Expanding Portable B-WIM Technology

By

Dr. Wilbur A. Hitchcock, Dr. Talat Salama, Mr. Hua Zhao
Department of Civil, Construction, and Environmental Engineering
The University of Alabama at Birmingham
Birmingham, Alabama

Dr. Dale Callahan
Department of Electrical Engineering
The University of Alabama at Birmingham

Dr. Houssam Toutanji
Department of Civil Engineering
The University of Alabama at Huntsville

Dr. Jim Richardson
Department of Civil Engineering
The University of Alabama

And

Dr. Joshua Jackson
Jackson Consulting LLC

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16. Abstract

Advances in weigh-in-motion technology over the past 15 years have led to successful field application of a commercial grade portable Bridge WIM system (B-WIM) in Europe. Under a previous UTCA Research Project No. 07212, UTCA tested the state-of-the art commercially available B-WIM technology on two interstate highway bridges. The equipment tested was developed by CESTEL, a Slovenian technology company, and is commercially referred to as the SiWIM system. Some technical difficulties occurred during the Project 07212 field tests; however, the SiWIM system was successfully installed, calibrated, and placed into a data gathering mode at both sites. The objective of the research described in this report was to develop a practical recommendation for installation of SiWIM technology at potentially multiple locations in the State of Alabama for the primary purpose of traffic enforcement. The researchers worked with the Alabama DOT to select a bridge for instrumentation that has the potential for an excellent accuracy classification rating. The bridge selected is located on US Highway 78 East in Graysville, Alabama. The bridge structure consists of three forty-two foot simply supported reinforced concrete T-beam spans with two traffic lanes in one direction. In addition, an ALDOT-operated Bending Plate Weigh-In-Motion System (BP-WIM) is located approximately four miles to the west also on US Highway 78. After installing the SiWiM system on the bridge, calibration and three in-service simulated enforcement test exercises were conducted. Over one hundred trucks were weighed by the SiWIM system and compared to their static weights. Many of the trucks were also weighed by the BP-WIM system. The accuracy classification established for the SiWIM system during the calibration and subsequent in-service tests varied between ±20% and ±44% of the static weight with a confidence level of 85%. This level of accuracy is not precise enough to be used with confidence to screen trucks for weight enforcement. The additional BP-WIM data collected during this program indicated that the SiWIM system may be as accurate as the nearby BP-WIM system tested. Lessons learned from the work reported here have been of benefit. In March, 2011, ALDOT personnel installed, calibrated, and operated a newer model of the SiWIM system on a shorter span bridge, achieving B(10), C(15), AND B(10) accuracy classification in random truck weighing for gross vehicle weight, group axles, and single axles, respectively.

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Executive Summary

Advances in weigh-in-motion (WIM) technology over the past 15 years have led to successful field application of a commercial grade portable Bridge WIM system (B-WIM) in Europe. One such system was developed by CESTEL, a Slovenian technology company, and is commercially referred to as the SiWIM system. Under UTCA Research Project No. 07212, a UTCA research team tested this state-of-the art commercially available B-WIM technology on two interstate highway bridges. Project No. 07212 established a baseline understanding of the commercial SiWIM system, but many questions remained as to the suitability of the SiWIM system for use on highway bridges in ALDOT's inventory to help enforce weight limits on heavy freight trucks. The objective of this research was to develop a practical recommendation for installation of SiWIM technology at multiple locations in the State of Alabama for the primary purpose of traffic enforcement and to demonstrate the ability to install the SiWIM system and achieve an acceptable accuracy classification for screening heavy freight for static weighing. The researchers worked closely with ALDOT to determine the most ideal bridges for a quasi-permanent installation in order to select a bridge for instrumentation. The bridge selected for the SiWIM installation is located on US Highway 78 East in Graysville, Alabama three miles west of I-22. The bridge structure consists of three forty-two foot simply supported reinforced concrete T-beams spans with two lanes in the east-bound direction. In addition, an ALDOT operated Bending Plate Weigh-In-Motion System (BP-WIM) is located approximately four miles to the west on US Highway 78. Live measurement exercises of trucks crossing the bridge were conducted on four different days. More than one hundred trucks of known static weight crossed the bridge and the SiWIM system successfully measured a weight estimate for most of them. Of those trucks, over sixty trucks were weighed by both the SiWIM and BP-WIM systems, and the accuracy of the two methodologies were compared.

After discussion with ALDOT officials, researchers determined that this research effort should focus on a bridge type and traffic flow configuration which would be as near optimal conditions for the SiWIM system on a bridge in the ALDOT inventory. The hope was to demonstrate that the SiWIM system could be installed and provide impressive accuracy in weighing heavily loaded trucks moving across the bridge based on the European Specification for WIM systems. Ideally the system would perform with suitable accuracy for prescreening trucks in traffic for static weighing.

After installing the SiWIM system in one day, a one-day calibration exercise was conducted where two 5-axle trucks of known weight were weighed as they crossed the bridge with at least 10 runs per traffic lane. Following calibration, three live in-service enforcement exercises were conducted. As mentioned in the previous paragraph, the location of the bridge selected for this research was within 4 miles of an existing Bending Plate Way-In-Motion (BP-WIM) installation operated by ALDOT. During two of the in-service exercises, some of the trucks weighed by the SiWIM system were also

weighed by the BP-WIM system, and the weights measured from both of these systems were compared to the static weights of the trucks. The static weights were obtained by pulling candidate trucks from the traffic flow, and an ALDOT portable weighing team measured the trucks' axle weights and dimensions. This allowed the researchers to demonstrate the relative accuracy of the two WIM systems under the same weather and traffic test conditions, and researchers found the two WIM systems to be similar in accuracy for the test conditions.

This project was successful in expanding the understanding of the practical issues associated with installing SiWIM in multiple quasi-permanent installations around the State of Alabama. The accuracy classification established for the SiWIM system during the calibration and subsequent in-service tests did not meet the targets in that the level of accuracy varied between ±20% and ±44% of the static weight with a confidence level of 85%. While this level of accuracy falls within the experienced categories of the European WIM Specifications (COST 323), it is not precise enough to be used with confidence as a screening tool for preselecting vehicles for weighing. The results from the calibration and the in-service testing are summarized in Table i. In that table, the value in parenthesis in the "Accuracy Class" column represents the confidence interval (expressed in error %) for the confidence level.

Table i. Summary of SiWIM performance results using European WIM Specification Terminology

Testing Condition	Confidence Level (π)	Confidence interval δ	Accuracy Class
Calibration			
Lane 1	85%	22.4%	D(25)
Lane 2	85%	18.4%	D+(20)
In-Service 1	87.1%	33%	E(30)
In-Service 2	89.8%	39%	E(35)
In-Service 3	89.5%	44%	E(40)
Combined In-Service	88.9%	33%	E(30)

The comparison of the measurement results of the SiWIM system and the BP-WIM installation for the trucks captured by both systems revealed that substantial ranges in measured accuracy as compared to the static weights is a characteristic of both systems. Summarized in Table ii below are the means of the differentials between the measured results and the known static weights and the standard deviations for the three test days when both the SiWIM and BP-WIM systems were used to measure truck weights of 3-axle and 5-axle trucks. The best results were for the 5-axle trucks because the system was calibrated using 5-axle trucks. Only the results for the 5-axle trucks are shown in Table ii.

Table ii. Test Comparisons SiWIM vs BP-WIM

Test Condition	SiWIM Mean Differential	SiWIM Standard Deviation	BP-WIM Mean Differential	BP-WIM Standard Deviation
Calibration				
Lane 1	-1.23%	7.39%	-.95%	6.43%
Lane 2	2.18%	6.76%	-.65%	10.2%
In-Service 2 5 axle trucks	.1%	7.87%	-.98%	7.02%
In-Service 3 5 axle trucks	4.5%	12.8%	-2.8%	9.3%

There are a number of considerations for improving performance. The most striking should be to insure road surfaces are smooth leading up to the bridge and on the bridge itself, and the traffic flow pattern should generally be such that the vehicles crossing the bridge do not change lanes on the bridge and ride in the middle of the lane. In addition, the length of the bridge span is also very important; fewer axles are on the instrumented span at any one time for shorter spans.

Conclusions

This research project was challenging in that an important element of the work was to establish a straightforward approach to installation, calibration and in-service use of a SiWIM system for heavy truck freight screening for bridges in the ALDOT inventory and at the same time demonstrate an installed SiWIM system with an excellent accuracy classification. While the methodology of installation and use of the equipment has been successfully accomplished, the accuracy classification of the system based on the variance of the system measurements as compared to the actually static measurements was very disappointing. Clearly the site conditions for a SiWIM installation must be "excellent" as defined by the European Specification for WIM (COST 323) if the SiWIM equipment is to operate with measurements within a confidence interval necessary for an accuracy classification suitable for screening trucks for weight enforcement. Three bridge candidates from the ALDOT inventory were carefully selected for testing, and the SiWIM results were disappointing on all three bridges. The pavement condition and flexibility of the bridges was a factor in all cases.

Specific conclusions reached by the investigators in this project are summarized as follows:

- A two-lane bridge with two-way traffic would be preferable to a two-lane bridge with one-way traffic (the configuration of the bridge instrumented for this project). The bridge selected for this project had essentially no shoulders (the curbs were less than a foot from the edge of each lane). It was anticipated that the narrow bridge would force trucks to stay in the lane and hence reduce errors due to variations in the transverse position of trucks crossing the instrumented span. However, many trucks were observed to cross partially into the other lane while approaching the bridge, apparently to avoid the nearby curb. Crossing into the other lane would be much less likely on a two-lane bridge with moderate to heavy two-way traffic.
- The Researchers calibrated the SiWIM system with two fully loaded 5-axle trucks with nearly the same gross weight and axle configuration. Based on the recommendations of the prior research, each truck would pass ten times over both test lanes of the bridge. This approach provides a confidence level of approximately 85% in the accuracy classification calculated for the system, and can be done in a fraction of the time and expense required to establish a 95% confidence level.

- The scatter in the accuracy of the results from the in-service tests revealed that a calibration plan using a combination of trucks that are representative of the actual traffic could provide better results than using only one axle configuration for calibration. However, as noted in UTCA Project 07212,the cost of calibration in terms of equipment, manpower, and time substantially increases when more complex calibration schemes are employed. Nevertheless, future calibration should strongly consider 5-axle and 3-axle trucks if experience suggests that 3-axle trucks represent a significance portion of the heavy freight weight violators. Calibration can still be accomplished in one day, but the number of truck runs and static weighing events will double. If 3-axle trucks are not a concern (usually the problem is axle weight, not total weight), then 3-axle trucks can be eliminated from the calibration, though the SiWIM weight measurements of 3-axle trucks during actual testing will not be as good as the weight measurements of the types of trucks used for calibration.
- In the SiWIM system, the axle weights of vehicles crossing the bridge are calculated based on the least square method to minimize the difference between the measured bridge response (the total strains of all the girders) and the predicted strain based on calibrated influence lines. It is difficult to separate the bridge response for each vehicle if multi-vehicles are on the bridge at the same time. In addition, the detection of the passing vehicles is based on the detecting sensors (FAD sensors) mounted under the bridge slab These sensors provide data to calculate the vehicle axle configuration and speed. In order to correctly identify the vehicle, the signal of these sensors must be strong enough to be detected. If the traffic flow is complex, meaning that here are more than two heavy vehicles on the bridge at the same time, the bridge deflections due to the combined load results in trivial FAD sensors readings. The readings are below the threshold to be detected owing to the transversal effects of the other heavy vehicles. Consequently, the complexity of the traffic flow directly affects the ability of the SiWIM system to 1) capture vehicles at all, and 2) accurately determine axle weights and total weight. Therefore, based on the present algorithm of the system, it is better to use this system in two lane or one lane bridges with short spans to avoid multiple presences of heavy vehicles.
- The one camera and eight sensor setup configuration is ideal for two lane bridges similar to the one selected for this research work.   The single camera reduces power demands on the power supply, and the eight sensor configuration permits rapid system analysis and reporting to users of the equipment. The camera is a crucial part of the process allowing the SiWIM system to provide enforcement officers pictures of a suspected overweight vehicle in sufficient time to identify the vehicle as it passes by so that it can be pulled over for further inspection.
- The versatility of the SiWIM system compared to the BP-WIM system could prove beneficial to ALDOT by saving time and money if the accuracy can be improved. The system would also improve the safety afforded to installation crew by getting them off the road during installation. The portability of the system is a huge benefit in that the system can be disassembled and relocated in two days under ideal

working conditions. This would be useful in the event that a site were to become ineffective due to drivers avoiding the route in which it is located.

- The SiWIM system demonstrated a wide swing in accuracy when the entire population of trucks that crossed the bridge was considered. This experience was also reported in UTCA Project Number 07212 for the two bridges tested in that project. Such performance is not surprising in the sense that similar performance has been experienced by practitioners in Europe for some bridge installations as discussed during the B-WIM symposium in Birmingham in August of 2008. (UTCA Project Number 07212). The quality of the results depends on the excellence of the site conditions and the bridge configuration. This fact must be recognized by prospective users of the equipment so that expectations are not out of balance with the reality of the system capabilities and the site conditions of selected bridges. During the discussions at the August 2008 symposium, Enforcement officials understand the limitation and may adjust the SiWIM estimated weight they will react with (for example 10% overweight as measured by SiWIM).
- According to CESTEL, the SiWIM system has been demonstrated to provide very consistent and accurate results in several bridges in Slovenia and Europe (FHWA 2007). However, in this research the accuracy classification of the SiWIM system ranged between D(20) and E(35). It is important to note in the context of this research that the bridges referenced by CESTEL are short span rigid bridges (bridges with spans less than 10 meters), and in many cases one lane in each direction.
- The accuracy classification performance of the SiWIM system on the three bridges tested for UTCA Projects 07212 and 08204 may be attributed to a combination of the bridge configuration, the traffic flow, road surface condition, and bridge span flexibility. The researchers cannot confidently predict comparable performance of a SiWIM system installed on more complex bridge structures than the ones tested in UTCA Projects 07212 and 08204 such as continuous span steel girders or bridges with steel form plates under the decks.
- The temperature also appeared to be a factor in the accuracy. Further study is needed with a wider range of temperatures to determine the extent temperature influences results. If temperature is a significant factor, the system may require supplementary calibration if the equipment is to be utilized at a temperature significantly different from the temperature at calibration.
- The power supply system developed during this research project should adequately address the power continuity problems incurred in prior research so long as the same configuration of cameras and processor usage is maintained. In addition, the cabinet design and suggested locking system should provide vastly improved security from vandals and weather.
- Lessons learned from the work reported here have been of benefit. In March, 2011, ALDOT personnel installed, calibrated, and operated an updated model of the SiWIM system on a shorter span bridge (30-foot simply supported) with two lanes and two-way traffic, achieving B(10), C(15), AND B(10) accuracy classification in random truck weighing for gross vehicle weight, group axles, and single axles, respectively.

Recommendations

While the accuracy classification performance of the SiWIM system in this project did not meet the targets, useful field experience was gained. The importance of the pavement condition of the ramp, the smoothness of the joint between the ramp and the bridge deck, and smoothness of the bridge deck itself and the flexibility of the bridge spans cannot be overemphasized when utilizing a SiWIM system. Excellent conditions for all three considerations are necessary for a high accuracy classification, such as B+(7) or B(10).

The recommendations of the researchers based on the field research in this project supplement and reinforce the observations gained during UTCA Project 07212 and are summarized as follows:

- When utilizing the SiWIM system, the system measurement operators and the law enforcement agency involved must have a clear understanding of the range of accuracy of results received from a SiWIM system so that expectations do not exceed the capabilities of the equipment. The range of truck measurements used for the calibration is a good indicator of what to expect.
- Bridges with two lanes or less are recommended for SiWIM applications because they will reduce the number of sensors required and limit to some extent the impact of multiple vehicle presence on the bridge.
- Selection of bridges with no skew will simplify the installation plan.
- Single spans with fixed supports, and spans of 10 meters or less will likely provide more consistent results.
- The smoothness of the bridge deck and the entrance ramp must be observed and evaluated prior to installation. Rough entrance ramps and roadway surface clearly add to the dynamic 3-dimensional movement of the trucks on the bridge, and this impacts the sensor signal substantially.
- The round trip distance for calibration trucks should be carefully checked prior to bridge selection. Round trip time of the trucks directly impacts the time and expense of calibration.
- Based on UTCA Project #07212 experience, half-load vehicles are difficult to identify and the accuracy of measurements is not helpful in calibration. The reason is that if the bridge is sufficiently rigid, the signal response caused by these vehicles is not the same scale as the fully loaded vehicles, and the effects of other “noise” in the data is more pronounced. As the calibrated influence line for the SiWIM system is based on the measured bridge response of the vehicles used for calibration, including readings from half-loaded vehicles will adversely impact the calibration. It is strongly recommend to use fully loaded vehicles during calibration tests, and only expect accurate future measurements to occur when similar vehicle weights and configurations cross the bridge.
- The system should be calibrated using the number of axles of the types of trucks expected to be the greatest over weight offenders. If it turns out that there is a mix

of 5-axle and 3-axle trucks, then use both axle configurations during calibration. If the concern is 5 and 6-axle trucks and not 3-axle trucks, then use 5 and 6-axle trucks for calibration.

- At least 10 quality data runs per truck per lane is sufficient for calibration with an 85% confidence level in the system accuracy class.
- Vehicles should be selected for static weighing after crossing the bridge for calibration runs. When this approach is taken, only those trucks successfully captured by the SiWIM system will be stopped and weighed.
- The installation of an automatic Camera on/off switch will preserve power and lengthen the time span the system will gather data.
- The power supply configuration developed during this research should be evaluated before every installation to insure it is adequate for the expected type of service requirements.
- CESTEL service personal should be either present or available for consultation for the first ALDOT installation and any future installations on bridge configurations which are substantially different from those instrumented before. Communications by Skype at the site is possible and recommended.
- Sufficient PDAs should be procured by ALDOT to insure measurement operators, enforcement personnel, and static weigh teams can communicate truck identification and weight information effectively during enforcement activities.
- A communications protocol should be worked out between the SiWIM operators, static weigh teams, and enforcement personnel. In order to be effective, the involved parties must be familiar with the SiWIM system configuration, the information transmitted by the system, and the interpretation of the information transmitted. As a minimum, there should be present two SiWIM system operators to monitor the readings and assist Department of Public Safety (DPS) officers in selecting trucks to be pulled from traffic for static weighing. The DPS vehicles and static weighing team will be downstream of the bridge traffic flow sufficiently spaced so that trucks can be identified and pulled from the traffic flow.
- Before the next field installation, a tabletop exercise involving all of the groups expected to participate in the field should be conducted to familiarize/refresh individuals about the sequence of events that will take place.

Section 1.0 Introduction

1.1 Project Overview

Advances in weigh-in-motion (WIM) technology and field testing over the past 15 years in Europe have led to successful field application of a commercial grade portable Bridge WIM system (B-WIM). The European initiatives in WIM research and implementation are well documented as a result of two massive research efforts, the COST 323 (COST 323) and WAVE (Jacob 1999) Projects. In the summer of 2006 an FHWA/AASHTO scan tour team visited Europe to investigate commercial motor vehicle size and weight enforcement initiatives. The team reported that a commercial B-WIM system developed by a Slovenian company, CESTEL, showed excellent promise for commercial motor vehicle weight enforcement in the United States (FHWA 2007). The system is marketed under the trademark name “SiWIM”. As a direct result of the scan tour team experience and observations with respect to the SiWIM system a UTCA research team tested a SiWIM system on two interstate highway bridges in Alabama (UTCA 2008).

This project is an extension of work initiated in 2007 under UTCA Project No. 07212 “Bridge Weigh-in-Motion (B-WIM) System Testing and Evaluation” which established a baseline understanding of the commercial SiWIM system. The approach to statistical analysis and accuracy classification for the calibration and in-service tests was based on the guidelines and methodologies provided in the European WIM Specification (COST 323). Under UTCA Project No. 07212, two different bridges were instrumented with the SiWIM system. Rigorous calibration testing programs were run on both bridges. As is often the case with field testing of equipment in a new environment, numerous technical and power supply problems were encountered and addressed during the first two bridge tests.

In this project, one additional bridge was instrumented, calibrated, and live in-service enforcement exercises using the measurements of the SiWIM system were conducted. The European WIM Specification test recommendation procedures and evaluation methodology were again applied. This project was successful in expanding the understanding of the practical issues associated with installing SiWIM in multiple quasi-permanent installations around the State of Alabama and useful experience in using a SiWIM system for live traffic enforcement was achieved. However, the accuracy classification of the SiWIM system was disappointing, as detailed in Sections 6.0 and 7.0 of this report.

The project involved a multi-disciplinary collaborative team from three different campuses working on technology development with international applications. The research team worked closely with ALDOT throughout, and support was provided by some of the members of the 2006 Scan Tour Team.

1.2 Task Descriptions

The initial project plan contained 5 distinct tasks designed to be completed in 12 months. After some delays in scheduling the system installation and then the enforcement exercise, the project required 18 months to complete.

Task 1: This task was dedicated to a face-to-face meeting between the project research team, key ALDOT personnel and representatives from the Alabama Department of Public Safety (DPS). The meeting took place in Montgomery, Alabama in July 2008. The agenda included a summary of the field testing results from the first two bridge installations followed by a discussion about the best approach to deal with the described tasks in the proposal. Of particular importance would be the collaborative effort to select the best bridge candidate for the next SiWIM system installation and the expectations of the enforcement test exercise. Tentative schedules would be established along with communications procedures and protocols. This Task was the responsibility of Dr. Wilbur Hitchcock.

Task 2: An important technical issue that must be resolved for the expanded field testing of the SiWIM system and ultimately the application at quasi-permanent sites is the power supply options. Multiple possibilities exist to provide power for the SiWIM installation. However, the right configuration depends on the expected need for continuous use of the system, how often the cameras will be employed (a big power consumer), space considerations, and equipment protection issues. To determine the solutions, the research team would work with ALDOT traffic enforcement to determine the system operating standards that would be acceptable to ALDOT. The alternatives for power supplies would then be coordinated with ALDOT to find an alternative which is similar to the solar panel technology installations employed by ALDOT. This task was headed by Dr. Dale Callahan with assistance from Dr. Joshua Jackson.

Task 3: This task consisted of field experiments on one bridge specifically selected for an enforcement exercise. In addition, the data collected from the B-WIM enforcement exercise would be compared to similar test results obtained using permanent weigh-in-motion (WIM) sites. The bridge was selected in collaboration with ALDOT engineers and traffic management experts. Field bridge experimental tests require substantial resources and therefore, careful coordination between ALDOT and the research team was required well in advance of the installation and calibration period. Dr. Jim Richardson and Dr. Talat Salama jointly shared responsibility for this task. Dr. Salama was responsible for managing graduate students, developing work plans, preparation of the equipment for installation, and materials acquisitions. Dr. Richardson was responsible for coordinating the installation plan, calibration plan, and enforcement test with ALDOT and collaborating with Dr. Salama in completing the report results for this portion of the task. Dr. Toutanji was responsible for the coordinating the efforts to compare the measurement effectiveness of the SiWIM system with a similarly situated in-pavement WIM site. He was also responsible for acquiring prior enforcement data from DPS (in full cooperation with Randy Braden at ALDOT), developing a methodology for comparing historical experience at WIM sites with the experience at the SiWIM site(s), and preparation of the quarterly and final report content for this part of the task.

Task 4: This task was the compilation of the final detailed report. The project work tasks above were documented by the responsible investigator(s) in collaboration with ALDOT stakeholders and expert consultants. This documentation formed the core elements of the final report.

Task 5: This task is a closeout technology exchange workshop. Now that the field testing has been completed, the SiWIM system will be turned over to ALDOT for service use. The experience of installation, calibration and ongoing system monitoring gained by the research team will be passed on to ALDOT personnel.

Section 2.0 SiWIM Testing Research

The expansion in freight shipments on the nation's highways has led to a substantial decrease in the structural health of bridges. Of particular concern is the increase in the weight, number, and size of heavy commercial vehicles. Because of the limited resources available to agencies, an effective program of highway maintenance and safety could benefit substantially from an affordable traffic sampling and maintenance 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 very attractive. The objective of this research was to validate the effectiveness of the use of a commercially available Bridge Weigh-In-Motion (B-WIM) system to measure accurately the weight of trucks as they pass over instrumented bridges. UTCA Project 08204 continued the testing of a commercially available B-WIM system after completing the system familiarization study under UTCA Project 07212, "Bridge Weigh-In-Motion (B-WIM) System Testing and Technology". A full description of the SiWIM system provided by CESTEL, a Slovenian company, is available in the UTCA Project 07212 report and will not be repeated in this report.

In summary, the main advantages of a portable B-WIM system are:

- Can be employed to monitor truck weight and size without interfering with traffic flow.
- Portable installations are not visible to truck traffic as it crosses the instrumented bridge.
- Can be installed without damaging the pavement or interfering with the traffic.
- Can be moved from one location to another without influencing accuracy of the results.
- Can be further enhanced by adding video technology to the basic sensor system in order to provide visual data to the user.

While still based on an evolving technology, B-WIM-based vehicle size and weight enforcement programs could realize additional benefits, including:

- Effective and efficient delivery of performance monitoring and vehicle size/weight enforcement services;
- Enhanced commercial motor vehicle productivity (i.e., supply chain velocity) by reducing the total number of vehicles required to stop for enforcement purposes;
- Reduced emissions through the reduction of unnecessary deceleration, idling, and acceleration of compliant vehicles;

- Enhanced commercial and general motor vehicle safety levels by limiting the operation of non-permitted, non-compliant (i.e., overweight or oversized) vehicles; and
- Enhanced data quantity and quality to support pavement design, bridge/structural design, transportation planning, and traffic safety.

UTCA Project Number 07212 was limited to confirm performance capabilities of the SiWIM system and to determine potential applications of the system. This research project expands on that body of knowledge gained from the initial testing coupled with the guidance for performance testing and accuracy classification provided by the European WIM Specification (COST 323). The hope was to be able to successfully install the SiWIM system in one day, then calibrate the system using enough vehicle runs to reach at least an 85% confidence level in the accuracy classification, and finally to reach system accuracy suitable for screening trucks for enforcement weighing.

Section 3.0 Bridge Selection

This research relied heavily on prior research work completed in Europe over the last 15 years and particularly the European WIM Specification (COST 323) and conversations with the European experts who have developed the technology and standards. As part of the previous UTCA Project Number 07212, two members of the research team visited the 5th International Conference on Weigh in Motion (ICWIM) in Paris on May 19 through May 22, 2008. Additional dialogue with European experts took place at the UAB International B-WIM workshop held in August 2008 in Birmingham, Alabama. Appendix I of the European WIM Specification provides a detailed explanation of suggested standards for testing and classifications for WIM system performance, and it is referenced in multiple places throughout this report.

The value of a BWIM system to a user depends not only on the accuracy of readings obtained for a given bridge configuration and environment, but also on the intended use of the measurement results. The accuracy of the equipment is defined in a statistical way based on calibration testing and in-service testing. The European WIM Specification (COST 323) explains system accuracy in this way,

> *The accuracy of a WIM system in its conditions of use, i.e., under moving traffic tyre loads, may only be defined in a statistical way (B. Jacob, 1997), by a confidence interval of the relative error of a unit (an axle, an axle group or a gross weight), defined by : (Wd-Ws)/Ws, where Wd is the impact force of dynamic load measured by the WIM system and Ws the corresponding static load/weight (or any other specified reference value) of the same unit. Such a confidence interval centred on the static load/weight, is : [-δ, +δ], where δ is the tolerance for a confidence level π (for example 90 or 95%).*

The system user selects the confidence level desired (π_o), and statistical calculations with the gathered calibration test data (or in-service test data) determine the δ (expressed as a percentage of error) for the installed system under the test conditions. Accuracy requirements depend on the needs of the user. The European specification suggests the use of a class identification system which explains the accuracy of the system coupled with corresponding usefulness of the data. Classifications are explained as follows:

Class A(5): *legal purposes such as enforcement of legal weight limits and other particular needs, to provide reference weight values for in-service checks, if the classes B(10), C(15), D+(20) or D(25) are required for all the traffic flow vehicles (assuming that it is not possible to weigh in static such a large population);*

Class B+(7): *enforcement of legal weight limits in particular cases, if the class A requirements may not be satisfied, and with a special agreement of the legal authorities; efficient preselection of overloaded axles or vehicles; to provided reference values for in-service checks, if the class C(15), D+(20) or D(25) are required for all the traffic flow vehicles (assuming that it is not possible weigh in static such a large population);*

Class B(10): *Accurate knowledge of weights by axles or axle groups, and gross weights, for:*

- *infrastructure (pavement and bridge) design, maintenance or evaluation, such as aggressiveness evaluation, fatigue damage and lifetime calculations,*
- *preselection of overloaded axles or vehicles,*
- *vehicle identification based on the loads.*

Class C (15) or D+(20): *Detailed statistical studies, determination of load histograms with class width of one or two tones, and accurate classification of vehicles based on the loads; infrastructure studies and fatigue assessments.*

Class D (25): *Weight indications required for statistical purposes, economical and technical studies, standard classification vehicles according to wide weight classes (e.g. by 5 t)*

Additional classes ***E(30), E(35),*** *etc., are defined for WIM systems which do not meet the class D(25) requirements. These classes are specified in the chapter 8, to assess accuracy of rough systems or of systems installed on poor WIM sites. However, they may be useful to give indications about the traffic composition and the load distribution and frequency.*

As users become more familiar with BWIM systems, and particularly the SiWIM system used in this research, they will want to consider what classification the SiWIM system installation must achieve to be of use to them. It is important to understand that the achievement of an A(5), B+(7), or B(10) accuracy classification requires an excellent BWIM technology AND an installation site with exceptional characteristics. The explanation of quality site conditions in the European WIM Specification echoes the explanation in this research report. It does categorize sites in three categories; site I (Excellent), site II (Good), and site III (Acceptable). The Table 3.1 presented in the European WIM Specification summarizes the site conditions necessary to achieve accuracy classification levels.

Table 3.1. Site Condition Requirements (COST 323)

Accuracy	site I (Excellent)	site II (Good)	site III (Acceptable)
Class A (5)	+	-	-
Class B+(7)	+	-	-
Class B (10)	+	+	-
Class C (15)	(+)	+	+
Class D+(20)	(+)	(+)	+
Class D (25)	(+)	(+)	+

Legend ' – ' means insufficient, '+' means sufficient, "(+)" means sufficient but not necessary

After evaluating the experience gained from the two bridges instrumented during UTCA Project 07212, the research team met with ALDOT representatives on June 5, 2008 to determine the desired characteristics of the bridge to be instrumented and monitored under UTCA Project 08204. The bridge selection was a very important part of the evaluation process of the SiWIM system because the research team wanted to compare the measurement performance of the SiWIM system with not only static scales, but also a Bending Plate Weigh-In-Motion System (BP-WIM). The team also wanted to install the SiWIM system and establish an excellent accuracy classification {ideally B(10) but no less than C(15)}.

The scope of work for this research project did not entail a rigorous procedure to classify the Site Condition in accordance with the European specification. However, minimum selection criteria were established in order to refine the search for the best bridge candidate for this research, that is to find a bridge which would yield as high an accuracy classification as possible. The ***minimum criteria*** established during the meeting included:

- The bridge selected for the B-WIM installation must have a short span length and no skew.
- A bridge with two lanes was ideal for accurate data collection.
- B-WIM systems are usually used with reinforced concrete bridges. However, the SiWIM manufacturer claims that the system is applicable to steel bridges. Steel bridges would require more resources for installation such as a certified welder.
- The condition of the bridge is also a key factor for selection. The bridge should be free from too many cracks that may weaken the structure and give inaccurate data; be smooth and accessible. This criteria would be a matter of judgment employed by the selection team.
- Ideally the bridge will not have metal decking under the slab portion of the bridge because this makes installation of the sensors more difficult.
- The bridge must be subjected to sufficient heavy vehicle traffic to provide adequate data for analysis.

Numerous bridges were considered and site visits conducted by Dr. Jim Richardson, Dr. Nasim Uddin and Dr. Talat Salama. After considering the multiple criteria established, a single candidate was isolated. The bridge selected for the SiWIM installation is located on US Highway 78 East in Graysville, Alabama three miles west of I-22. The bridge structure consists of three forty-two foot simply supported reinforced concrete T-beams spans with two lanes in the east-bound direction.   Another advantage of this particular bridge is that an ALDOT operated Bending Plate Weigh-In-Motion System (BP-WIM) is located approximately four miles to the west on US Highway 78.

Section 4.0 SiWIM Installation

The SiWIM system installation does not require cutting into the pavement surface as opposed to Bending Plate Weigh-In-Motion (BP-WIM) systems which require cutting of the pavement and installation of visible bending plates (see Figure 4.1). The SiWIM system is mounted under the bridge structure out of view of vehicle operators (see Figure 4.2). This procedure minimizes the disruption to traffic flow and improves safety conditions for installation crews. The SiWIM system is portable allowing the system to be easily relocated if a site was to become ineffective in monitoring and regulating oversized loads.

The third span of the bridge was selected for SiWIM sensor installation. The two-lane bridge carries one-way traffic for the four-lane divided highway. The bridge superstructure consists of a reinforced concrete slab supported by four cast-in-place reinforced concrete girders. Eight transducers were attached to the underside of the bridge, four to measure axle weights, and four to measure axle spacing. A transducer was mounted to the soffit of each of the four girders (see Figure 4.3) to measure axle weights. Two pairs of transducers, one pair for each lane, were mounted to the soffit of the slab beneath the anticipated wheel paths to measure axle spacings.

Vehicle classification is determined by the SiWIM system based on the number of axles detected when the truck crosses over the bridge. Figure 4.4 illustrates a typical array of voltage readings from the strain transducers as a vehicle moves across the bridge structure.

A camera is mounted to take a photo of each vehicle as it crosses the bridge (Figure 4.5). The camera is out of view of vehicle operators and is mounted at the optimum height and angle to produce the best descriptive photo to be relayed to a Personal Digital Assistant (PDA) along with the vehicle's weight, axle spacing, and classification. The photo is used by enforcement personal to help identify the vehicle they want to remove from the traffic flow. Figure 4.6 shows the installation of the wireless antenna used by the system to relay the data collected. Data transfer is accomplished through a wireless cell phone network. The system is powered by six batteries contained in a steel box, shown in Figure 4.8. The batteries are recharged by six solar panels as shown in Figure 4.7.

Figure 4.1 Bending Plate Installation

Figure 4.2 SiWIM Installation

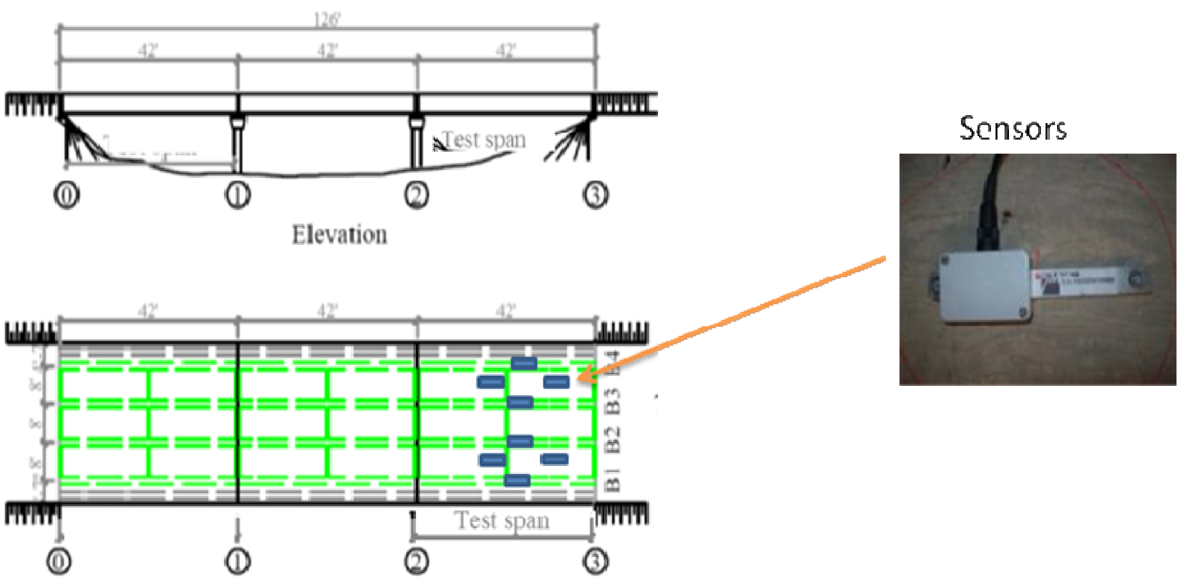

Figure 4.3 Strain Gage Transducer Layout on Bridge

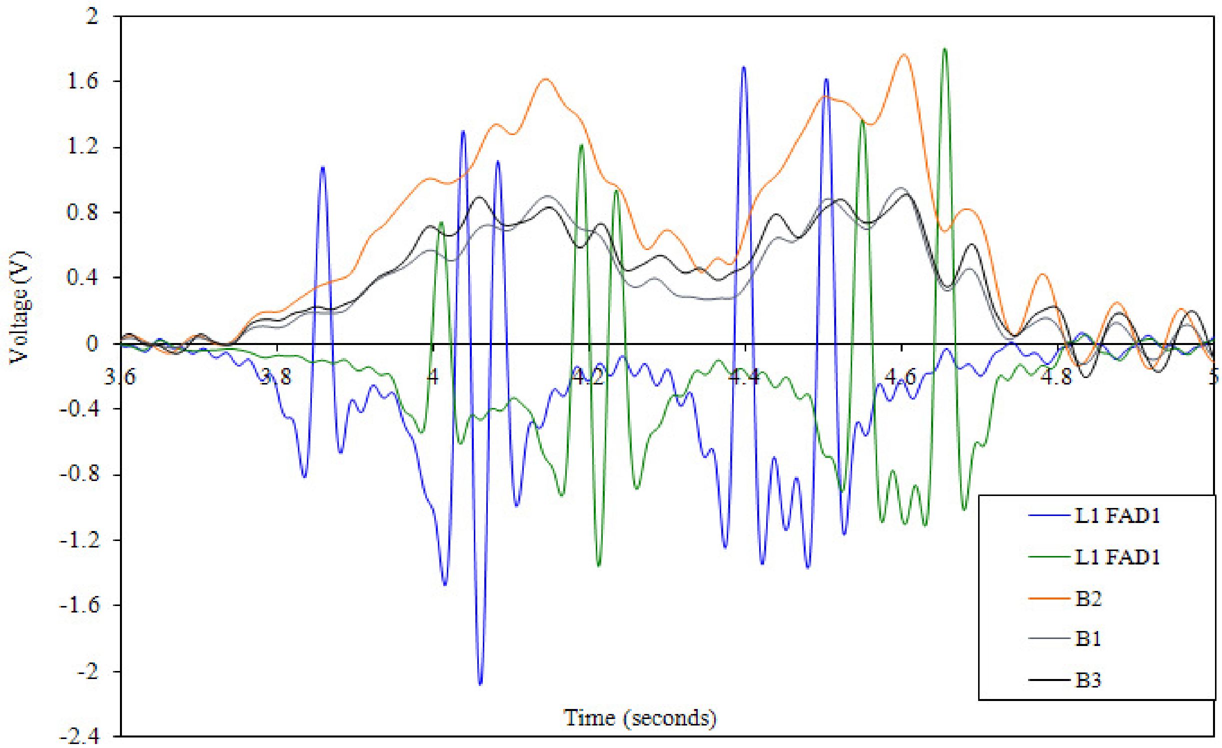

Figure 4.4 Strain Transducer Voltage Readings

Figure 4.5 SiWIM Camera Installation


Figure 4.6 SiWIM Wireless Antenna

Figure 4.7 SiWIM Solar Panel Installation

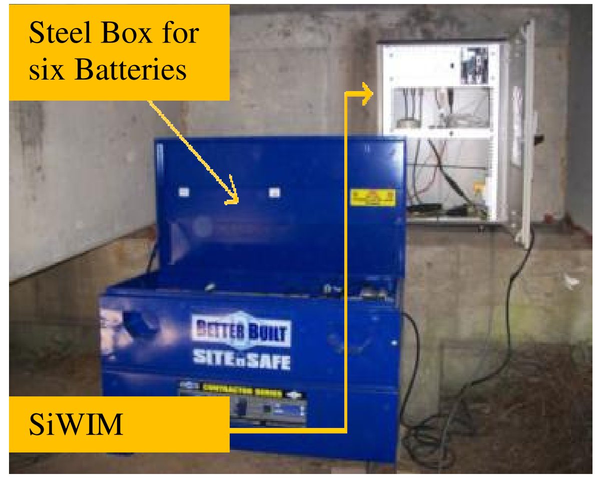

Figure 4.8 SiWIM System and Battery

Section 5.0 Power Supply for the SiWIM System

The marketer of the SiWIM system recommended a fuel-cell based system to power the processor and cameras. The fuel cell alternative was evaluated and found to be overly expensive. In addition, based on the widespread use of solar power within ALDOT, a solar power system was determined to be the most attractive alternative. A solar power system was designed and implemented by Joshua Jackson and Dale Callahan at UAB, and Eddie Lindsey from ALDOT.

Several configurations were tested before standards were agreed on for use at the I-459 test site in Hoover (UTCA Project No. 07212). Three solar panels attached to three regulator/chargers were supplied by ALDOT. Joshua Jackson constructed two portable housings to hold six large, deep cycle, 12V batteries as shown in Figure 5.1. These housings were secure and could be locked in place. This system was tested and found to provide acceptable power although there were some doubts about long term performance during inclement weather with the traffic cameras enabled.

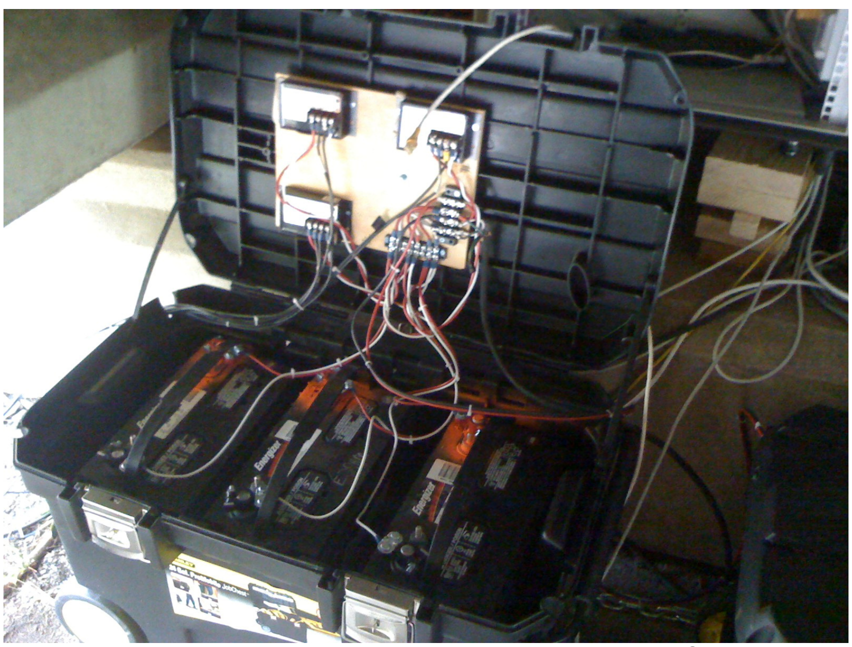

Figure 5.1 The Primary Housing with Three Regulator/Chargers

Unfortunately, the housings, batteries, and regulator/chargers were stolen from the test site before the system was moved to the Hwy 78 location. Building on the results and feedback from the first system, Joshua Jackson constructed a new housing as shown in Figure 5.2. This housing consists of a large steel tool box. The housing was fixed in place by ALDOT maintenance by bolting it directly to the bridge abutment where the bolts where only accessible from the inside. Six batteries were used again, although this time two sets of three solar panels were employed; one set aimed towards the sunrise and one set aimed towards the sunset. A single, heavy duty regulator/charger was used instead of the smaller units. This new housing was also designed with a long-term voltage monitor and logger that could be plugged into a laptop to transfer voltage recordings taken at regular intervals. The housing was also equipped with a standard 12V power outlet to power a laptop during system maintenance and testing. This configuration is considered well suited for a variety of weather and environmental applications, and the enhanced security measures will provide a higher degree of confidence against theft.

Figure 5.2 The Improved Secure Housing

Section 6.0 System Calibration

The calibration procedure is a critical part of the SiWIM installation and use. Using trucks of known weight and dimensions, the dynamic measured weight results are obtained and compared with the accurate static weights to calibrate the SiWIM system. A high confidence level in a calculated accuracy class confidence interval for the installed SiWIM system depends on the quality and rigor of the calibration procedure.

The accuracy of SiWIM system measurements depends on: (1) the type of bridge, (2) the installation procedure, (3) the selection of the influence line, and fine tuning of the weight parameters, (4) the smoothness of the pavement on the bridge and in the bridge approach, and (5) the accuracy of the static weighing method.

The guidelines for the system calibration plan for this research were obtained from the European WIM Specification (COST 323). From the tables of accuracy included in the specification, two levels of confidence are provided:

> *π_o, which is the minimum confidence level desired for the achieved confidence interval ; and π, which is the actual confidence level for the achieved confidence interval. Generally, π is greater than π_o .*

It is important to note that π_o is selected by the owner of the equipment.

Four different test conditions and three different environmental conditions can potentially exist for a qualifying calibration test (COST 323). The test conditions are defined as follows:

(1) full repeatability (r1) (1 vehicle under the same loading and traffic conditions);
(2) limited repeatability (r2) (1 vehicle with different loads under changing traffic conditions);
(3) limited reproducibility (R1) (2 to 10 different trucks which were driven at several times under changing traffic conditions)
(4) full reproducibility (R2) (more than 10 vehicles form the traffic flow).

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

For the above mentioned test conditions (1) and (2), only 1 vehicle is needed in repeated runs. The difference between the two is that the former is under the same loading and traffic conditions, while the latter is under different cases. Test condition (3) requires from 2 to 10 different trucks which must be driven several times over the bridge under changing traffic conditions. Test condition (4) requires that more than 10 vehicles form the traffic flow.

The European WIM Specification (COST 323) defines accuracy classes with a letter and 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 is error %) for a given confidence level π.

The exact level of confidence depends on the number of test vehicles included in the test, on the type of the check (initial calibration or subsequent in-service validation) and on test and environmental conditions. Table 6-1 shows the confidence level achieved for different test sample sizes and varying test conditions. A study of the table reveals the sample size of truck measurements required to achieve various confidence levels that the measured results will fall between $\pm\delta$ around the true (static) value for the case (1) environmental condition and the possibility of using all four of the test conditions. Note that it is necessary to gather 10 to several hundred of measurements, depending on the test conditions and the desired confidence interval.

Table 6-1 Minimum Levels of Confidence (of the centred confidence intervals in %) - case (I) for Environmental Repeatability π_o

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: from Weigh in Motion of Road Vehicles (Cost 1999)

Figure 6-1 graphically displays the sample size required for a desired minimum confidence level π_o for twelve different combinations of testing and environmental conditions based on the European WIM Specification (COST 323). The Europe WIM Specification is mainly focused on two cases, R1-I which stands for the initial calibration, and R2-I which represents the case for the in-service check. The environmental conditions of both cases are environmental repeatability.

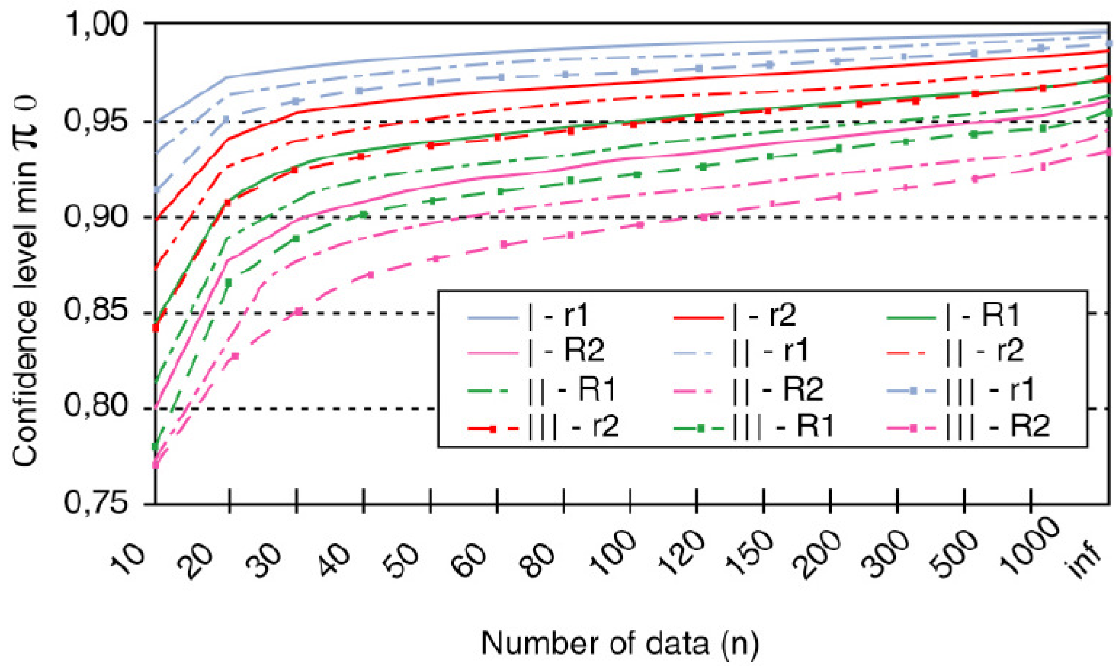

Figure 6-1 Minimum confidence level π_0 with number of data (COST 323)

Table 6-2 shows the confidence interval requirements when confidence level is 95% for different accuracy classes based on gross vehicle weight, group of axles, single axle, and axle of a group. For example, accuracy class B(10) means that approximately 95 % of the gross weight results (Table 6-2) 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 B+(7) on very good structures with smooth pavement to class E(50) on less ideal bridges with very rough pavement. Typically classes B(10) or C(15) can be expected if the site conditions are excellent for a SiWIM installation.

Table 6-2 Tolerances of the Accuracy Classes (confidence interval δ in %) (COST 323)

Criteria (type of measurement)	**Accuracy Classes: Confidence interval width 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	…

When a SiWIM system is installed in the field, the accuracy class is determined through statistical analysis of the test data. In order to calculate the accuracy class, the minimum confidence level must be selected (for example 85%). The value of δ is determined using the equations presented in the European Specification [(COST 323)

The basic statistical approach for determining δ for a desired π_o found on page 46 of Appendix I of the specification is shown in the box below (COST 323):

> A lower bound π, of the probability for an individual value of a relative error, taken randomly from a normally distributed sample of size n, with a sample mean m and standard deviation s, to be in the centred confidence interval $[-\delta; \delta]$, is given at the confidence level (1-α) by (B. Jacob, 1997):
>
> $$\pi = \Phi(u_1) - \Phi(u_2)\text{ , with } u_1 = (\delta - m)/s - t_{\nu,1-\alpha/2}/n^{1/2} \quad \text{and} \quad u_2 = (-\delta - m)/s + t_{\nu,1-\alpha/2}/n^{1/2} \qquad (2)$$
>
> where Φ is the cumulative distribution function of a Student variable, and $t_{\nu,1-\alpha/2}$ is a Student variable with $\nu = n-1$ degrees of freedom. α is taken equal to 0.05.
>
> Remark: If n is greater than 60, the cumulative distribution function Φ may be approximated by the cumulative distribution function of a standardised Normal variable. But this approximation is not of a very high interest in practice, and should only be used if the Student distribution function is not available.
>
> Then the estimated level of confidence π, for each sample (and criterion) is calculated.

Once the statistical data is available from a calibration or in-service test, the above equation is utilized to calculate the mean and standard deviation of the sample. The value of δ is determined with an iterative technique which insures that the calculated δ is acceptable for a confidence level π. Recall that π must be greater than or equal to π_o. The accuracy class (such as C(15), D (20), etc.) can then be determined once the values for π and δ have been established by iteration.

The appropriate calibration test program is selected mainly based on the desired confidence level and accuracy classification. The higher the demands for certainty, the more elaborate and thus more time-consuming and expensive the calibration plan must be. It is important to recall that the rigor of the calibration and in-service tests can only return results commensurate with the quality of the installed equipment and the site characteristics.

During the first UTCA Project 07212, the research team worked with the SiWIM manufacturer, CESTEL, to organize and execute the calibration plan. The first installation calibration plan on I-59 utilized preloaded ALDOT vehicles with the plan to run each vehicle 10 times across the bridge in each lane (a total of 20 crossings per truck). Unfortunately, the ALDOT truck configurations, bridge flexibility and SiWIM internal strain voltage limitations combined to render the data useless for calibration. Under the direction of the CESTEL technical representatives, suitable five axle trucks were obtained, statically weighed and then released to cross the instrumented bridge. The measured results from 3 trucks were used for the calibration of the SiWIM equipment.

During the second installation on I-459, a much more rigorous calibration program was planned spanning two days. The plan desired to establish a 95% confidence level in the established confidence interval and accuracy classification. Based on the European WIM Specifications, (COST 323), a total of 110 runs involving 4 calibration truck crossings would be required. The details of the experience can be found in the referenced UTCA Report (UTCA 07212).

After conversations with ALDOT representatives concerning the cost of calibration and the number of vehicles required to reach varying levels of confidence, it was determined that running the required number of vehicles during calibration to reach 95% confidence on the US 78 bridge was not worth the cost, and that 10 quality passes per lane per calibration vehicle would be sufficient. Figure 6-1 and Table 6-1 indicate that at least 10 quality data runs per truck per lane would insure an 85% confidence level in the established confidence interval and accuracy classification. The planned calibration test conditions for this project was test condition (R1-I), that is to say, the test conditions are limited reproducibility (R1) (2 to 10 different trucks which were driven over the bridge several times under changing traffic conditions), and the environmental conditions are environmental repeatability (I), representing short measurements in mostly constant environmental conditions – weather.

The calibration of the system took place on November 18, 2008. Two 5-axle trucks loaded to a capacity of about 80,000 lbs performed ten test runs per lane on the BP-WIM system and B-WIM system (see Figure 6.2). Detailed information about the calibration vehicles is listed in table 6-3 and 6-4.

Table 6-3 Calibration Vehicle Information for Truck 1

axle weight (lb)					
Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	GVW
11,050	15,650	16,100	18,200	18,000	79,000
axle spacing (in)					
A1-A2	A2-A3	A3-A4	A4-A5		
170	53	440	51		

Table 6-4 Calibration Vehicle Information for Truck 2

axle weight (lb)					
Axle 1	Axle 2	Axle 3	Axle 4	Axle 5	GVW
10,050	16,000	15,800	18,300	18,050	78,200
axle spacing (in)					
A1-A2	A2-A3	A3-A4	A4-A5		
171	53	438	50		

During the calibration test, two trucks were running at different speeds and different lanes. The total runs were 24 runs (each lane with 12 runs). During the initial calibration, the researchers missed 1 run in each lane and also experienced multiple presence one time, rendering the measurement useless. However, the target of 10 good runs for each lane was achieved.

The data collected for lane one is shown in Table 6.5. The table shows the comparison of the SiWIM and the BP-WIM system readings with the static weights of the vehicles. The SiWIM system mean difference for lane one calibration was -1.23% with a standard deviation of 7.39%. It is interesting to note that the BP-WIM system performed in a similar way with a mean difference of -0.95 % and a standard deviation of 6.43 %.

The results for the lane two calibration tests are shown in Table 6.6. The SiWIM system mean difference for the lane two calibration runs was 2.18% with a standard deviation of 6.76% and the BP-WIM system had a mean difference of -0.65% with a standard deviation of 6.43%. This range of data experienced during calibration was not surprising because it was very similar to the results from the prior two bridges instrumented. A detailed description of the calibration process for the first two bridges is available in the UTCA Project Number 07212 report. Nevertheless, it was disappointing because the research team had hoped to see smaller range in the % differential between the SiWIM measurement and the static measurement.

Figure 6.2 ALDOT Calibration Trucks

Table 6.5 Lane One Calibration Results

Number	Static weight (lb)	SiWIM (lb)	Bending Plates Weight (lb)	SiWIM to Static Comparison (%)	BP to Static Comparison (%)
1	79000	70626	80800	-10.6	2.3
2	79000	70073	81700	-11.3	3.4
3	79000	83661	81300	5.9	2.9
4	79000	74181	86900	-6.1	10
5	79000	77499	76900	-1.9	-2.7
6	78200	77574	81400	-0.8	4.1
7	78200	80937	72400	3.5	-7.4
8	78200	77027	70300	-1.5	-10.1
9	78200	76245	74300	-2.5	-5
10	78200	88366	72700	13	-7
			Mean	-1.23	-0.95
			St Dev.	7.39	6.43

Table 6.6 Lane Two Calibration Results

Number	Static weight (lb)	SiWIM (lb)	Bending Plates Weight (lb)	SiWIM to Static Comparison (%)	BP to Static Comparison (%)
1	78200	78356	82400	0.2	5.4
2	78200	76792	76000	-1.8	-2.8
3	78200	88131	84700	12.7	8.3
4	78200	88992	86600	13.8	10.7
5	79000	83108	87800	5.2	11.1
6	79000	83108	72600	5.2	-8.1
7	79000	76156	71800	-3.6	-9.1
8	79000	76788	66600	-2.8	-15.7
9	78200	76636	83200	-2	6.4
10	79000	74971	69000	-5.1	-12.7
			Mean	2.18	-.65
			St Dev.	6.76	10.2

Once the data was collected at the test site, the calibration and class accuracy calculations were accomplished using the equations previously described. Table 6.7 is a summary of the calculated accuracy classes based on the gross vehicle weight according to European WIM Specification (COST 323).

Table 6.7 Accuracy Analysis of Initial Calibration

Lane	Number	Mean (%)	St. dev. (%)	π_o (%)	δ (%)	δ_{min} (%)	$\delta_{criteria}$ (%)	δ_{class}	π (%)	π_c (%)	Class based on GVW
1	10	-1.23	7.39	85.0	22.4	17.1	21.4	25	85.1	95.3	D(25)
2	10	2.18	6.76	85.0	18.4	16.0	20.0	20	85.2	91.4	D+(20)

Comparisons with static weight on a one-to-one basis for both SiWIM predictions and the BP-WIM station measurements have generally fallen below a 15% error for gross weights. Overall both systems provided similar level of accuracy. As to the SiWIM system, the accuracy class was determined to be Class D(25) at a confidence level of 85%.

What is the significance of D(25)? Recall that the acceptability of an accuracy class depends on what the user demands from the installation. In order to use the system for preselection of vehicles for weighing, ideally a class of B(10) or even C(15) must be achieved. Clearly this did not happen with the SiWIM installation in this case. Now that calibration was completed, Section 7 will describe in-service testing.

Section 7.0 In-Service Testing

7.1 In-Service Testing Methodology

The in-service testing program was designed to take readings from the SiWIM system on three different days with differing weather conditions. One of the objectives of this research project was to determine the accuracy of the SiWIM system as compared to a BP-WIM system when their readings are compared to static scale weights. This comparison was accomplished using three evaluation stations along US Highway 78 East as shown in Figure 7.1. The first station was the BP-WIM system, the second the SiWIM system, and the third a static scale crew located at the I-22 interchange. The static scale weights were used as the reference base weight for comparison with the BP-WIM and SiWIM weights.

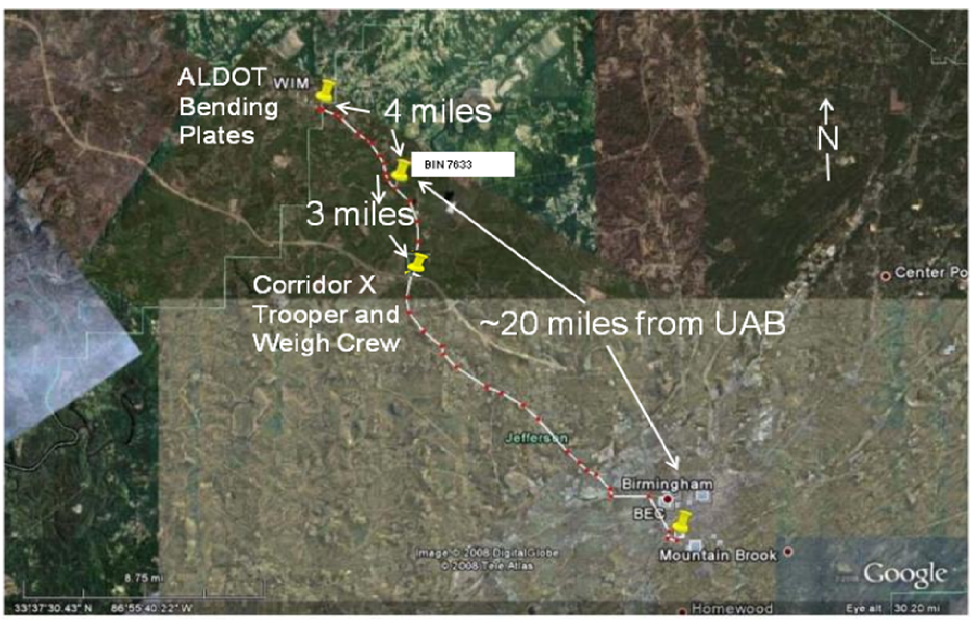

Figure 7.1 Station Location Layout

Experience gained from UTCA Project 07212 was very helpful in planning the approach to field in-service testing of the SiWIM installation. Researchers learned that not all trucks which cross a bridge instrumented with SiWIM will be recorded accurately by the system. In fact, some trucks pass over a bridge and the recorded data in the system is not useful for analysis. The primary reason for unusable data is multiple vehicle presence on the bridge. Another contributor is significant dynamic influence of rough pavement surface or bridge entrance ramps. For this reason, the researchers determined that the static weighing crew should be positioned downstream from the bridge. Only trucks with a quality SiWIM reading would be flagged to be pulled from traffic for weighing.

Gathering data at the BP-WIM site required the system to be calibrated and functioning. Researchers took photographs of candidate trucks as they crossed the BP-WIM system. The photos were later used to link the BP-WIM measured data with the SiWIM and static data measurements. Researchers were able to compare weight readings several days after the actual physical testing dates

The procedure for the in-service testing is straightforward. When a truck crosses the bridge, the SiWIM system recognizes the truck, photographs it, and determines the velocity, number of axles, and axle weights. This information is readable on any PDA screen or computer monitor connected to this system. Researchers were positioned under the SiWIM-instrumented bridge with the PDA. Once a good truck candidate was identified and analyzed, troopers were notified of the vehicle description (by radio) and the vehicle was pulled from the traffic flow and directed to the portable static weighing team. The team would then weigh each axle and measure the truck.

Three specific days between November 2008 and February 2009 were scheduled for testing the system. In order to schedule a day for testing, it was necessary to find a day when static weighing crews were available and Department of Public Safety personnel and equipment were available. ALDOT assisted in coordinating these teams for the tests. It is important to note that the original system calibration would be used for all three of the test days in order to observe the difference in system performance, if any, with varying weather conditions.

An explanation of the statistical approach for determining π and δ for the SiWIM installation was explained in the calibration section of this report (Section 6). This same statistical analysis procedure is followed when test data is gathered for an in-service check.

The number of vehicles planned for each day of testing was again based on the concept of an acceptable confidence level. Figure 6.1 provides a quick reference for the number of good truck runs necessary for a confidence level for 12 different testing conditions. The test program for this research wanted to insure at least an 85% confidence level. This means a sample size of at least 18 truck runs.

7.2 November 20, 2008

The first in-service testing was conducted on November 20, 2008. The test performed on this date included 5-axle trucks only, and the team wanted to focus testing on the SiWIM system only to insure the data made sense and the enforcement process was working. On the day of testing trucks were weighed statically and compared with the SiWIM system measurements. BP-WIM weight data was not gathered. The truck weights were measured when they crossed the bridge. In cases where the trucks were five axle and minimal multi-presence of other vehicles existed on the bridge, members of the Department of Public Safety were contacted by radio and the identified trucks were pulled from the traffic flow for static weighing. This approach of weighing trucks downstream of the SiWIM instrumented bridge was based on a recommendation following the prior testing program. When multiple presence of vehicles occurs on an instrumented bridge, the measurement results are often poor, and in the worst cases, trucks are not identified at all. The method used for the test proved to be much more efficient in that only trucks with useable SiWIM weight data were pulled from traffic.

In this case, the in-service test condition was test condition (R2-I). That is, the test conditions are full reproducibility (R2) (more than 10 vehicles form the traffic flow) and the environmental conditions are (1) environmental repeatability (I), representing short measurements in mostly constant environmental conditions – weather. From Table 6-1 and Figure 6-1, in order to achieve at least 85% confidence level, at least 18 vehicles should be pulled from traffic flow. During this in-service testing, 19 vehicles were preselected from traffic flow. The target confidence level with 19 vehicles is about 87%.

The data analysis of 19 trucks measured that day is shown in Table 7.2. The mean percent difference between the SiWIM system measurements and the static weights was 11.96% with a standard deviation of 8.6%. Figure 7.1 contains photos of two of the trucks as they were weighed by the SiWIM system and static weight crew. The temperature on this testing date was 35° F.

The class accuracy was then calculated using the approach explained in Section 6 of this report. Accuracy was determined for the gross vehicle weight only.

Table 7.2 illustrates the accuracy evaluation of gross vehicle weight according to European WIM Specification (COST 323). The accuracy class was determined to be Class E(30) at a confidence interval of 85%. This means that 85% of the truck weights can be expected between ±30% from the true static value.

The performance was worse than during calibration, and of course this was a concern to the researchers. During the initial calibration, only one truck configuration was used (5-axle). The configuration of some of the trucks in the in-service test was significantly different from the calibration vehicles. To improve performance and achieve better correlation of class accuracy performance for in-service testing versus calibration, using a variety of calibration vehicles with differing configuration may help. However, if the bridge site conditions are not excellent in all respects, the potential for improved accuracy will be limited.

After the first in-service test, the researchers concluded that the next test should draw more vehicles from the traffic flow. Certainly an increase in data points increases the confidence level in the results, but by no means suggests that the standard deviation of the measurement error would be reduced. The second test day also would provide the opportunity to test the system accuracy under another set of environmental conditions. It is important to maintain the initial calibration to test the system performance at differing times and under changing environmental conditions. With this initial SiWIM experience completed, the research team was confident to take readings from both the SiWIM and BP-WIM system during the next in service test.

Table 7.1 November 20, 2009 Data and Results

Number	Lane	Static weight (lb)	SiWIM (lb)	SiWIM to Static Comparison (%) (%)
1	2	27100	30542	12.7
2	1	86700	86853	0.2
3	2	36000	43067	19.6
4	2	87800	94475	7.6
5	2	87100	94340	8.3
6	2	75650	83261	10.1
7	2	78600	84994	8.1
8	2	88550	115700	30.7
9	2	79450	85866	8.1
10	1	88750	92588	4.3
11	1	86550	97125	12.2
12	2	29450	32890	11.7
13	2	86950	92551	6.4
14	2	87850	109488	24.6
15	2	81200	77806	-4.2
16	2	78300	87853	12.2
17	2	75350	90061	19.5
18	2	75700	93983	24.2
19	2	58650	65011	10.8
			Mean	11.96
			St Dev.	8.6

Table 7.2 Accuracy Analysis of In-service Testing November 20, 2009

Number	Mean (%)	St. dev. (%)	π_o (%)	δ (%)	δ_{min} (%)	$\delta_{criteria}$ (%)	δ_{class}	π (%)	π_c (%)	Accepted Class of GVW
19	11.96	8.6	87.1	33.0	26.2	26.2	30	87.2	96.7	E(30)

Figure 7.2 November 20 SiWIM and Static Weighing Photos of Trucks 1 and 2

7.3 January 26, 2009

During this in-service test, 31 vehicles were pulled from the traffic flow. From Figure 6.1, a 90% confidence level for the measured data would be expected with 31 good data points. On this testing day, the team gathered information from both the SiWIM installation and the BP-WIM installation.

The temperature for this testing date was 50° F. For this test 3-axle and 5-axle trucks were selected from the traffic flow. The trucks were weighed using all three stations (static, SiWIM and BP-WIM). The data gathered for the 5-axle trucks is summarized in Table 7.3. The mean percent difference for the BP-WIM system compared to the base weight was 0.98% with a standard deviation on 7.02%. The SiWIM system had a mean percent difference of 0.1% with a standard deviation of 7.87%. Figure 7.2 shows photos of two 5-axle trucks as they were weighed by the B-WIM system and static weight crew.

The 3-axle truck data is summarized in Table 7.4. The BP-WIM system for the 3-axle trucks had a mean percent difference compare to the base weight of 16.35% with a standard deviation of 22.14%. The SiWIM's mean was slightly better at 12.17% with a standard deviation of 18.61%. Figure 7.3 shows photos of a 3-axle truck as it was weighed by the Bending Plate, the SiWIM system, and the static weight crew. The measurement errors of the 3-axle trucks were clearly much more scattered than the 5-axle trucks. This is a direct result of the decision to use 5-axle trucks only for the calibration. If the user desires more accurate results for 3-axle trucks, then 3-axle truck calibration vehicles should be included in the calibration.

Table 7.3 January 26 In-service Testing Data for 5-Axle Trucks

Truck	Static Weight (lb)	SiWIM Weight (lb)	Bending Plates Weight (lb) (lb)	SiWIM to Static Comparison (%)	BP to Static Comparison (%)
1	84,900	83,258	90,600	-1.9	6.7
2	74,550	80,881		8.5	
3	64,950	66,048	69,900	1.7	7.6
8	77,550	76,220	82,500	-1.7	6.4
11	57,050	56,520	58,900	-0.9	3.2
12	68,200	53,800	73,600	-21.1	7.9
16	67,150	72,745	71,100	8.3	5.9
17	85,600	86,229	82,400	0.7	-3.7
19	87,200	93,241	/	6.9	/
20	33,850	36,047	31,000	6.5	-8.4
22	39,350	42,159	35,100	7.1	-10.8
23	85,550	80,585	84,000	-5.8	-1.8
24	85,450	89,623	81,600	4.9	-4.5
27	38,400	39,373	35,000	2.5	-8.9
28	40,800	39,440	37,200	-3.3	-8.8
31	68,850	61,464	65,700	-10.7	-4.6
			Mean	0.1	-0.98
			St. Dev	7.87	7.02

Table 7.4 January 26 In-service Testing Data for 3- Axle Trucks

Truck	Static Weight (lb)	SiWIM Weight (lb)	Bending Plates Weight (lb) (lb)	SiWIM to Static Comparison (%)	BP to Static Comparison (%)
4	37,500	40,002	42,600	6.7	13.6
5	31,600	31,552	/	-0.2	/
6	29,100	28,091	/	-3.5	/
7	41,550	53,688	68,600	29.2	65.1
9	34,250	38,451	42,300	12.3	23.5
10	28,200	30,563	/	8.4	/
13	59,900	41,957	65,500	-30	9.3
14	40,000	58,565	48,100	46.4	20.3
18	40,200	46,047	43,300	14.5	7.7
21	45,250	48,766	/	7.8	/
25	32,800	37,462	31,300	14.2	-4.6
26	32,550	35,440	31,200	8.9	-4.1
29	40,100	56,115	/	39.9	/
30	41,000	47,418	/	15.7	/
			Mean	12.17	16.35
			St. Dev	18.61	22.14

Figure 7.3 January 26th Bending Plate, SiWIM, and Static Weighing Photos of Truck 14

If the data used for system analysis is limited to the in-service testing data collected on January 26, 2009, the test conditions are (R2-I). That is, the test conditions are full reproducibility (R2) (more than 10 vehicles form the traffic flow), the environmental conditions are (1) environmental repeatability, and (I) means short-term measurements in mostly constant environmental conditions – weather. If the collected in-service testing data for both Nov. 20, 2008 and January 26, 2009 are considered jointly, the test conditions are (R2-III). That is, the test conditions are full reproducibility (R2) (more than 10 vehicles form the traffic flow), the environmental conditions are (3) environmental full reproducibility, and (II) means long-term measurements in changing environmental conditions – weather.

Table 7.5 summarizes the calculated accuracy class evaluation based on the gross vehicle weight according to the European WIM Specification (COST 323) and considering the data taken on this test day only (5-axle and 3-axle trucks combined). The accuracy evaluation of gross vehicle weight based on condition (R2-III) will be summarized later together with measured data from February 6, 2009.

Table 7.5: Accuracy Analysis of In-service Testing, January 26, 2009

Number	Mean (%)	St. dev. (%)	π_o (%)	δ (%)	δ_{min} (%)	$\delta_{criteria}$ (%)	δ_{class}	π (%)	π_c (%)	Accepted Class of GVW
31	5.73	14.99	89.8	39.0	32.5	32.5	35	89.8	95.6	E(35)

Note: considering test conditions (R2-I).

Accuracy Class E(35) is **not** an accuracy class suitable for screening trucks for enforcement. When comparing the data between Table 7.2 and Table 7.5, the deterioration of the accuracy classification from E(30) to E(35) largely occurred because some of the measured data shown in Table 7.5 included 3-axle vehicles with axle configurations substantially different from the calibration vehicles' configurations. This result strongly suggests that if 3-axle vehicle weight management is a concern of the user, a combination of different vehicles with different configuration, for example, adding 3 axle vehicles, should be included in the system calibration. This decision must be made by the user.

7.4 February 6, 2009

The final testing date was on February 6, 2009. On this day 31 vehicles were selected from the traffic flow. From Figure 6.1, a confidence level of 90% can be expected with this many data points. The temperature was 65°F when testing started. Both 5-axle and 3-axle trucks were selected for measurement. All three measurement systems were employed for this demonstration.

The data results for the 5-axle trucks are summarized in Table 7.6. The BP-WIM system had an average percent difference compared to the base static weight of 2.8% with a standard deviation of 9.3%. The SiWIM system's average percent difference was 4.5% with a standard deviation of 12.8%.

Table 7.7 summarizes the data for the 3-axle trucks for the February 6 testing date. The BP-WIM system had an average percent difference of 0.8% with a standard deviation of 16.1%. The SiWIM system had an average percent difference of 21% with a standard deviation of 14.4%. These values again demonstrate a much wider range of differences when compared to the 5-axle truck data.

Table 7.6 February 6 In-service Testing Data for 5- Axle Trucks

Truck	Static Weight (lb)	SiWIM Weight (lb)	Bending Plates Weight (lb)	SiWIM to Static Comparison (%)	BP to Static Comparison (%)
2	86,650		82,000		-5.4
5	86,950	98,252	81,800	13.0	-5.9
6	87,150	90,117		3.4	
7	72,250	71,464	67,200	-1.1	-7.0
8	86,900	100,545	83,400	15.7	-4.0
9	86,350	65,958		-23.6	
11	34,550	42,744	31,300	23.7	-9.4
12	60,450	66,093	72,500	9.3	19.9
13	48,050	50,250		4.6	
14	87,900	85,038	83,700	-3.3	-4.8
15	86,300	88,634	97,800	2.7	13.3
16	70,050	89,218	70,500	27.4	0.6
17	87,550	64,385	87,400	-26.5	-0.2
20	59,700	63,239	55,200	5.9	-7.5
21	50,800	55,756	48,900	9.8	-3.7
25	30,850	34,316		11.2	
26	86,600	91,510	81,800	5.7	-5.5
27	29,400	28,878		-1.8	
29	64,700	69,914	51,700	8.1	-20.1
30	29,500	30,024		1.8	
31	50,400	52,317	49,400	3.8	-2.0
			Mean	4.5	-2.8
			St. Dev	12.8	9.3

Table 7.7 February 6 In-service Testing Data of 3-Axle Trucks

Truck	Static Weight (lb)	SiWIM Weight (lb)	Bending Plates Weight (lb)	SiWIM to Static Comparison (%)	BP to Static Comparison (%)
1	24,100				
3	41,050	52,003	39,100	26.7	-4.8
4	27,550	40,609		47.4	
10	40,150	52,362	48,700	30.4	21.3
18	30,650	31,305		2.1	
19	23,500	25,596		8.9	
22	32,300	35,013		8.4	
23	39,300	51,958	30,500	32.2	-22.4
24	31,850	36,563	30,400	14.8	-4.6
28	39,650	46,834	42,100	18.1	6.2
			Mean	21.0	-0.8
			St. Dev	14.4	16.1

Table 7.8 summarizes the accuracy evaluation of gross vehicle weight according to European WIM Specification (COST 323), considering both the 5-axle and 3-axle truck data on this test day. The accuracy classification calculation for the gross vehicle weight was based on condition (R2-I). It turns out that the data collected for two of the vehicles was not useable reducing the sample size of 29.

Table 7.8 Accuracy Analysis of In-service Testing, February 6, 2009

Number	Mean	St. dev.	π_o	δ	δ_{min}	$\delta_{criteria}$	δ_{class}	π	π_c	Accepted Class of GVW
	(%)	(%)	(%)	(%)	(%)	(%)		(%)	(%)	
29	9.61	15.17	89.5	44.0	35.5	35.5	40	89.5	96.3	E(40)

Note: considering test conditions (R2-I).

The gathered truck weights from all three in-service testing days can be aggregated to form a larger sample size for analysis. Since the data was gathered on three separate days with differing environmental conditions, the test condition must be adjusted in accuracy classification calculation. Table 7.9 summarizes the accuracy classification for the gross vehicle based on the combined data from all three in-service test days. The test condition in this instance is (R2-III). The sampling number is 19+31+29=79. According to Figure 6.1, if we consider all three days measured data, a confidence level of approximately 88% is expected with a sample size of 79.

Table 7.9: Accuracy Analysis of Combined In-service Test Data

Number	Mean	St. dev.	π_o	δ	δ_{min}	$\delta_{criteria}$	δ_{class}	π	π_c	Accepted Class of GVW
	(%)	(%)	(%)	(%)	(%)	(%)		(%)	(%)	
79	8.69	13.85	88.9	33.0	29.4	29.4	30	89.0	93.2	E(30)

Note: Considering test conditions (R2-III).

The accuracy classification of E(30) is not suitable for screening heavy vehicles for weighing. Clearly the inclusion of 3-axle and 5-axle trucks in the sample downgraded the accuracy classification from the calibration accuracy classification of D(25). As a followup to this research work, researchers plan on evaluating the data for different types of trucks and determine if there are alternative ways to group data for accuracy evaluation. These studies are beyond the scope of this research and will be submitted for publication separately.

Section 8.0 Information and Equipment Transfer to ALDOT

The SiWIM system has been demonstrated under UTCA Projects 07212 and 08204. In order to learn how to install the system, calibrate it and interpret the in service results from the enormous amount of data gathered on a daily basis, close coordination and assistance from the CESTEL service personnel was required. CESTEL provides a detailed operating manual with their equipment which is helpful, but not sufficient to train installers and operators.

ALDOT personnel participated in the installation of the sensors on all three of the bridges used in the research projects. This participation is excellent hands on experience and established an understanding for ALDOT maintenance personnel of the equipment requirements necessary for installation. The only way to really understand how to install and use the system, however, is to do it. The experience gained during the research will be valuable to ALDOT if it elects to install the SiWIM system on other bridges.

Several ALDOT engineers participated in the training sessions conducted by CESTEL in the classroom prior to the first installation of the SiWIM system in October 2007. This training focused on the operation of the SiWIM system itself and the interpretation of data. They later observed the installation of sensors on the I-59 bridge north of Birmingham, Alabama. This experience is a great foundation for those in ALDOT who will be using the SiWIM equipment in the future.

The SiWIM system has been removed from the bridge and is available for ALDOT to utilize. The final battery box configuration is available with the SiWIM system. The solar panels used during the research were provided by ALDOT. Proficiency will be gained in the future during actual installation, calibration and service measurements. It is recommended that CESTEL be consulted prior to the next field installation to determine if any equipment upgrades are available and if involvement by CESTEL is required.

Section 9.0 Subsequent Testing

Lessons learned from the work reported here have been of benefit to ALDOT. ALDOT wanted to conduct additional testing to determine if accuracy levels could be improved. In early 2011, ALDOT obtained an updated SiWIM system model from CESTEL. Experience gained from the first three bridge tests could now be taken into account in selecting a bridge which displays excellent potential characteristics for an SiWIM installation. Keys to the bridge selection:

a. No skew
b. Simply supported spans short spans (spans of 30 feet or less will likely provide better results)
c. two lanes with two-way traffic
d. Quality smooth pavement on the entrance ramp.
e. Reduced probability of multiple presence of vehicles.

A two-lane concrete, tee-beam bridge with two-way traffic (BIN 4289) was selected. The span length was 30 feet, and daily truck traffic was 1,658 trucks per day with a speed limit of 45 miles per hour. Recall the span length of the bridge on the US Highway 78 bridge documented in this report was 41 feet.

As recommended in this report, on March 1, 2011 ALDOT personnel included a CESTEL technician to assist in the initial installation and calibration of the new SiWIM system the bridge. In addition, calibration included both 5-axle and 3-axle test trucks with gross vehicle weights near 80,000 pounds. Calibration consisted of 10 runs per truck in each of the two bridge lanes.

After calibration, ten trucks were weighed with SiWIM and then pulled from traffic, where axle measurements were taken and the trucks were weighed statically. Comparisons between SiWIM and static weights produced B(10), C(15), and B(10) accuracy classifications for gross vehicle weight, group axles, and single axles, respectively [5].

Section 10.0 Conclusions and Recommendations

This research project involved the installation of a SiWIM system on a three-span highway bridge with two lanes running each direction. The bridge selected for the SiWIM installation is located on US Highway 78 East in Graysville, Alabama and is three miles west of I-22. The bridge structure consists of three forty-two foot simply supported reinforced concrete T-beams spans. An advantage of this particular bridge location is that an ALDOT-operated Bending Plate Weigh-In-Motion System (BP-WIM) is located approximately four miles to the west on US Highway 78. Live measurement exercises of trucks crossing the bridge were conducted on four different days. Measurements were also collected from the BP-WIM system on three of the test days for comparison with the SiWIM measurements More than one hundred trucks of known static weight crossed the bridge and the SiWIM system successfully captured a weight estimate for most of them. In addition, over sixty trucks were weighed by both the SiWIM and BP-WIM systems, and the accuracy of the two methodologies were compared.

The experience gained in this testing program reinforced lessons learned from the initial field testing research conducted under UTCA Project No. 07212. After months of experience and data analysis involving the evaluation of over 500 truck measurements, the research team is confident in the physical installation and use of the SiWIM system. The bridge tested the SiWIM system did not demonstrate an accuracy classification suitable for screening trucks for weight enforcement. An accuracy classification of E(30) was obtained when analyzing the gross vehicle weights of all 79 vehicles weighed during the three test days. However, the additional data collected during this program demonstrated that the SiWIM B-WIM system can be as accurate as a BP-WIM system when weight measurements from those two systems are compared to the static weights of truck configurations typically encountered on highways in Alabama.

The bridge selected for this application demonstration test was considered one of the most ideal candidates from the ALDOT bridge inventory in terms of a design configuration and pavement condition most suitable for the SiWIM system. The SiWIM data had a larger error for 3-axle trucks compared to the 5-axle trucks. This could be due to the fact that the system was calibrated using a 5-axle trucks only.

Generally speaking the SiWIM system can be a useful tool for heavy freight weight enforcement provided the expectations of the users are in line with the accuracy limitations inherent with systems attempting to measure the weight of moving vehicles over multilane bridges and variable pavement conditions. Results consistently demonstrate that SiWim measured weights in the vicinity of 10% to 15% of the actual static weight, but outliers with much higher differences should be expected. It is important to point out that according to the European WIM Specification, this level of accuracy (confidence interval) is not suitable for screening vehicles for weight enforcement operation. Conclusions and recommendations based on this additional SiWIM testing experience follow.

10.1 Conclusions

This research project was challenging in that an important element of the work was to establish a straight forward approach to installation, calibration and in-service use of a SiWIM system for heavy truck freight screening for bridges in the ALDOT inventory. While the methodology of installation and use of the equipment has been successfully accomplished, the accuracy classification of the system based on the variance of the system measurements as compared to the actually static measurements was very disappointing. Clearly the site conditions for a SiWIM installation must be "excellent" as defined by the European Specification for WIM (COST 323) if the SiWIM equipment is to operate with measurements within a confidence interval necessary for an accuracy classification suitable for screening trucks for weight enforcement. Three bridge candidates from the ALDOT inventory were carefully selected for testing, and the SiWIM results were disappointing on all three bridges (this includes testing during this project and testing during UTCA Project #07212). The pavement condition and flexibility of the bridges was a factor in all cases.

Specific conclusions reached by the investigators in this project are summarized as follows:

- A two-lane bridge with two-way traffic would be preferable to a two-lane bridge with one-way traffic (the configuration of the bridge instrumented for this project). The bridge selected for this project had essentially no shoulders (the curbs were less than a foot from the edge of each lane). It was anticipated that the narrow bridge would force trucks to stay in the lane and hence reduce errors due to variations in the transverse position of trucks crossing the instrumented span. However, many trucks were observed to cross partially into the other lane while approaching the bridge, apparently to avoid the nearby curb. Crossing into the other lane would be much less likely on a two-lane bridge with moderate to heavy two-way traffic.
- The Researchers calibrated the SiWIM system with two fully loaded 5-axle trucks with nearly the same gross weight and axle configuration. Based on the recommendations of the prior research, each truck would pass ten times over each lane of the bridge. This approach provides a confidence level of approximately 85% in the accuracy classification calculated for the system, and can be done in a fraction of the time and expense required to establish a 95% confidence level.
- The scatter in the accuracy of the results from the in-service tests revealed that a calibration plan using a combination of trucks that are representative of the actual traffic could provide better results than using only one axle configuration for calibration. However, as noted in UTCA Project 07212,the cost of calibration in terms of equipment, manpower, and time substantially increases when more complex calibration schemes

are employed. Nevertheless, future calibration should strongly consider 5-axle and 3-axle trucks if experience suggests that 3-axle trucks represent a significance portion of the heavy freight weight violators. Calibration can still be accomplished in one day, but the number of truck runs and static weighing events will double. If 3-axle trucks are not a concern (usually the problem is axle weight, not total weight), then users can exclude 3-axle trucks in calibration and not expect the SiWIM weight measurements of 3-axle trucks to be as good as the weight measurements of the types of trucks used for calibration.

- In the SiWIM system, the axle weights of vehicles crossing the bridge are calculated based on the least square method to minimize the difference between the measured bridge response (the total strains of all the girders) and the predicted strain based on calibrated influence lines. It is difficult to separate the bridge response for each vehicle if multi-vehicles are on the bridge at the same time. In addition, the detection of the passing vehicles is based on the detecting sensors (FAD sensors) mounted under the bridge slab These sensors provide data to calculate the vehicle axle configuration and speed. In order to correctly identify the vehicle, the signal of these sensors must be strong enough to be detected. If the traffic flow is complex, meaning that here are more than two heavy vehicles on the bridge at the same time, the bridge deflections due to the combined load results in trivial FAD sensors readings. The readings are below the threshold to be detected owing to the transversal effects of the other heavy vehicles. Consequently, the complexity of the traffic flow directly affects the ability of the SiWIM system to 1) capture vehicles at all, and 2) accurately determine axle weights and total weight. Therefore, based on the present algorithm of the system, it is better to use this system in two lane or one lane bridges with short spans to avoid multiple presences of heavy vehicles.
- The one camera and eight sensor setup configuration is ideal for two lane bridges similar to the one selected for this research work. The single camera reduces power demands on the power supply and the eight sensor configuration permits rapid system analysis and reporting to users of the equipment. The camera is a crucial part of the process, allowing the SiWIM system to provide enforcement officers pictures of a suspected overweight vehicle in sufficient time to identify the vehicle as it passes by so that it can be pulled over for further inspection.
- The versatility of the SiWIM system compared to the BP-WIM system could prove beneficial to ALDOT by saving time and money if the accuracy can be improved. The system would also improve the safety afforded to the installation crew by getting them off the road during installation. The portability of the system is a huge benefit in that the system can be disassembled and relocated in two days under ideal working conditions. This would be useful in the event that a site were to become ineffective due to drivers avoiding the route in which it is located.
- The SiWIM system demonstrated a wide swing in accuracy when the entire population of trucks that crossed the bridge was considered. This experience was also reported in UTCA Project Number 07212 for the two bridges tested in that project. Such performance is not surprising in the sense that similar performance has been experienced by practitioners in Europe for some bridge installations as discussed during the B-WIM symposium in Birmingham in August of 2008. (UTCA Project Number 07212). The quality of the results depends on the excellence of the site conditions and

the bridge configuration. This fact must be recognized by prospective users of the equipment so that expectations are not out of balance with the reality of the system capabilities and the site conditions of selected bridges. Enforcement officials understand the limitation and may adjust what SiWIM estimated weight they will react with (for example 10% overweight as measured by SiWIM).

- According CESTEL, the SiWIM system has been demonstrated to provide very consistent and accurate results in several bridges in Slovenia and Europe (USDOT/FHWA July 2007). However, in the UTCA research the accuracy classification of the SiWIM system was very disappointing ranging between D(20) and E(35). It is important to note in the context of this research that the bridges referenced by CESTEL are short span rigid bridges (bridges with spans less than 10 meters), and in many cases one lane in each direction.
- The accuracy classification performance of the SiWIM system may be attributed to a combination of the traffic flow, road surface condition, bridge span flexibility. The researchers cannot confidently predict comparable performance of a SiWIM system installed on more complex bridge structures than the ones tested in UTCA Projects 07212 and 08204 such as continuous span steel girders or bridges with steel form plates under the decks.
- The temperature also appeared to be a factor in the accuracy. Further study is needed with a wider range of temperatures to determine the extent temperature influences results. If temperature is a significant factor, the system may require supplemental calibration if the equipment is to be utilized at a temperature significantly different from the temperature at calibration.
- The power supply system developed during this research project should adequately address the power continuity problems incurred in prior research so long as the same configuration of cameras and processor usage is maintained. In addition, the cabinet design and suggested locking system should provide vastly improved security from vandals and weather.
- Lessons learned from the work reported here have been of benefit. In March, 2011, ALDOT personnel installed, calibrated, and operated an updated model of the SiWIM system on a shorter span bridge (30-foot simply supported span as compared to the 41-foot simply supported span of the bridge in this study), achieving B(10), C(15), AND B(10) accuracy classification in random truck weighing for gross vehicle weight, group axles, and single axles, respectively.

10.2 Recommendations

The recommendations of the researchers following this research project supplement and reinforce the observations gained during UTCA Project 07212 and are summarized as follows:

- When utilizing the SiWIM system, the system measurement operators and the law enforcement agency involved must have a clear understanding of the range of accuracy of results received from a SiWIM system so that expectations do not exceed the capabilities of the equipment. The range of truck measurements used for the calibration is a good indicator of what to expect.

- Bridges with two lanes or less are recommended for SiWIM applications because they will reduce the number of sensors required and limit to some extent the impact of multiple vehicle presence on the bridge.
- Selection of bridges with no skew will simplify the installation plan.
- Single spans with fixed supports and spans of 10 meters or less will likely provide more consistent results.
- The smoothness of the bridge deck and the entrance ramp must be observed and evaluated prior to installation. Rough entrance ramps and roadway surface clearly add to the dynamic 3-dimensional movement of the trucks on the bridge, and this impacts the sensor signals substantially.
- The round trip distance for calibration trucks should be carefully checked prior to bridge selection. Round trip time of the trucks directly impacts the time and expense of calibration.
- Based on experience from UTCA project #07212, half-load vehicles are difficult to identify and the accuracy of measurements is not helpful in calibration. The reason is that if the bridge is sufficiently rigid, the signal response caused by these vehicles is not the same scale as the fully loaded vehicles and the effects of other "noise" in the data is more pronounced. As the calibrated influence line for the SiWIM system is based on the measured bridge response of the vehicles used for calibration, including readings from half-loaded vehicles will adversely impact the calibration. It is strongly recommend to use fully loaded vehicles during calibration tests, and only expect accurate future measurements to occur when similar vehicle weights and configurations cross the bridge.
- The system should be calibrated using the number of axles of the types of trucks expected to be the greatest over weight offenders. If it turns out that there is a mix of 5-axle and 3-axle trucks, then use both axle configurations during calibration. If the concern is 5 and 6-axle trucks and not 3-axle trucks, then use 5 and 6-axle trucks for calibration.
- At least 10 quality data runs per truck per lane is sufficient for calibration with an 85% confidence level in the system accuracy class.
- Vehicles should be selected for static weighing <u>after</u> crossing the bridge for calibration runs. When this approach is taken, only those trucks successfully captured by the SiWIM system will be stopped and weighed.
- The installation of an automatic Camera on/off switch will preserve power and lengthen the time span the system will gather data.
- The power supply configuration developed during this research should be evaluated before every installation to insure it is adequate for the expected type of service requirements.
- CESTEL service personal should be either present or available for consultation for the first ALDOT installation and any future installations on bridge configurations which are substantially different from those instrumented before. Communications by Skype at the site is possible and recommended.

- Sufficient PDAs should be procured by ALDOT to insure measurement operators, enforcement personnel, and static weigh teams can communicate truck identification and weight information effectively during enforcement activities.
- At a minimum, two SiWIM system operators should be present to monitor the readings and assist Department of Public Safety (DPS) officers in selecting trucks to be pulled from traffic for static weighing. The DPS vehicles and static weighing team will be downstream of the bridge traffic flow sufficiently spaced so that trucks can be identified and pulled from the traffic flow.
- Before the next field installation, a tabletop exercise involving all of the groups expected to participate in the field should be conducted to familiarize/refresh individuals about the sequence of events that will take place.

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