent the impact of multiple vehicles being on the bridge at the same time.
- Select a bridge with no skew.
- Single spans with fixed supports will likely provide more consistent results.
- The smoothness of the bridge deck and the entrance ramp must be observed prior to installation.
- Be sure to determine the round-trip distance for calibration trucks prior to bridge selection. The time it takes for the trucks to make a round trip directly impacts the time and expense of calibration.
- Fewer calibration runs will be adequate for calibration, as described in the report's recommendations.
- Use fully loaded test vehicles.
- Try to capture ten quality data runs per truck per lane.
- Consider the pre-selection of vehicles after crossing the bridge for in-service checks.
- Use a cell-phone amplifier for the VPN connection.
- Install an automatic camera power-off switch to preserve power when the camera is not in use.
- Be sure to secure the power supply and processor in locked weather-tight boxes.

5.2.2 Future Workshops

- Future workshops would be particularly beneficial if other states are considering the purchase and installation of SiWIM equipment.

- Participants in the one-day workshop associated with this research should maintain communications and hopefully participate in international WIM conferences.

Section 6.0
Acknowledgements

This project presented many challenges because of the many participants required to accomplish all the tasks and also because the technical-support experts were in Europe most of the time. The success of the one-day workshop demonstrated the great interest in the topic and the value of sharing experiences and observations.

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Section 7.0
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