

BRIDGE WEIGH-IN-MOTION DEPLOYMENT
OPPORTUNITIES
IN ALABAMA

by

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A THESIS

Submitted in partial fulfillment of the requirements for the degree
of Master of Science in the Department of Civil,
Environmental and Construction Engineering
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2011

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ABSTRACT

Overweight vehicle enforcement is a continuous problem for all state Departments of Transportation. Various technologies are in use across the US to aid in the enforcement of vehicle weight limits. However, to date, no technology has been shown to be a definitive solution. The various technologies currently available were researched and the pros and cons of each highlighted. Focus was placed on Bridge Weigh-in-Motion (B-WIM) and an extensive literature review has been conducted following all developments in the field of B-WIM since 1979. The advantages of B-WIM include its ease of installation, portability and potential for high accuracy vehicle weight measurements. Accuracy however is site specific, which makes the selection of a bridge an extremely important element in the success of a B-WIM installation.

A bridge selection tool prototype was developed using ArcGIS. The tool was designed to select bridges with the physical characteristics associated with achieving high B-WIM weight measurement accuracies. Daily truck volumes and current Weigh-in-Motion (WIM) sites were also included in the tool to allow for an effective choice of route for installation. As the systems use cellular data signals to transfer data to the weigh crew during the pre selection process, cell service maps were also included in the tool. The prototype showed that such a tool is feasible and should be beneficial for ALDOT.

ALDOT owns two B-WIM systems which it intends to use for overweight vehicle enforcement. An accuracy test of the system was conducted. A bridge in West Alabama was selected for installation. Calibration was conducted and random vehicles were statically weighed

to verify the accuracy of the system. A gross vehicle weight accuracy of B (10) was obtained which is more than sufficient for pre-selection of potentially overweight vehicles.

Alternative sensor locations and orientations were also investigated and signals were compared. It was found that longitudinal axle detectors located close to the bridge supports provided the cleanest and most distinct signals at the test location. Weighing sensors located at the mid-span provided the best signals for weighing trucks.

LIST OF ABBREVIATIONS AND SYMBOLS

AADTT	Average Annual Daily Truck Traffic
ABIMS	Alabama Bridge Information Management System
ABST	Alabama B-WIM Bridge Selection Tool
AD	Axle Detector
ALDOT	Alabama Department of Transportation
ARCHES	Assessment and Rehabilitation of Central European Highway Structures
B-WIM	Bridge Weigh-in-Motion
BIN	Bridge Identification Number
CB	Citizen's Band
COST	Co-operation in the field of Scientific and Technical Research
FAD	Free of Axle Detectors
FAF	Freight Analysis Framework
FCC	Federal Communications Commission
FE	Finite Element
FFT	Fast Fourier Transformation
GVW	Gross Vehicle Weight
HS-WIM	High Speed Weigh-in-Motion
LCPC	Laboratoire Central des Ponts et Chaussees
LS-WIM	Low Speed Weigh-in-Motion
MFI	Moving Force Identification

MS-BWIM	Multiple Sensor Bridge Weigh-in-Motion
MS-WIM	Multiple Sensor Weigh-in-Motion
NOR	Nothing On Road
OECD	Organization for Economic Cooperation and Development
PDA	Personal Digital Assistant
TRL	Transport Research Lab
WAVE	Weighing-in-motion of Axles and Vehicles for Europe
WIM	Weigh in Motion

ACKNOWLEDGEMENTS

First I want to thank my parents, who have supported me wholly my entire life. They have provided me with the opportunity to succeed and have always been extremely encouraging in all my endeavors to date. To them, I owe everything.

I would also like to express my sincere gratitude to Dr. Steven L. Jones who provided me with the opportunity to study and live in Tuscaloosa, Alabama. He has always been at hand to help with any issues, and I have sincerely enjoyed all interactions with him. I admire and respect him greatly and without him this chapter of my life would not have been possible.

Dr. Richardson has also been an extremely helpful and supportive mentor and it has been an honor to work with him on this project for the past year. He has always made himself available to help with any situations and to discuss any matters which have arisen.

I would also like to extend my gratitude to Dr. Lindly and Dr. Weber for agreeing to serve on my committee. Dr. Graettinger has provided valued guidance in relation to using ArcGIS in this project. I also am very appreciative to the entire UTCA and CE staff who lended their assistance in various matters.

I appreciate massively the friendship, support and guidance which I have received from all the graduate students in CE. Special thanks must go to Elsa, Guarav, Kenny, Kenyona, Moses, Menasse, Mohammed and Saravannan.

I would also like to thank ALDOT (Alabama Department of Transportation) and the staff in the Bridge Rating and Loading Department for allowing me the opportunity to work with

them throughout this project. They have always been available to answer questions or to obtain information and without them, this project would not have been possible.

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CHAPTER 1

INTRODUCTION

1.1 Background

Overweight trucks are known to contribute significantly to the degradation of the nation's road infrastructure. A vehicle axle 20% overweight will consume more than twice as much pavement life as the legal load (SDDOT Briefing, 2003). It is believed that \$1 investment into overweight truck enforcement can lead to the avoidance of \$4.50 of pavement damage (Straus & Semmens, 2006). With truck volumes across the US expected to increase significantly in the coming decades it becomes clear that investment into overweight truck enforcement is necessary for State Departments of Transportation. One promising method of enforcement is B-WIM.

B-WIM was first developed in 1979 in the United States by Fred Moses. The motivation behind its development was to overcome the deficiencies which had been identified with pavement-based WIM. WIM systems only receive a signal for a passing axle for milliseconds and so it becomes impossible to account for the dynamic loading fluctuations which a moving vehicle has. B-WIM systems, on the other hand, record a strain signal for a passing truck or axle for the complete time it is in contact with the bridge span. As such, adjustments, mathematical procedures, and specifically developed algorithms can all be implemented to take account of dynamic oscillations and to provide more accurate axle weight calculations. Many transportation authorities wish to utilize WIM technologies for vehicle weight enforcement (Krupa & Kearney,

2009). However, to use it as a direct enforcement tool or as a pre selection tool, a high confidence level in weight estimations is required.

Another drawback of pavement-based WIM systems is the associated installation and maintenance. To safely install such a system or to carry out maintenance, a traffic lane must be closed. A considerable amount of civil engineering work is required to install the system in the pavement. B-WIM systems on the other hand are installed below the bridge deck and can be installed without closing lanes or otherwise interfering with passing traffic. As the system only requires strain gauges to be bolted to the underside of a bridge, a system can easily be removed and installed on another bridge in a short amount of time, allowing authorities to manage a large number of bridges with a much smaller number of B-WIM devices.

1.2 Thesis Objective

This thesis aims to identify the potential of B-WIM as an overweight vehicle enforcement tool for the state of Alabama. An extensive literature review was conducted to identify the benefits, drawbacks and areas of research in the area of B-WIM. With over 19,000 bridges in the ALDOT inventory, it was also intended to develop a tool for use by ALDOT to select bridges with the optimum potential for enforcement using their B-WIM systems.

To have potential as a viable overweight vehicle enforcement tool, B-WIM systems must show that consistently accurate truck weights can be obtained. The installation of the system on a bridge in West Alabama is reported. Alternative sensor locations are investigated, calibration procedures are discussed and accuracies of calibration are presented. Testing of the system on random traffic passings was carried out and the results are discussed.

1.3 Organization

To understand the importance of this work chapter two will review the literature currently available. In chapter three the scope of the project and methodology used will be discussed. Chapter four will present the results from the development of the bridge selection tool. Chapter five will analyze and compare the signals obtained from different sensor locations. Accuracies obtained for calibrations and random vehicle passings will also be presented. B-WIM weights will be compared to static weights. Finally, a summary of the main findings of the report will be presented in chapter six as well as recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

This chapter summarizes much of the published literature in the area of B-WIM with particular attention given to information relevant to its use as an enforcement tool. Upon review of the available literature a number of topics were identified as being predominant in the published materials:

- Early B-WIM systems
- Accuracy Classification
- Axle Detection
- Dynamic Algorithms
- Accuracy

A brief history of weighing of vehicles and details of alternative WIM systems are provided in Section 2.1 before each of the five identified topics is addressed.

2.1 Static Weighing

The weighing of vehicles for enforcement first began in the United Kingdom in 1741 when the Turnpike Act was introduced. This act decreed that tolls were to be paid for using the roads according to the weight of the vehicle. The money raised from these tolls was to be used for the maintenance of the roads, similar to how raised revenue is used today (Sanders, 1960).

Nowadays, three types of static weighing devices are generally used:

- Fixed Systems are permanently mounted to the pavement, either in a concrete frame or platform. All weighbridges and some wheel and axle scales work like this.
- Semi-Portable Systems use permanent grooves and road installations to which portable scales are installed only while weighing operations are being carried out.
- Portable Systems use either wheel or axle scales which are placed on the pavement surface. These can be complimented with leveling plates or ramps to ensure that the wheels being weighed are on the same plane.

Efforts have been made to move away from static weighing methods as they have a number of limitations. Staff and time are required to select and intercept trucks, to perform measurements and to issue fines where appropriate. Increased heavy vehicle traffic on highways and motorways has led to static weighing becoming ineffective and it has been seen to only be a limited deterrent. Static weighing induces delays of between 10 to 30 minutes which results in truck operators who comply with regulations being penalized (Jacob & La Beaumelle, 2010).

2.2 Weigh-In-Motion (WIM)

In an effort to overcome the limitations of static weighing of vehicles, WIM technologies have been developed and a number of types are currently in operation. Each type of system exhibits unique advantages and disadvantages. Pavement based WIM systems use sensors which are embedded in the pavement and lie perpendicular to the direction of traffic. WIM systems operate on the principal that a property measurable by the sensor varies according to the magnitude of an applied load (Quilligan, 2003). The most common types of WIM system shall be briefly outlined.

2.2.1 Low Speed WIM (LS-WIM)

LS-WIM systems use wheel or axle scales mainly equipped with load cells, and are installed into concrete or asphalt platforms which are at least 30-40 m in length. The processing system analyzes the signal from the load cells and takes vehicle speed into account to accurately calculate wheel or axle loads. These systems are generally located outside traffic lanes and in a controlled area such as a weighing area or toll gate. The operating speed range is between 5 and 15 km/h. These systems are very accurate and have been approved legally for enforcement in many US states as well as several European countries. (Jacob & La Beaumelle, 2010)

2.2.2 High Speed WIM (HS-WIM)

High speed WIM systems take readings and calculate axle and wheel weights of vehicles travelling at full highway speed. The main advantages of HS-WIM can be summarized as:

- It is a fully automated weighing system
- It can weigh all vehicle types regardless of speed or axle configuration
- It does not require additional infrastructure; it can be installed on good pavements and road sections (Jacob & La Beaumelle, 2010).

The most common types of HS-WIM are bending plates, load sensors, strip sensors, Multiple Sensor WIM (MS-WIM) and B-WIM. Each type is explained in the following sections.

2.2.2.1 Bending Plate and Load Sensors

These systems use metal plates which have been instrumented with sensors on their underside. Load cell systems can either use hydraulics or strain gauges to obtain measurements (Quilligan, 2003). Typically two of these plates 0.6m x 1.8m (2ft x 6ft) are placed adjacent to each other on a 3.7m (12ft) lane. The measured strain is analyzed and the axle load is calculated (Bushman & Pratt, 1998). The main disadvantage of these plates is their installation

requirements. A large amount of civil engineering work is required and some damage can be caused to the pavement while the installation work is carried out. In some countries this type of WIM is forbidden on motorways and principal highways. For operational and economic reasons, current practice is to avoid the use of these plates in favor of strip sensors (Jacob & La Beaumelle, 2010).

2.2.2.2 *Strip Sensors*

This type of WIM system was introduced in the early 1980's. A typical strip sensor consists of a narrow bar, a strip or wire with a cross section of a few mm² or cm². Strip sensors can be the length of either a traffic lane or half a traffic lane. Unlike plates, where the full tire imprint is on the sensor, these are very narrow and do not measure directly the wheel or axle load. These sensors measure the pressure, strain or force and use an algorithm to calculate the loads with respect to vehicle speed and estimated tire characteristics. Various types of strip sensors are currently in use and these include piezo-ceramic, piezo-quarz, piezo-polymer and fiber optic strips. Strip sensors are cheaper than plates and require less civil engineering work for installation. Despite these advantages, their accuracy is highly dependent on pavement characteristics (especially its modulus), and they cannot be calibrated using standard masses. (Jacob & La Beaumelle, 2010)

2.2.2.3 *Multiple Sensor WIM (MS-WIM)*

The latest WIM technology is Multiple Sensor WIM (MS-WIM). It has been shown in the OECD/DIVINE (Organization for Economic Cooperation and Development) project that the dynamic effect can cause the dynamic load to have a ratio of 1.1-1.15 to the static load on a good pavement and a ratio of 1.2-1.25 on an average or rough pavement (OECD, 1998). It is therefore impossible for any pavement-based WIM system to accurately measure wheel or axle loads. For

enforcement purposes, this level of inaccuracy is intolerable and so the concept of using MS-WIM was suggested by the Transport Research Laboratory (TRL). MS-WIM involves the installation of many sensors along a stretch of roadway (10 to 50m) which allows for multiple measurements of the wheel load. Much research has been conducted to determine the optimal sensor spacing, as a sample frequency (in space) close to the signal frequency must be avoided. One recognized issue with MS-WIM is the fact that the individual sensor accuracy for axle force measurement and calibration is best established using true axle dynamic loads rather than static loads. The accuracy of these systems depends upon the number and quality of sensors, the algorithm being used and the pavement condition (Jacob & La Beaumelle, 2010).

2.3 Early B-WIM Systems

B-WIM systems are based on the measurement of strain as a vehicle crosses a bridge structure. Strain measuring devices are attached to the bridge soffit while axle detectors record the vehicle speed and axle configuration. The recorded strains and the information provided by the axle detectors are fed into an algorithm which calculates axle and gross vehicle weights. The algorithm works by comparing measured responses against a theoretical model. B-WIM systems are the only WIM system able to achieve an uninterrupted record of a vehicle crossing and as such, efforts can be made to account for dynamic effects (Quilligan, 2003). The majority, if not all, of the system is installed below the bridge which makes installation and maintenance easier than WIM systems.

Fred Moses published the first account of using bridge response to measure vehicle weights in 1979 (Moses, 1979). One of the chief motivations for instrumenting a bridge was to overcome the dynamic effects which Moses claimed can cause 30-40% errors in predicted weights using pavement scales. A typical scale measures load for only several milliseconds.

Moses felt that by instrumenting bridge girders that the dynamic oscillations in tire contact force would be greatly reduced by the large inertia of the bridge and by utilizing a statistical smoothing algorithm. The system would also be hidden from drivers by being predominantly below the bridge and would also be inexpensive and deployable at other bridge sites. The system developed by Moses has several components:

- Button Box – An operator was located approximately 30.48m (100ft) before the bridge with a button box. When a truck is seen, the operator presses the button which alerts the system of a truck arrival.
- Tape Switches – Two tape switches were located, parallel in one lane, a precise distance from each other and were used to determine axle spacing and velocity. A third tape switch was located immediately before the bridge and this was used to tell the system to begin taking strain readings for a set amount of time. This time was based on the lowest expected velocity of a truck crossing the bridge. A tape switch consists of two metallic strips which are held out of contact. As a tire passes over the switch the metallic strips are forced into contact and a signal is obtained at that instant at which the axle crosses the switch.
- Strain Transducers – Strain gauges were placed on the bottom flange of each girder along a line normal to the direction of the bridge. The mid-span was suggested as being the most suitable location. The strain record for each gauge was recorded separately on magnetic tape. The signals were summed in the processing program after collection so that malfunctioning gauges could be disregarded.

- Instrument Van – The signals from the traffic detectors and strain transducers were sent to a van which was located beneath the bridge to avoid detection from passing vehicles. The traffic signals, which were already in digital form, went directly into the computer while the strain signals were sent to the signal conditioners. The output signals were then sent to the analog-digital converter of a minicomputer system for recording on magnetic tape.

Each individual girder stress is related to girder moment from the relationship:

$$\sigma_i = \frac{M_i}{S_i} \quad (1)$$

Where:

$i = 1 \dots G$ (number of girders),
 σ_i = the stress in the i^{th} girder
 M_i = the bending moment in the i^{th} girder,
 S_i = the section modulus

The moment can be expressed in terms of strain as:

$$M_i = S_i \sigma_i = E S_i \epsilon_i \quad (2)$$

Where:

E = the modulus of elasticity of the bridge material,
 ϵ_i = the strain in the i^{th} girder.

The gross bending moment is then obtained by summing the individual girder moments,

M , and taking E and S_i as constants:

$$M = \sum_i^G M_i = \sum_i^G E S_i \epsilon_i = E S \sum_i^G \epsilon_i \quad (3)$$

It can therefore be seen that the sum of girder strains is proportional to the gross bending moment.

Weigh in motion is an inverse type problem, as the structural response is recorded and the load causing that response must be calculated. The number of unknowns for each vehicle is equal to the number of axles, N , of that vehicle. These unknowns are determined from N different bending moments (strains) recorded for N different positions of the truck along the bridge. As data is recorded for the entire passage of the truck crossing, there is a large number of separate weighings and the results can be averaged to reduce any errors. Moses developed an algorithm to calculate axle weights. The theoretical bending moment is given by the following expression:

$$M(t_k) = \sum_{i=1}^N A_i I_i(t_k) \quad (4)$$

Where:

N = the number of axles,

A_i = the weight of axle i

$I_i(t_k)$ = the gross bending moment influence line at gage location for i^{th} axle at time t_k .

Figure 2.1 compares the dynamic response of the bridge to the static response. The dynamic bridge response can be filtered out by defining an error function, E , which is the difference between the measured response and the predicted response:

$$E = \sum_{k=1}^T [M(t_k) - M^*(t_k)]^2 \quad (5)$$

Where:

$M^*(t_k)$ = the measured response,

T = the number of time increments used in the smoothing process.

The influence line of the bridge must either be calculated by indeterminate structural analysis or by using a calibration truck of known static axle weights.

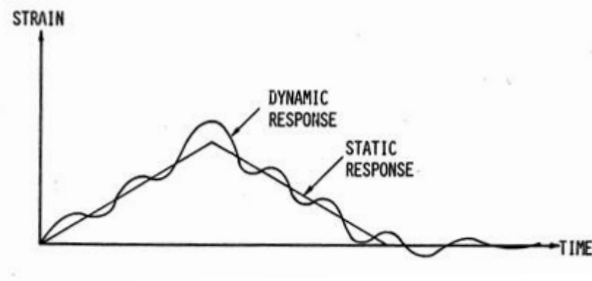


Figure 2.1 Dynamic vs. static response (from Moses 1979)

As shown above, the equations to solve for axle weight use bending moments, which are linearly related to strains. The elastic and section modulus can be calculated from the section drawings and material properties. In this study however, these values were not required as a calibration vehicle of known axle weight was used.

Moses suggests that single short spans (under 18.3m (60ft)) were most suitable to predict individual axle weights while a larger span (over 24.4m (80ft)) was more appropriate for determining gross weight.

A three span, continuous beam and slab bridge was used for testing Moses' system. Only the first span of the bridge was instrumented. The calibration tractor-trailer vehicle passed over the bridge 13 times and it was found that the coefficient of variation of the prediction was 5%. The coefficient of variation for the rear tandem weights was found to be 10.1%. Weighing of random vehicles was also conducted in conjunction with a static weighing station located 40 miles downstream from the bridge. As a result of this long distance between them only 20 vehicles were positively identified as having crossed the bridge and weighed at the station.

Moses concluded that a system which predicts axle and gross weights had been developed and results from tests had shown that truck weight predictions were feasible. The calibration crossings showed that the output was repeatable and the results from the small

number of direct truck comparisons were quite promising. The accurate calculation of velocity and axle spacing was already known to be extremely important in accurate weight predictions but the least squares procedure in the processing program was somewhat forgivable for truck dimension errors if they were not too large. Moses points out that the greatest potential for extending the system towards wide-scale implementation was to design a self-contained, stand alone system which can be easily transported, installed and processed. Although a single span bridge with no skew is suggested as most suitable, Moses predicted that any bridge, including concrete slab, prestressed beam, truss, skewed girder etc. would satisfy as weigh in motion spans. It is noted however that problems such as gauge attachments and the influence of lateral positioning of trucks on skewed or long span bridges would arise and that future work would be necessary to determine which bridge types would most effectively serve as weigh in motion spans.

The next major development in B-WIM came in 1984 from Australia when R.J. Peters developed the AXWAY system. Peters (1984) proposed to weigh axles and gross weights of passing trucks using an instrumented bridge. Electrical resistance strain gauges were bonded to the deck reinforcement of Maddington Bridge on the Beechboro Gosnells Highway in 1980 while it was being built. As predicted, the strain readings from the gauges were too small to be consistently measured, and so the first mechanical strain amplifier (MSA) was developed. This MSA gave amplification of between four and ten times actual strain. It is noted by Peters that the development of axle detectors was one of the most difficult problems in the implementation of AXWAY. The author stated that they must be reliable, waterproof and durable. Air hoses were found to give good speed measurements but were poor at counting axles, often overestimating the number of axles a truck had. Photo-electric cells, where a beam of light is directed across the

road just above the surface, were found not to provide encouraging results. A third system using burglar alarm mats was found to be 95% accurate which was satisfactory for the AXWAY system. Calibration of the system was conducted using a test vehicle to traverse the bridge several times in each lane. Calibration factors for the particular site were determined during post processing. The raw strain response was smoothed using an algorithm which took into account that the dominant vibration is that of the natural frequency on the bridge. The post processor program calculated all axle weights on an individual basis but outputted tandems and triples as having equal axle weights as it is unrealistic to distinguish between loads at close spacing.

The gross weight of a vehicle is proportional to the area under its influence line. A weight correction factor was applied to the calculated area below the curve to determine the gross weight. To calculate the axle weights, the strain response was smoothed, and the time base of the recording was converted to a length base by removing the speed component. The vehicles gross weight was equally apportioned to each of the axles and an iteration process began whereby:

- An expected response curve was generated using the most recent axle weight estimates and the unit influence line.
- This was then compared to the smoothed line.
- The biggest difference between the two lines was found and the axle most likely causing this difference was located (nearest axle). The axles weight was either increased or decreased in accordance with the magnitude of the misfit and the other axle weights were readjusted to maintain correct gross vehicle weight.
- This process was repeated until stability had been reached.

Features of the AXWAY system included the ability to weigh up to 500 trucks per hour using only one or two operators. The system was inexpensive and data could easily be stored for

post processing. It was noted that the system could only deal with a single vehicle present on the bridge at any one time. Gross vehicle weights were found to be within 3% while axle group weights were within 10%. The exact experiment setup has not been detailed by the author. The preferable bridge type for AXWAY was a single span, with one or two lanes and with a smooth road surface prior to and on the bridge in order to reduce vibration amplitudes. Peters proposes that future work on the system would include the real time processing of gross vehicle weights (this was not achievable with the computational power being used), having an unmanned operation and implementing alternative solution algorithms such as matrix solution technique as used by Moses and Ghosn, 1981 (Peters, 1984).

As AXWAY was a manned system it was expensive to collect large volumes of data with it. Peters tried to overcome this issue and in doing so he developed a new unmanned system CULWAY (1986) which he described as a 'low cost/low power single lane system for unattended operation'. CULWAY weighed an axle of a vehicle as it crossed over a culvert. Dynamic effects and vibration, which are a major source of error when using bridges for WIM purposes, are virtually non-existent with culverts as the soil between the culvert and the pavement acts like a cushion and damps out the vibration. Also, unlike bridges, there is no joint between the culvert and the road which helps to reduce dynamic loading. Two tape switch axle detectors were placed on the road surface. The first was placed 9.8m before the center of the culvert span while the second was placed 0.2m past the center. These were then used to determine the vehicle speed, the axle spacing and to tell the system to begin taking strain measurements. Mechanical strain amplifiers were attached to the roof of the culvert.

The first trials took place in July 1984 and the strains plotted were both substantial and free of the vibrational problems found on bridges. The culvert used had a continuous lid over the

two cells of the culvert which caused the instrumented cell to go into negative bending when the uninstrumented cell was loaded. This meant that this type of culvert would be unsuitable for CULWAY. The next two installations were unsuccessful as both had over 2m of fill which meant that the strain signals were very weak. The first trials with test trucks took place on a culvert with a span of 2.4m. This trial achieved good results although some issues arose. The road surface on the approach to the culvert was uneven. Settlement had taken place as the culvert had been constructed after the road. The 2.4m span also meant that the measured strain value for one axle of a tandem or triaxle was not independent. From these trials the following criteria were set for the selection of suitable culverts: Should be single span of less than 2.7m, should have a good road surface, should have no skew, soil cover should be between 200mm and 1500mm.

The test site for the CULWAY prototype was located on the Albany Highway, 94km south of Perth as shown in Figure 2.2. A micro processor data logger was programmed to work unattended. The microprocessor was only capable of capturing data which then had to be processed later on a personal computer. When a non-linearity was found, a function was derived to correct for the misfit between the measured and actual tonnages of the axles. The overlapping influence of axles occurred when the culverts effective span was more than twice the axle spacing and this often occurred for tandem or triaxles. Without a correction these axles would be overweighed, especially the middle of a triaxle group. The CULWAY system required calibration using trucks of known weight. Although it is recommended that random trucks from the traffic stream are used and are statically weighed, the use of at least one articulated, tandem drive vehicle with a triaxle semi-trailer of known static weight can also suffice. An accuracy of $\pm 10\%$ was obtained on a sample of 1,296 trucks. (Peters, 1986)

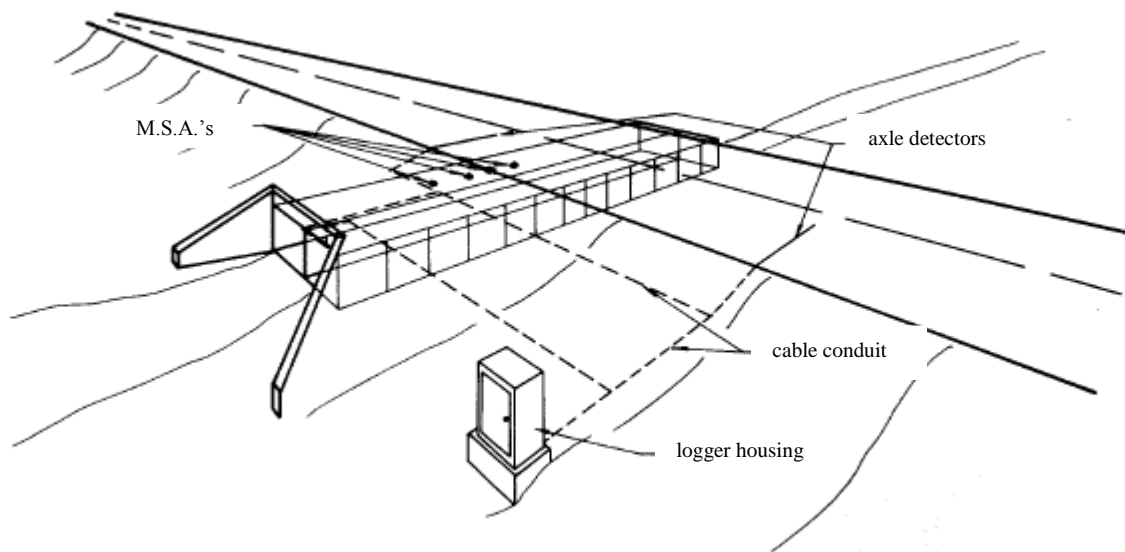


Figure 2.2 CULWAY setup on the Albany Highway (From Peters, 2006)

2.4 European Research Programs

Outside of Australia, there was little interest in or development of B-WIM until the late 1990's. This interest came in the form of the COST 323 (1999) program. COST is an intergovernmental framework for European Co-operation in the field of Scientific and Technical Research. It was the first European co-operative action on weigh-in-motion of road vehicles and it resulted in a specification of WIM systems, two conferences and some large scale tests of B-WIM systems (Jacob, 1998).

As well as COST 323, the WAVE (Weighing-in-motion of Axles and Vehicles for Europe) (2001) program resulted in extensive research into WIM. WAVE was a research and development project of the fourth Framework Programme (Transport). The project succeeded in improving B-WIM by developing improved multi-sensor and Bridge WIM systems. These programs will be referenced extensively in the following sections.

Major efforts have taken place since the commencement of the COST 323 program to improve the accuracy, reliability and usability of B-WIM systems. The following sections shall look at the research that has occurred and how that research has helped improve B-WIM accuracy.

2.5 Accuracy Classification

To clarify the real levels of accuracy and performance of various WIM systems throughout Europe, a common European WIM Specification was developed. This task was one of the main priorities of the COST 323 action on WIM of road vehicles. The first two years of its development involved analyzing existing and emerging specifications and other technical documents. After discussions with European manufacturers and users' representatives, a revised draft of the specifications was published in June 1997. The appendix of the specification provides a set of rules for categorizing the accuracy of a WIM system based on a statistical comparison between the WIM-determined weights and the corresponding static-scale-determined axle weights. A good explanation of factors affecting WIM site accuracy and an example accuracy classification using real WIM data are provided by Jacob, O'Brien and Newton, (2000).

Six accuracy classes are defined (see Table 2.1): A(5), B+(7), B(10), C(15), D+(20), D(25) and E (COST 323, 1999). The last class can be split further: E(35), E(40) etc. The numbers in brackets represent the allowable errors or tolerances (in %) in the WIM-measured weights when compared to static weights. There are also specified error limits (δ) for the weights of single axles, the weights of an axle group, and the vehicle gross weight. If the same data is used for calibration and for calculation of the accuracy class, then the tolerances should be multiplied by 0.8.

Table 2.1 Tolerances (δ in %) for each accuracy class. (after Jacob et al, 2000)

Type of Measurement	Domain of use	Accuracy Classes:					
		Confidence interval width δ (%)					
		A(5)	B+(7)	B(10)	C(15)	D(25)	E
1. Gross Weight	Gross weight >3.5 t	5	7	10	15	25	>25
Axle Load:	Axle load > 1 t						
2. Group of axles		7	10	13	18	28	>28
3. Single axle		8	11	15	20	30	>30
4. Axle of a group		10	15	20	25	35	>35

Classes A(5) and B+(7), are recommended for legal purposes such as overload enforcement; classes B(10) and C(15) are recommended for overload pre-selection and detailed traffic analysis, and classes D+(20) and D(25) are mainly used for economic and technical studies and general traffic evaluation. Accuracy is defined for the GVW, single axles and group axles of a vehicle. Group axles include tandem and triaxle configurations. In determining the overall accuracy of an installation, the lowest accuracy from GVW, single and group axles is retained.

For a given accuracy class, there must be an acceptable level of confidence that WIM weights will be within a specified tolerance of the reference (static) values. Minimum acceptable levels of confidence are defined which depend on the number of vehicles in the data set, on the variability of the test (variability of the truck speed, lateral position and axle configuration), and on the variability of the environmental conditions (principally temperature). Four sets of test conditions are defined in Table 2.2, shown in order of increasing variability. Three sets of environmental conditions are shown in Table 2.3, also shown in order of increasing variability.

Table 2.2 Test condition sets (after Jacob et al, 2000)

Test Conditions	Description
r1. Full Repeatability	One vehicle passes several times at the same speed, load and lateral position.
r2. Extended Repeatability	One vehicle passes several times at different speeds and with small variations in lateral position (in accordance with typical traffic).
R1.Limited Reproducibility	A small set of vehicles (usually 2 to 10), representative in weight and silhouette of typical traffic is used. Each vehicle passes several times, at different combinations of speed and load and with small variations of lateral position.
R2. Full Reproducibility	A large sample of vehicles (some tens to a few hundred), taken from the traffic flow and representative of it, is used for the calibration.

Table 2.3 Environmental condition sets (after Jacob et al, 2000)

Environmental Conditions	Description
I. Environmental Repeatability	The test time period is limited to a couple of hours within a day or spread over a few consecutive days, such that the temperature, climatic and environmental conditions do not vary significantly during the measurements.
II. Limited Environmental Reproducibility	The test time period extends at least over a full week or several days spread over a year, such that the temperature, climatic and environmental conditions vary during the measurements but no seasonal effect has to be considered.
III. Full Environmental Reproducibility	The test time period extends over a whole year or more, or at least over several days spread over a year, such that the temperature, climatic and environmental conditions vary during the measurements and all the site seasonal conditions are encountered.

The minimum acceptable levels of confidence that the WIM weights will be within a specified tolerance (from Table 2.1) for Environmental Condition set I: Environmental

Repeatability are shown in Table 2.4. Note that for a given number of trucks, the minimum acceptable levels of confidence decrease as the variability of the test conditions increase. Tables 2.5 and 2.6 show the minimum acceptable levels of confidence for the other two environmental condition sets.

Table 2.4 Minimum acceptable levels of confidence under *Environmental Repeatability (I)* (after Jacob et al, 2000)

Calibration Conditions	Number of						
	Calibration Trucks:	10	20	30	60	120	∞
r1. Full Repeatability		95	97.2	97.9	98.4	98.7	99
r2. Extended Repeatability		90	94.1	95.3	96.4	97.1	98
R1. Limited Reproducibility		85	90.8	92.5	94.2	95.2	97
R2. Full Reproducibility		80	87.4	89.6	91.8	93.1	95

Table 2.5 Minimum acceptable levels of confidence under *Limited Environmental Reproducibility (II)* (after Jacob et al, 2000)

Calibration Conditions	Number of						
	Calibration Trucks:	10	20	30	60	120	∞
r1. Full Repeatability		93	96.2	97	97.8	98.2	99
r2. Extended Repeatability		88	92.5	93.9	95.3	96.1	98
R1. Limited Reproducibility		82	88.7	90.7	92.7	93.9	96
R2. Full Reproducibility		77	84.9	87.4	90	91.5	94

Table 2.6 Minimum acceptable levels of confidence under *Full Environmental Reproducibility (III)* (after Jacob et al, 2000)

Calibration Conditions	Number of						
	Calibration Trucks:	10	20	30	60	120	∞
r1. Full Repeatability		91	95	96	97	97.6	99
r2. Extended Repeatability		85	90.7	92.4	94.1	95.1	97
R1. Limited Reproducibility		79	86.4	88.7	91.1	92.5	95
R2. Full Reproducibility		73	82.3	85.1	88.1	89.8	93

Test condition R1. Limited Reproducibility is recommended for WIM site calibration. Because calibration is typically completed in a single day, environmental condition I. Environmental Repeatability usually applies. Environmental condition II. Limited Environmental Reproducibility typically applies for in-service weighing of trucks from the traffic stream. Collecting WIM data for a year or more without recalibration is not recommended.

2.6 Axle Detection

Axle detection provides information such as vehicle class, velocity, number of axles and axle spacing. It was recognized by Moses (1979) that accurate velocity and axle spacing calculations were extremely important in accurate weight predictions. Peters (1984) noted that the development of axle detectors was one of the most difficult problems in the implementation of AXWAY. More recently, Znidaric et al (1999) also alluded to the importance of axle detectors by listing the assessment of vehicle velocity as one of the most important factors in achieving high accuracy. In the first B-WIM system developed, Moses used two parallel tape switches for axle detection. Peters (1984, 1986) investigated a variety of axle detection methods. Air hoses were found to be poor at counting axles and a photoelectric cell which passed a beam of light across the road was found not to provide adequate results. For AXWAY, a burglar alarm mat

was found to provide the most accurate results but by the time CULWAY was developed Peters had settled upon the use of tape switches which he placed in parallel 10m apart.

In 1995 an American B-WIM system based on Moses' algorithm and an Irish prototype system based on a method described by Dempsey were compared. The American system used tape switches for axle detection while the Irish system used pneumatic tubes placed before and after the bridge. During the comparison study in Slovenia, axle detector durability was a major issue and the tape switches were found to fail during heavy rain events. The pneumatic tubes which were fixed using an asphalt based tape gave accurate results and were significantly more durable and reliable than the tape switches (O' Brien et al 1999).

Installation and maintenance of axle detectors can cause considerable traffic delays (Kalin et al, 2006) The durability of 'on the road' axle detectors is also an issue as they are the only part of the B-WIM system in direct contact with traffic. They are also the only piece of B-WIM hardware viewable by the traffic being weighed. To overcome these issues focus was put on the development of Free of Axle Detectors (FAD) or Nothing on the Road (NOR) detectors. One of the principal objectives of the WAVE project was the extension of B-WIM algorithms to new kinds of bridge types. As part of this objective an orthotropic steel bridge deck in France was instrumented by LCPC (Laboratoire Central des Ponts et Chaussees). The pavement of the bridge was quite thin and so to ensure the waterproofing of the deck was maintained no axle detectors were allowed on the bridge deck. To overcome this issue, the idea of FAD B-WIM system was investigated (WAVE, 2001).

A new algorithm was developed which attempted to calculate truck velocity and axle spacing directly from strain data. A three span bridge was instrumented at two longitudinal locations. The first method tested was a modified version of Moses' original algorithm. As each

axle passed over an instrumented span a peak strain occurred. Velocity was calculated by taking the time between the peak strains at one section to the peak strain at the second section, as the distance between the two is known. An average of the velocity of all axles of the vehicle was determined. This method was found to produce errors of up to 20% and sometimes the strain gauges only provided one peak for a tandem/tridem.

A second, more robust algorithm was developed. Instead of optimizing the objective function to just find axle weights, it was minimized to find axle weights, axle spacing, truck velocity and a reference position. The optimization procedure does not find the number of axles as this is a discrete variable, and discrete variables cannot generally be dealt with by optimization techniques. The procedure found a number of minima but if there was a good initial estimate of velocity then the probability of finding the correct minimum was greatly increased. A one-dimensional optimization routine was used to calculate velocity within $\pm 5\%$. The only parameter not determined by the optimization routine was the number of axles. As a truck passed over the bridge, six objective functions were minimized (2-, 3-, 4-, 5-, 6- and 7-axles functions) and the number of axles determined by the minimization which gave the smallest value. This method was computationally demanding in real time so an alternative was devised whereby only one objective function (7-axle truck) was used to determine the parameters for all truck configurations. This method was based on the fact that some of the axle spacing and weights would tend to zero if it was not a 7-axle truck. This was tested and found to be work effectively (Dempsey et al, 1998a).

Orthotropic bridges were shown to be suitable for FAD and this is largely due to the fact that their thin decks provide definitive peak strains. Kalin et al (2006) state that not all bridges are suitable for NOR installations. On longer bridges, the measured strain signal can represent

the contributions of several axles which are on the bridge at the same time, and this makes it more difficult to identify individual axles. It is suggested that ideal NOR bridges be either short or have secondary elements that divide the main span into shorter ‘sub-spans’ such as cross beams or cross stiffeners. Thicker superstructures smear the individual peaks in the signal making it difficult to identify axles.

Although orthotropic bridges were shown to be suitable, they are scarce and so slab bridges were instrumented. Encouraging results were obtained from these installations (Znidaric et al, 2002), but a more robust algorithm which would work on most “real-life” structures was necessary. Strain signals from four bridge types were examined after the crossing of a fully loaded 5-axle truck. A thin long bridge (See example A in Figure 2.3) had high vehicle-bridge interaction dynamics which resulted in some additional peaks in the signal. A 6m long integral bridge (example B) had very little dynamics but peaks from individual axles in a group were smeared making them harder to identify. The orthotropic bridge (example C), as already identified by WAVE, proved itself as suitable for NOR installations. The sharpest individual peaks however were obtained from a 30.5m simply supported beam-deck bridge (example D).

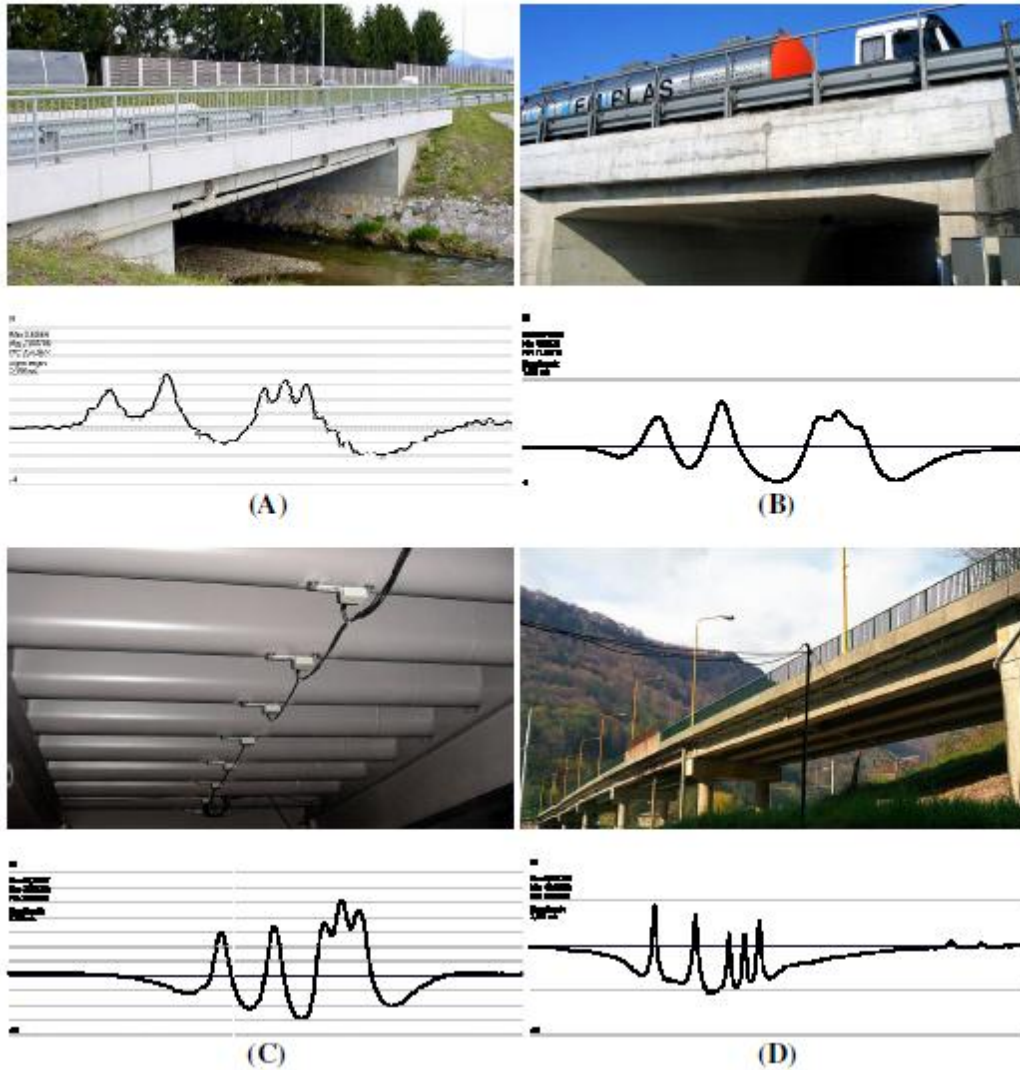


Figure 2.3 Four bridge types tested with NOR axle detection (From Kalin et al, 2006)

In general the middle axle of a tridem generated the highest response owing to the fact that it was a partial summation of the signals from the first and last axles of the tridem. The first step in developing a NOR algorithm was to determine the vehicle velocity. The WAVE project proposed to calculate it from the time difference of peaks in the strain signal, which gave satisfactory results on “ideal” bridges. A more robust method, whereby a correlation function is calculated with the help of a Fast Fourier Transform, was developed for the new algorithm. The

signal is filtered twice with a low-pass filter to account for bridge dynamics. The first filter (filter length 1.3m) discards all dynamics and axles, while the second filter (filter length 0.6m) discards dynamics and keeps axles. The filtered signals are subtracted from each other and the difference is searched for peaks. From then on, the SiWIM system proceeds as though axles were identified with axle detectors.

The efficiency of the new NOR algorithm was examined using the bridges from examples B and D (Figure 2.3). For the thick slab bridge (example B) the algorithm identified the correct number of axles for 90% of the 202 heavy vehicles recorded, but the axle spacing varied by up to 15cm resulting in 19 of the 182 vehicles being wrongly classified. On the beam-deck bridge (example D), the algorithm only missed one axle from 261 vehicles, and this belonged to a light trailer. The paper concluded that the NOR algorithm developed produced far more accurate results than would be expected from the NOR method proposed in WAVE (Kalin et al. 2006).

As the less pronounced strain signals from thicker bridge deck structures make it difficult to detect axles, Chatterjee et al. (2006) investigated a mathematical approach to extract information from them. A wavelet analytical technique has recently emerged as a powerful mathematical tool to extract information from strain signals and this was utilized on strain signals received from a numerical model and from measurements taken at Ravbarkomanda Bridge in Slovenia. NOR signals are non-stationary in nature and the wavelet based analysis has proven its efficacy in solving problems of this nature and is the most recent solution in overcoming the shortcomings of the Fourier transform.

Strain signals for 21 vehicle passes on the Ravbarkomanda Bridge were analyzed using the wavelet analysis with the primary purpose to identify axles correctly on a time scale and so to

determine the vehicle velocity and axle spacing. The first five vehicle passes were arbitrarily used for calibration. An example of a signal before and after the regularization procedure is presented in Figure 2.4. Out of 47 axle spacing used for testing, five had errors in excess of 0.2m. Given that tire contact surface on a road is 0.3m, this was considered as a good result for 90% of vehicles. The strain signal for the vehicle with the greatest error was examined. The error, the axle spacing from second to third, can be clearly read from the original signal before transformation occurs. Therefore it was concluded that the errors were derived from inaccuracies in measurements on site as opposed to the wavelet transformation.

The wavelet approach (using `rbio2.4`) has been shown to be highly effective at identifying the presence of an axle and in all cases it transforms the signal into one in which axles can be clearly identified. (Chatterjee et al, 2006)

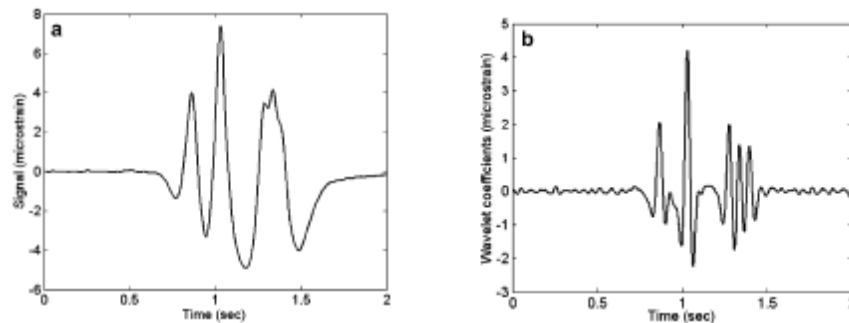


Figure 2.4 Strain signal before and after the regularization procedure (From Chaterjee et al, 2006)

Great progress has been made in the last decade in the area of axle detection. Permanent axle detectors fixed to the road surface, which have installation and durability issues, have been replaced with FAD or NOR B-WIM systems. Algorithms have been developed to increase the accuracy of these systems in determining important parameters such as vehicle velocity, number of axles and axle spacing. The future of B-WIM systems lies with FAD and it is probable that

much of the research in the coming years will work to improve these types of installations further.

2.7 Development of New Algorithms

As previously stated, Moses was the pioneer in B-WIM research and developed the static algorithm which remains the basis for B-WIM systems today. However, a number of inadequacies were identified with the original algorithm and, as such, much work has taken place to either modify Moses' original algorithm or to develop new and innovative algorithms. The various researches in this area shall be discussed herein.

2.7.1 *Dynamic Algorithm*

The dynamic effects of a truck passing over a bridge were identified early by researchers as a major source of inaccuracy. As such, continuous efforts have been made to firstly quantify these effects and to secondly account for them in the calculation of axle weights. After a detailed study conducted in the OECD/DEVINE project it was shown that on an average pavement surface that the ratio between dynamic load and static load can reach 1.25 (Jacob & La Beaumelle, 2010). Throughout the 1990's and continuing into the 21st century many innovative approaches have been developed and tested to take account of these dynamic effects and to ultimately produce an algorithm to accurately calculates axle weights. These attempts will now be discussed.

Moses' (1979) original algorithm did not take dynamics into account in an adequate manner. Dempsey et al (1998b) developed an iterative dynamic bridge algorithm which dealt with the issue of bridge vibration. The accuracy was considerably improved with the use of this algorithm. Unlike previous approaches, where weights are calculated by comparing strain measurements to corresponding theoretical values, the dynamic algorithm developed by

Dempsey et al utilizes the frequency components of the strain signal and requires no prior knowledge of the influence line. The frequency domain representation of the signal also allowed the suppression of high frequency events and reduced errors caused by speed measurement.

Gonzalez and O'Brien (1998) investigated the effect of different parameters on the accuracy of a dynamic algorithm which they developed based on a frequency spectrum approach. The frequency components of the strain signal were utilized and no prior knowledge of the influence line was required. The dynamic algorithm was found to be less sensitive to road conditions. For average road conditions the static algorithm had a maximum error in axle weight of 2.75% compared to 1.47% with the dynamic algorithm. It was also found to be less sensitive to lowering of the bridges natural frequencies and was found to be as accurate as the static with the advantages of not requiring a previous knowledge of the influence line. The dynamic algorithm is also less sensitive to errors in speed measurement which could make it ideal for FAD systems (Gonzalez & O' Brien, 1998).

2.7.2 Regularized B-WIM Algorithm

Rowley et al. (2008) suggest that Moses' algorithm can be bettered by implementing a regularization procedure. Moses' algorithm is described as being ill-conditioned which means that small changes in the input values can cause very large fluctuations in the solution. Using the mathematical tool of regularization, Rowley et al. state that it is possible to obtain accurate solutions to ill conditioned problems. The method of regularization is often referred to as Tikhonov regularization and was developed by Tikhonov and Arsenin (1977). A regularizing parameter, λ , is incorporated into the B-WIM algorithm. λ is found by using the L-Curve method, which involves plotting the discrete smoothing norm of the regularized solution versus

the residual norm of the error on a log-log scale. This plot will have a corner with maximum curvature that will provide the optimal regularization parameter λ_{opt} (Rowley et al, 2009a).

A Moving Force Identification (MFI) algorithm was developed by Rowley et al and is an extension of the one dimensional algorithm by Law and Fang to two dimensions. The MFI algorithm required a finite element (FE) mathematical model which accurately represents the static and dynamic behavior of the bridge. The regularization procedure described is implemented to provide a bound to the error and smoother solutions to the MFI problem which is ill-conditioned.

Testing of the algorithm was carried out as part of the European 6th Framework Project ARCHES (Assessment and Rehabilitation of Central European Highway Structures). The Vranksko Bridge, with a span of 26m, is situated in Slovenia and consists of five concrete longitudinal beams and two diaphragm beams in the transverse direction over the supports. Data was collected using the SiWIM system. By summing the identified forces in the middle 60% of the time history for each axle and averaging the result, the accuracy of the algorithm could be assessed. The maximum error in GVW was 3.8% while the maximum error for axles two and three was 6.9%. However for one truck passing event, the error for the first axle was 17% while the GVW error was only 0.3%. It was reasoned that this is likely due to an error in the calculated vehicle velocity. It is concluded that while MFI is computationally demanding, it is feasible for on-site application and it allows information to be collected on the frequency and amplitude of dynamic forces (Rowley et al 2009).

2.7.3 *Influence Line*

The influence line of a bridge depicts the bridges static behavior to a point load moving across its span. All B-WIM systems require the use of a bridge's influence line to estimate gross

vehicle and axle weights. With regards to B-WIM, the influence line can be defined as the bending moment at the point of measurement (Quilligan, 2003). The derived influence line must closely resemble the bridge's actual influence lines for accurate weight estimations to be made. Znidaric and Baumgartner (1998) conducted a study into the importance of choosing an influence line which is close to the true influence line. The true influence line lies between the ideal simply supported and completely fixed conditions. The effects of influence line were compared for a short span (2m) and a longer span (32m). For the very short bridge, the errors were found to be below 10% for GVW and axle weights. However, when the influence lines were applied to the longer span, errors greater than 200% were observed. Although the GVW was still within acceptable limits, the axle weights had been severely redistributed. The study concluded that the greater the difference in areas below the corresponding influence lines, the higher the error in results (Znidaric and Baumgartner, 1998).

Influence lines can be readily found by analysis but the results often do not match measurements on site. As such it is often useful to derive the influence line from direct measurements using a vehicle of known weight. O' Brien et al (2006) describe a method to derive an influence line from the measured multi wheel response of a vehicle. The method described is tested on two bridges in Sweden. A three-axle pre-weighed truck was used for the 10.5m span Ostermalms IP Bridge. The matrixes for calculating the influence line were of the order of 1500-2000. The predicted strain from the derived influence line and the measured response were shown to be an excellent match. A seven-axle calibration truck was used to find the influence line for the 14m span of the Kramfors Bridge. Strain data was collected using the SiWIM system. Once again the predicted response compares very well to the measured response. Some small differences were observed and the authors suggest that the increased number of axles

were the most probable cause. In conclusion, the matrix equation presented for the calculation of influence ordinates for a bridge was shown to be very effective, especially for two- and three-axle calibration trucks (O' Brien et al 2006).

Quilligan et al (2002) conducted tests to develop a 2-D influence surface and multi-vehicle algorithm. This test consisted of 27 single vehicle and 5 multi-vehicle events using 2-axle and 3-axle trucks. Theoretically derived influence lines are unsuitable for B-WIM due to a number of factors, including pavement flexibility, soil-structure interaction, ageing of materials and unknown boundary conditions. Moses (1979) devised an objective function which minimized the squares of the differences between measured and theoretical strain records, denoted M^M and M^T respectively as:

$$Obj = \sum_{k=1}^K [M_k^M(x_k) - M_k^T(x_k)]^2 \quad (6)$$

$$= \sum_{k=1}^K \left[M_k^M(x_k) - \sum_{i=1}^N A_i I(x_k) \right]^2 \quad (7)$$

Where:

- k = scan number
- x_k = the location of the first axle
- K = the number of scans
- N = the number of axles
- A_1, \dots, A_N = the vehicle axle weights
- L_1, \dots, L_{N-1} = the axle distances
- $I(x_k)$ = the influence line ordinate at location x_k

For a two axle truck, for example, this can be expanded to:

$$Obj = \sum_{k=1}^K [M_k^M(x_k) - (A_1 I_{xk} + A_2 I_{xk-L})]^2 \quad (8)$$

The influence line was derived from this method and the predicted strain was found to be a very close match to the measured strain. An accuracy class of B(10) was achieved from the Ostermalms test which illustrated the effectiveness of the derived influence line method. Traditionally in B-WIM the total strain record is used in calculations. To use an influence surface for each strain gauge the summation of the squared differences between measured and predicted strains is used. Generation of an influence surface requires the transverse location of vehicles during the calibration runs to be known. Three methods were developed to record the transverse position. The first used a thin layer of sand where the inner tire of the vehicle was expected to pass. Although accurate, this method was seen to be a safety hazard as the roadway had to be entered to obtain readings. The chosen method used reflective strips at measured spacings on the road surface and a digital camcorder. An estimate of the transverse position was made by post processing the images. The mean difference between the sand method and the reflective strip method was -3.55% (Quilligan et al, 2002).

The 2-dimensional algorithm is based on an optimization routine which minimizes the sum of the squares of differences between measured and theoretical results and can be defined as:

$$Obj = \sum_{j=1}^S \sum_{K=1}^K [M_{jk}^M(x_k) - M_j^T(x_k)]^2 \quad (9)$$

Where:

S = the number of sensors

2.7.4 Multi-Sensor BWIM (MS B-WIM)

O' Brien and Kealy (1998) describe a method of improving B-WIM accuracy by measuring strain at multiple longitudinal locations to obtain more equations relating strain to

axle weights. For a conventional B-WIM system the theoretical strain at a location, A, is a function of the influence line and the axle weights:

$$\varepsilon_A^{TH}(x) = W_1 I_A(x) + W_2 I_A(x - L_1) + W_3 I_A(x - L_2) + \dots + W_n I_A(x - L_{n-1}) \quad (10)$$

Where:

$\varepsilon_A^{TH}(x)$ = theoretical strain at A when the first axle is at a distance x from the start of the bridge,

W_1, W_2, \dots, W_n = axle weights,

n = number of axles,

$I_A(x)$ = influence function (strain at A due to unit load at a distance x from the start of the bridge) and,

L_1, L_2, \dots, L_{n-1} = distances of axle numbers 2, 3, n respectively from axle No. 1.

Strain is recorded as a truck crosses the bridge and the axle the best fit solution is chosen

i.e. the axle weights which minimize:

$$O = \sum_{i=1}^m \{\varepsilon_A^{ME}(x_i) - \varepsilon_A^{TH}(x_i)\}^2 \quad (11)$$

Where:

O = objective function

m = number of measurements

$\varepsilon_A^{ME}(x_i)$ = measured strain when the first axle is at a distance x_i from the start of the bridge

A major source of inaccuracy comes from truck bouncing and rocking motions. By measuring strain at n different longitudinal locations, n independent equations of the form of equation (10) could be applied and then all n axle weights can be calculated for each value of x_i , i.e. an instantaneous calculation of axle weights would be possible. The problem of varying axle forces would be overcome by providing a complete history of such forces as the truck crosses the bridge. A single span bridge is looked at first with two longitudinal sensor locations. The influence function for a strain at distance 'a' from the start of such a bridge is given by:

$$I(x) = \begin{cases} \frac{a(l-x)}{EZl} & \text{for } a \leq x \\ \frac{x(l-a)}{EZl} & \text{for } a > x \end{cases} \quad (12)$$

Where:

a = distance of strain gauge location from start of bridge,
 l = span of bridge,
 x = distance of unit load from start of bridge,
 E = modulus of elasticity,
 Z = section modulus (relating moment to stress).

There will be two longitudinal sensor locations in the form of equation (10) and these can be expressed in matrix form as:

$$\begin{Bmatrix} \varepsilon_A^{ME} \\ \varepsilon_B^{ME} \end{Bmatrix} = \begin{bmatrix} I_A(x)I_A(x - L_1) \\ I_B(x)I_B(x - L_1) \end{bmatrix} \begin{Bmatrix} W_1 \\ W_2 \end{Bmatrix} \quad (13)$$

$$D = I_A(x)I_B(x - L_1) - I_B(x)I_A(x - L_1) \quad (14)$$

These can only be solved for W_1 and W_2 if the determinant (D) of the matrix is non-zero. When both axles are before the first sensor or after the second sensor a determinant of zero is obtained by substituting (12) into (14). However, when both axles are between the sensors, equation (14) reduces to $D = IL_1$. This is clearly non-zero. A simply supported bridge with three longitudinal sensor locations was also investigated but for all truck locations, two of the equations were found to be dependent. Therefore, for a simply supported bridge only two independent equations are possible and simultaneous calculation of axle weights is only possible for 2-axle trucks.

Five longitudinal sensor locations were investigated by O'Brien and Kealy for a two-span bridge and three independent equations were found to exist for two parts of the bridge. If it is assumed that individual axles within a tandem or triaxle are of equal weight then instantaneous calculations for most truck types is possible. (O'Brien & Kealy, 1998)

An algorithm introduced by Gonzalez et al. (1999) overcame the problems encountered by O' Brien & Kealy by adopting the dynamic response as the reference so that the measured strain is compared to the theoretical total (static plus dynamic) strain instead of just static (as given by influence lines). The equations of the total strain were derived from the mechanical characteristics of the bridge and the variables representing its general dynamic behavior: natural frequencies, mode shapes and damping. The dynamic multi-sensor system is based on the accurate determination of the theoretical strain response due to a moving constant load at different bridge locations. This theoretical strain response was obtained by a) experimental determination of the natural frequencies and damping of the bridge, b) calculation of the mode shapes based on the bridge geometry and c) adjustment of the unit response curves to give a best fit to the known loads applied by the calibration vehicle.

The effects of altering certain vehicle parameters on the dynamic algorithm was studied by modifying its value by a percentage while leaving other parameters at their original value. Vehicle parameters included the distribution of load between axles, axle spacing, tire stiffness and the position of the centroid of the body mass. It was found that the dynamic algorithm was less susceptible to the change of vehicle parameters and was more accurate with a smaller standard deviation for all parameters (Gonzalez et al, 1999).

A number of algorithms have been developed and tested since Moses' original algorithm in 1979 with the overall goal to increase the accuracy of B-WIM systems. The success of these efforts shall be analyzed in the following section.

2.8 Accuracy

Since its original development in 1979, researchers have sought to improve the accuracy of B-WIM systems. This work has involved the development of new hardware such as

mechanical strain amplifiers (Peters 1984), a commercially available system (SiWIM), and a variety of new algorithms. COST-323 accuracy classifications have been published for a number of B-WIM sites, mostly in Europe. Brief descriptions of the bridge, data analysis techniques, and reported accuracies for nine B-WIM sites are provided below; the data is summarized in Table 2.7.

A reinforced concrete box girder bridge in Slovenia (Site 1 in Table 2.7) was instrumented and tested with two early B-WIM systems: one from the US and one from Ireland (O' Brien et al, 1999). Gross weight accuracy was D (20) and overall accuracy was E (50) for both systems. The authors attribute the poor accuracy to bridge and vehicle dynamics at the less-than-ideal site.

Strain gages were attached to longitudinal stiffeners on an orthotropic steel bridge in eastern France (Site 2) (Dempsey et al, 1999). The stiffeners were spaced 600mm apart, and spanned 4.62m between floor beams. The signals from stiffeners located beneath wheel lines were used as axle detectors, making the B-WIM site the first NOR or FAD site. The strains in the longitudinal stiffeners were very sensitive to the transverse position of the trucks (measured using an infrared sensor), prompting the authors to implement a two-dimensional influence “surface”. Reported accuracies were D+(20) for the conventional influence line, and C(15) using the 2D influence surface.

Accuracy results from several B-WIM sites were reported by Znidaric, Lavric and Kalin, (1999). At the first site (Site 3 in Table 2.7), an integral slab bridge was analyzed using an experimentally-determined influence line but no other data processing enhancements with a resulting overall accuracy of D+(20). The accuracy improved to B(10) when the same data was reanalyzed with the following enhancements:

- one calibration factor for tractor/trailers and a separate one for two-axle trucks,
- vehicle velocity and axle loads were optimized by minimizing the error between the measured and the calculated strain histories, and
- 4% of the B-WIM measured front axle loads was shifted to the following axles for all but two-axle trucks

The same authors analyzed two very similar bridges (Sites 4 and 5 in Table 2.7) that differed only in the amount of skew. The axle group and gross weight accuracies were B(10) or better for both bridges, demonstrating that acceptable accuracies can be obtained from B-WIM installation on a skewed bridge.

Finally, the same authors analyzed B-WIM data from a bridge with a bump in the pavement (Site 6). Overall accuracy improved from E(40) to C(15) when lightly-loaded trucks (gross weights less than 20 kN) were removed from the data set. In a later paper (Znidaric et al, 2008), the authors show that dynamic amplification factors are much higher for lightly-loaded trucks than for heavily-loaded trucks.

Data from an integral slab bridge in Sweden near Stockholm (Site 7) was analyzed three different ways, (Quilligan et al, 2002). The first analysis, using a typical one-dimensional influence line, produced an overall accuracy of B(10). The second analysis used a two-dimensional influence “surface” and the accuracy improved to B+(7). The final analysis included data from multiple presence events (two trucks running beside each other) which are typically excluded from weight calculations, and produced a very respectable accuracy of B(10).

Another integral slab bridge in Sweden (Site 8), this time near the Arctic Circle, was tested in summer 1997, winter 1998 and summer 1998 (McNulty and O’Brien, 2003).

Accuracies reported for the three test periods were C(15), D+(20) and B(10), respectively. The authors noted that the bridge response was noticeably different in winter.

A pair of short-span concrete bridges were instrumented in France (Sites 9 and 10) in the summer of 2005 with the SiWIM system (Bouteldja et al, 2008). The accuracies were generally good, ranging from C(15) to B+(7). Two lanes of a four-lane steel orthotropic bridge were instrumented with the SiWIM system in 2006. The accuracy was reported to not be as good as for the short slab bridges, due largely to the sensitivity of the instrumented longitudinal stiffeners to variations in the lateral position of truck traffic. Accuracy classifications were not reported for this bridge, due to the small number of trucks weighed statically. The authors plan to implement a 2-dimensional influence surface with an updated version of the SiWIM system and expect accuracies ranging from C(15) to B(10).

Table 2.7 Accuracy classifications from nine B-WIM sites

Site	Bridge Type	Length of Inst'd Span	Traffic	Location	Reference	Comment	---- Accuracy Classification ----			
							Single Axle	Axle Group	Gross Wt.	Overall
1	RC Box Girder	11.8 m	2-lane, 2-way	Slovenia	O'Brien 1999	American System	E(50)	E(50)	D+(20)	E(50)
	"	"	"	"	"	Irish System	E(50)	E(50)	D+(20)	E(50)
2	Steel Orthotropic Deck	75 m	4-lane, 2-way	Autreville France	Dempsey 1999	1D Influence Line	D+(20)	D+(20)	D+(20)	D+(20)
	"	"	"	"	"	2D Influence Surface	C(15)	C(15)	C(15)	C(15)
3	RC Integral	10 m	2-lane, 2-way	Slovenia	Znidaric 1999	Experimental influence line	D+(20)	B+(7)	C(15)	D+(20)
	"	"	"	"	"	Data processing enhancements	B(10)	B(10)	B(10)	B(10)
4	RC Integral	9.6 m	2-lane, 2-way	Slovenia	Znidaric 1999	Skewed 7°	D+(20)	B+(7)	B(10)	D+(20)
5	"	"	"	"	"	Skewed 26°	C(15)	B+(7)	B+(7)	C(15)
6	RC Integral	8 m with a bump	2-lane, 2-way	Slovenia	Znidaric 1999	All trucks	D(25)	E(40)	B(10)	E(40)
	"	"	"	"	"	Only trucks heavier than 20 kn	C(15)	C(15)	B(10)	C(15)
7	RC Integral	10 m	4-lane, 2-way	Sweden	Quilligan 2002	1D Influence	B(10)	B+(7)	B(10)	B(10)
	"	"	"	"	"	2D Influence	B+(7)	A(5)	B+(7)	B+(7)
	"	"	"	"	"	2D Infl. + Multi-Pres.	B(10)	A(5)	B(10)	B(10)
8	RC Integral	15 m	2-lane, 2-way	Sweden	McNulty, 2003		C(15)	B(10)	B(10)	C(15)
	"	"	"	"	"		C(15)	D+(20)	C(15)	D+(20)
	"	"	"	"	"		B(10)	B(10)	B(10)	B(10)
9	RC Integral	8 m	2-lane, 1-way	France	Bouteldja 2008		B(10)	C(15)	B(10)	C(15)
10	RC Slab	10 m	2-lane, 1-way	France	Bouteldja 2008		B(10)	B+(7)	B+(7)	B(10)

2.9 Conclusion

The work and results of numerous research efforts with regards B-WIM have been reviewed. Major research efforts have been undertaken in the areas of NOR systems and developing and refining algorithms to improve the accuracy of B-WIM systems. The goal of all of these research efforts is to ultimately provide B-WIM readings accurate enough to use for direct enforcement. Although this goal has not been reached to date, major strides towards it have been made. MFI provides a promising method to account for dynamic effects of vehicle crossings but requires further development for real time calculations. B-WIM accuracies have improved as a result of continued research into the technology. Accuracies capable for use during pre-selection have been obtained at a number of test sites.

CHAPTER 3

SCOPE AND METHODOLOGY

This chapter outlines the scope of the project undertaken for this thesis. It also describes the methods of analysis which were used and outlines how these methods were applied to the development of a bridge selection tool and the installation of a B-WIM system for the accuracy testing scenario.

3.1 Scope

This project looked at B-WIM as a technology and examined the deployment opportunities of this technology within the state of Alabama. ALDOT have expressed interest in utilizing B-WIM to enhance overweight truck enforcement activities in the state by using it as a pre-selection tool. The state of Alabama has over 19,000 bridges in its inventory and currently two B-WIM systems. It is clearly apparent that the systems owned by ALDOT must be deployed in an effective manner to maximize their enforcement potential. A large percentage of this bridge inventory is either not suitable for achieving accurate weight measurements or not located on a state route with high truck volumes. As such, it was decided to develop a bridge selection tool for B-WIM deployment. The Alabama B-WIM Bridge Selection Tool (ABST) was developed using ArcGIS software. The tool aims to determine if bridges can be instrumented and also rank bridges based on their suitability for achieving high accuracy weight measurements by analyzing the physical characteristics of each structure. It also highlights bridges which are on routes with high truck volumes and which can receive cellular data signals.

It was also important to test the system's accuracy on a typical bridge from the Alabama bridge stock. To verify that sufficient accuracies for pre selection could be obtained using B-WIM, a system was installed on a bridge in Alabama and an accuracy test conducted. Tests were also carried out to determine the optimum location of B-WIM strain sensors for both weighing and axle detection.

3.2 Data Collection for Selection Tool

The selection tool was initially developed in Microsoft EXCEL and solely used information contained within the ABIMS (Alabama Bridge Information Management System) database. ABIMS is an extensive database providing details of every bridge in the state. With hundreds of data elements for each bridge a multitude of information was readily available to assess a bridges potential suitability. Data fields range from 'Operational Status' to 'Paint Color'. Based on the reviewed literature, an initial 24 fields were selected, to base the selection tool on. Each bridge was assigned a pass/fail or a score based on the data attributed to a certain field. A bridge passing all fields was assigned a score which determined the level of suitability of that bridge. Upon review of the initial tool, it was determined that Microsoft EXCEL had limited potential as a usable tool for ALDOT as a graphical interface could not be provided and usability of the tool was quite low.

ArcGIS was chosen as a preferred interface within which to develop the bridge selection tool. ArcGIS allows storage, retrieval and analysis of both graphic and attribute data. A shapefile containing all bridges within the state was obtained. All bridges in the state were plotted using XY-coordinates. Verification of the accuracy of the file was carried out by using aerial imagery and zooming to the bridge location. This file was paired with shapefiles of 'Alabama State and Counties' and 'Alabama Roads'. As can be seen in Figure 3.1, this graphical interface allows the

tool to be more user friendly and more powerful as a bridge can be strategically selected based on its physical location.



Figure 3.1 Screenshots from ABST

A subdatabase was constructed from ABIMS to use within ABST. Information pertinent to determining the suitability of a bridge for installation, which shall be detailed in Section 3.3, was chosen along with informative fields such as ‘Features Intersected’, ‘Year Built’ and ‘County’. A join was created between the new database and the bridge shapefile using the BIN (Bridge Identification Number) field which is common to both.

The road network used was obtained from the FAF (Freight Analysis Framework) network. This nationwide network was clipped in ArcGIS to remove all features outside the state of Alabama. All routes are attributed with information regarding the most currently available (2007) flows and future (2040) truck flows.

Efforts were made to obtain a breakdown of truck flows by commodity. It was believed that this breakdown of the FAF data could provide clues as to the routes of overweight trucks.

Industries such as logging, mining, scrap haulage and steel manufacturing are known to have a heavy truck fleet. This data was not made available during the development of the prototype tool.

Aerial imagery from ArcGIS was added as a basemap in the tool. The imagery provides high resolution images, allowing bridges and surrounding features to be viewed.

ALDOT owns two SiWIM systems. SiWIM, a B-WIM system developed in Slovenia by Cestel, uses a cellular data signal to communicate with weigh crews downstream and also to allow the system to be controlled and configured remotely. Transfer of data is subject to a high speed data signal being available at the bridge and static weighing sites. To aid ALDOT in their selection of a bridge, it was thought that knowledge of the data signal strength at a particular bridge location would be beneficial. Efforts were made to obtain ArcGIS information regarding signal strength of the four main cellular providers, namely AT&T, Verizon, Sprint and T-Mobile, across the state of Alabama. Data signal information was not readily available in this format and so an alternative method was investigated.

All four providers publish maps on their websites depicting their expected coverage across the US, as shown in Figure 3.2. These images were saved and cropped to include just the state of Alabama. Images were then imported into ABST as rasters. All four images had to be rescaled and shifted so as to align them with the state line boundaries. Data coverage rasters were overlaid on the county file allowing ALDOT to determine whether any of the cell providers provide sufficient data coverage at any particular bridge site.

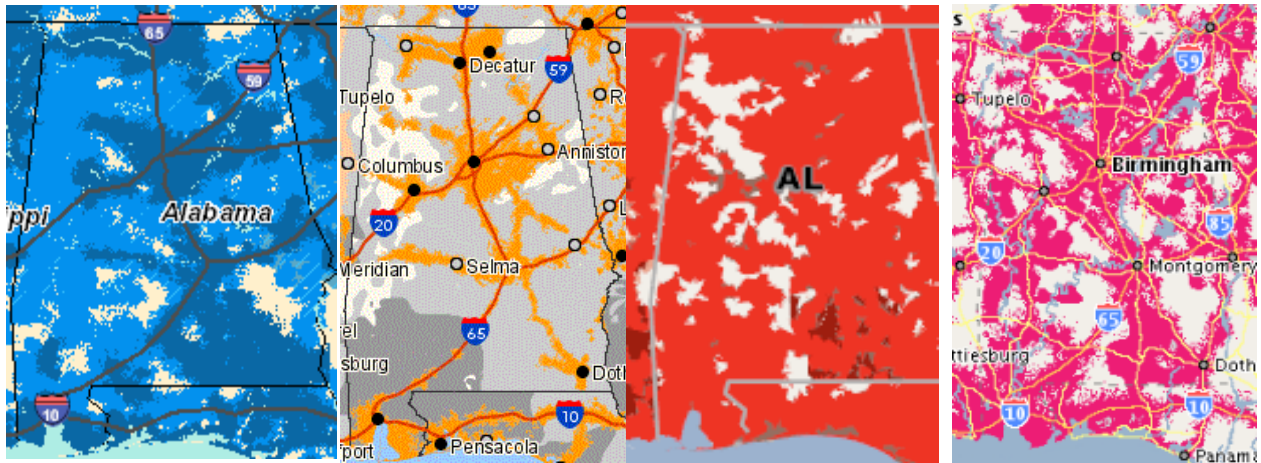


Figure 3.2 Data coverage maps of Alabama for cell providers

ALDOT has a number of pavement based WIM devices installed throughout the state. Although a shapefile was not available showing those WIM sites, one was constructed for use within the tool. A map of Alabama was obtained showing the locations of 12 WIM sites throughout the state. A shapefile depicting the approximate location of each site was constructed. Installation of B-WIM on a route previously installed with a WIM system nearby would not be practical for overweight vehicle enforcement. The visual display of the WIM locations will help to choose routes or sections of road that do not contain other weighing devices.

3.3 Creation of Selection Tool

It was first necessary to remove all bridges which could not be installed with a B-WIM system by ALDOT. Only instrumentable bridges were to be assigned accuracy rankings using ABST. The number of bridges assigned rankings in ABST was reduced significantly using a number of queries within ArcGIS, as per Figure 3.3:

- State Owned Bridges
- Operational Bridges

- Bridges that carry a Highway
- Only Steel and Concrete Structures
- Bridge Types: Culverts, Truss-Deck, Truss-Thru, Arches eliminated

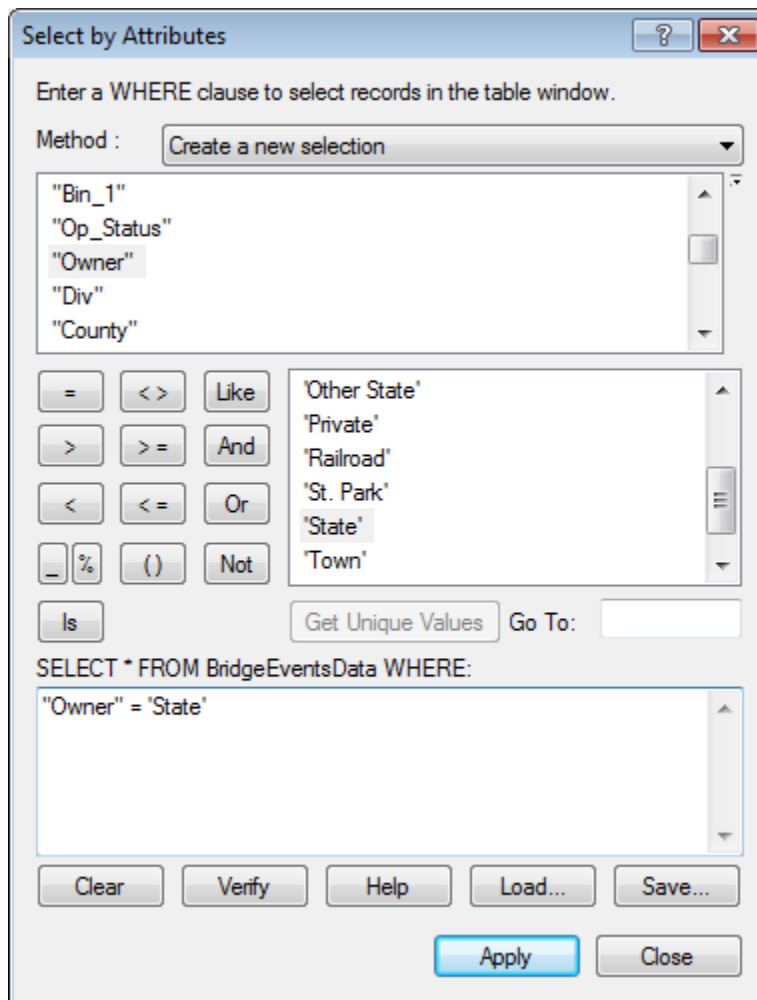


Figure 3.3 Screenshot showing query tool in ABST

Nine criteria were chosen from the ABIMS database which could be used to determine the potential accuracy of B-WIM installations. Based on the ABIMS data a score was assigned to each bridge based on the criteria. The sum of the nine scores for each bridge was calculated and a percentage of the total possible score was determined. As the assignment of scores to the

criteria is highly subjective, it was decided to develop four alternative scoring schemes, and compare the results of each. The criteria used and the scoring schemes are detailed in Table 3.1.

Table 3.1 ABIMS criteria and scoring schemes

Criteria	Categories	Score 1	Score 2	Score 3	Score 4
Number of Lanes	<=2	30	20	20	50
	<=4	10	10	0	10
	>4	0	-10	-10	-20
Skew Angle	=0	30	30	30	50
	<=30	0	0	0	10
	<=45	-50	-50	-50	-30
	>45	-200	-200	-200	-200
Horizontal Misalignment at Joint	< ½ in.	10	20	20	10
	< 1 in.	5	0	0	5
	< 3 in.	0	-10	-20	-10
	> 3 in.	-10	-20	-40	-20
Vertical Misalignment at Joint	< 1/4 in.	30	40	40	60
	< 1/2 in.	15	15	20	30
	< 1 in.	0	-10	-20	-10
	> 1 in.	-20	-30	-80	-40
Approach Roadway Condition	> satisfactory	30	20	30	10
	> poor	20	0	0	0
	poor	0	-20	-30	-10
	< poor	-30	-40	-80	-20
Hor. Or Ver. Curve	neither	30	30	40	20
	either	0	-20	-20	-10
	both	-20	-40	-80	-30
Deck Condition	> fair	10	20	40	40
	> Serious Condition	5	0	0	10
	<= Serious Condition	-30	-40	-80	-40
Span Type	Concrete	50	30	0	20
	Steel	0	0	0	0
Lanes & Direction	2-way/2-lane	50	30	0	20
	not	0	0	0	0

Nine criteria from the ABIMS database were chosen for use in the tool. The importance of each will be explained below in relation to achieving high B-WIM accuracies.

Number of Lanes/Direction: Fewer lanes are preferred for B-WIM installations. If one lane is present, the transverse position of a vehicle is known and there is no possibility for multiple presence events. Each additional lane increases the uncertainty of the transverse

position of the truck and the possibility of multiple presence events increases. Two-way/Two-lane bridges ensure vehicles maintain their transverse position.

Skew Angle: It is recommended that bridges without skew are used for installation when possible. Skew induces complications in the installation and setup of the B-WIM system. Sensors, on bridges with low skew, should be placed in a line perpendicular to traffic lanes. For bridges with high skew, sensors should be installed in a line following the skew of the structure. Low skew is defined as $L' > 0.8*L$ as per Figure 3.4. An upward limit of 45 degrees is suggested for B-WIM installation (Znidaric et al, 2011).

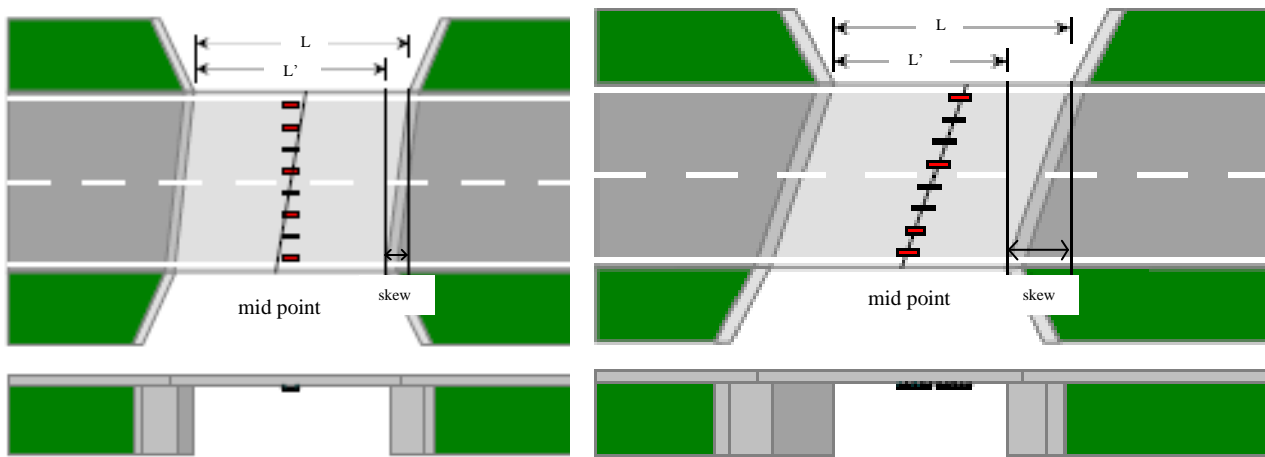


Figure 3.4 Definition of skew (From Znidaric et al, 2011)

Vertical/Horizontal Misalignment at Joint: All moving vehicles bounce on their tires and suspensions. Bouncing axles induce ‘noise’ in the measured strain which is difficult to filter out. Misalignments at joints can cause increased bouncing of axles and thus increased ‘noise’ in the signal. Bridges with smaller misalignments should therefore provide higher accuracies than those with large misalignments. Two examples of joint conditions are shown in Figure 3.5.



Figure 3.5 Photo of two expansion joints

Approach Roadway and Deck Conditions: Similar to misalignment at joints, pavements in poor condition, either on the bridge or directly prior to the span, cause axle bouncing. Smooth pavements will provide cleaner signals and more accurate results.

Horizontal/Vertical Curve on Approach: Horizontal curves cause vehicles to alter their transverse positioning on the roadway, and there is often little consistency of the wheel path of vehicles. Vertical curves can cause vehicles to alter their velocity as they cross the bridge. As previously outlined, accurate velocity calculations are pertinent to obtaining accurate results.

Span Type: B-WIM can be installed on both steel and concrete bridges. Accuracy is not adversely affected by choice of a material type. Installation of sensors is more complicated on steel structures and requires the use of an epoxy to fix them to the steel. A preference is therefore shown towards concrete structures.

Factors which would negatively affect the accuracy of B-WIM results were assigned negative scores while ideal conditions were awarded positive scores. Bridges were divided into

ranks according to their percentage score. Three alternative ranking systems were investigated as shown in Table 3.2.

Table 3.2 Three Systems for Ranking Bridges

Ranking System 1	Ranking System 2	Ranking System 3
100% - Rank 1	100% - Rank 1	100% - Rank 1
80 - 99% - Rank 2	75 - 99% - Rank 2	90 - 99% - Rank 2
50 - 79% - Rank 3	50 - 74% - Rank 3	70 - 89% - Rank 3
Below 50% - Rank 4	25 - 49% - Rank 4	50 - 69% - Rank 4
-	Below 25% - Rank 5	30 - 49% - Rank 5
-	-	Below 30% - Rank 6

The score ratio and rank of each bridge is obtainable in ABST. According to its rank, each bridge is assigned a symbol which allows ALDOT to easily identify the bridges which should provide the most accurate results.

Selection of a route is primarily concerned with the truck flow volumes on that route. 2007 truck flow volumes for all state routes are provided in the reduced FAF road network. A query is used to select routes with truck flow volumes greater than a user defined threshold. After a route is selected, the rankings of bridges along that route can be viewed and a selection of candidate bridges can be made.

3.4 B-WIM Installation & Accuracy Testing

To verify accuracy of the system, it was required to install the system on a bridge in Alabama, calibrate it, and verify that accurate weights for random traffic passings could be achieved. Factors such as bridge type, construction methods, vehicle type and even climatic conditions could all play a role in obtaining accuracy results not consistent with previous studies from Europe. ALDOT purchased a B-WIM system in Fall 2010. CESTEL is currently the only commercial developers of B-WIM systems. To train staff from ALDOT, and faculty and students from the University of Alabama, as to the proper installation, setup and calibration procedures of

their SiWIM system a representative from CESTEL arrived in Alabama on February 28th 2011 and a two week extensive training workshop was attended. The workshop included class and field demonstrations whereby the hardware, software and correct installation procedures were described.

3.4.1 Selection of Bridge for Testing

Selection of a suitable bridge in an ideal location is extremely important when using B-WIM for pre-selection. The choice of an unsuitable bridge can negate later efforts and ultimately end up in the installation being a failure. The selection of a suitable bridge must consider both the physical attributes of and traffic conditions on the bridge to make it suitable for pre-selection use.

The selection tool described in Section 3.3 which was being developed was not at a stage where it could be utilized for choosing a bridge for accuracy testing. An alternative method was employed for choosing a suitable bridge.

ALDOT identified a section of highway on US-82 in west Alabama as a target for weight enforcement. This section of highway had heavy truck traffic, suspected overweight vehicles, and no intersections with major highways which can cause interruptions to traffic flow and speed. The bridge database indicated three bridges in this section were good candidates for B-WIM installation. The structures were not culverts, had only two lanes, and had relatively short simply-supported spans. Few lanes, short span lengths, and simply-supported (vs. continuous) spans reduce the likelihood of multiple-presence strain measurements due to more than one vehicle. Determination of vehicle weights from multiple-presence events is possible but more difficult. Each of the three bridges was inspected to further determine suitability for B-WIM.

Table 3.3 presents the findings from the inspection of the candidate bridges. The significance of many of these criteria has been outlined in the previous sections.

Table 3.3 Characteristics of three candidate bridges

Criteria	Bridge 1	Bridge 2	Bridge 3
<i>Horizontal/Vertical Curve</i>	Vertical	None	Vertical
<i>Skew</i>	None	None	None
<i>Accessible</i>	Ladder	Yes	No (Water)
<i>Joints</i>	Disrepair	Good Condition	Disrepair
<i>Service Below</i>	Rail	Creek	Stream
<i>Service On</i>	2-way/2-lane	2-way/2-lane	2-way/2-lane
<i>Construction</i>	Concrete Tee Beam	Concrete Tee Beam	Concrete Tee Beam
<i>Daily Truck Traffic</i>	Heavy (1,709)	Heavy (1,658)	Heavy (1,759)
<i>Static Weighing Location</i>	Yes	Yes	Yes
<i>Span Length (max)</i>	13.4m (44ft)	9.1m (30ft)	10.4m (34ft)
<i>Power Supply</i>	Portable	Portable	Portable

Fixed power supplies are favored for installation but are regularly not present at potential bridge sites. All inspected bridges were without fixed power supply and as such a portable power supply was required for installation. Easy access to the underside of the bridge is preferred so that strain sensors can be installed with ease. Bridge 1 was accessible with the use of a small ladder, while Bridge 2 had two spans accessible without the need for equipment. Bridge 3 had water beneath all spans and as such, special arrangements would be necessary for installation. After reviewing the three bridges it was decided that Bridge 2 was the optimum choice and should provide the most accurate results. Figure 3.6 presents photos of Bridge 1 and Bridge 2. Bridge 2 has a BIN of 4289.



Figure 3.6 Photos of bridge 1 (a & b) and bridge 2 (c & d)

3.4.2 B-WIM Installation

BIN 4289 is a five span, two lane bridge located Southeast of Gordo Alabama. Each of the five spans is 9.1m (30ft) in length. The bridge has a width of 9.4m (31ft). Two way traffic is carried and the road connects Tuscaloosa AL to Columbus MS. US-82 is a heavily travelled rural route with an annual daily traffic of 9,210. An estimated 18% of these vehicles are trucks. In the remainder of this text the first span will be considered as the span closest to Tuscaloosa. A

location map, elevation of BIN 4289 and its cross section are provided in Figures 3.7, 3.8 and 3.9 respectively.

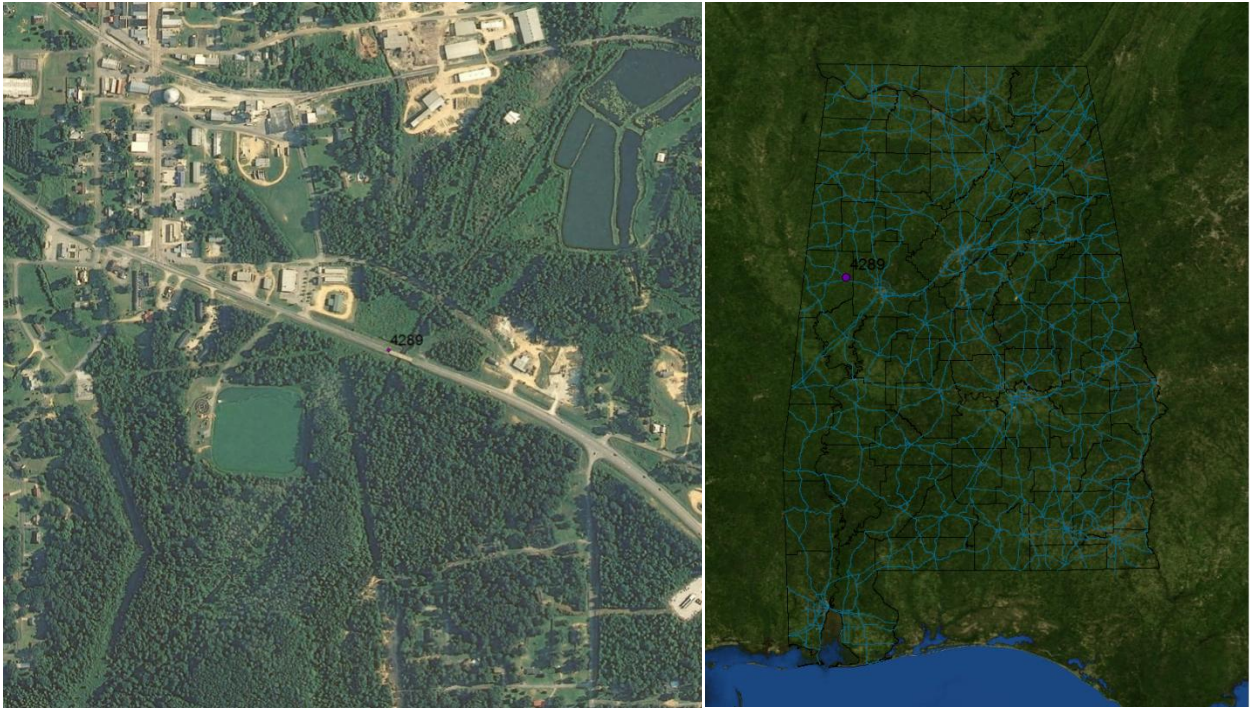


Figure 3.7 Location map of BIN 4289

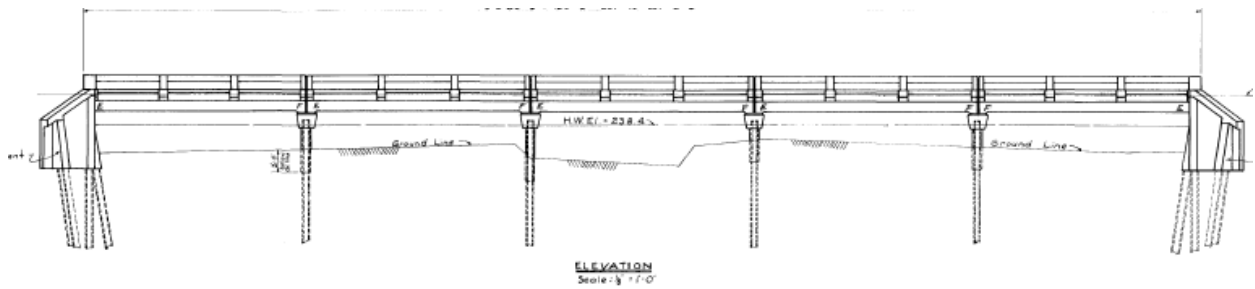


Figure 3.8 Elevation of BIN 4289

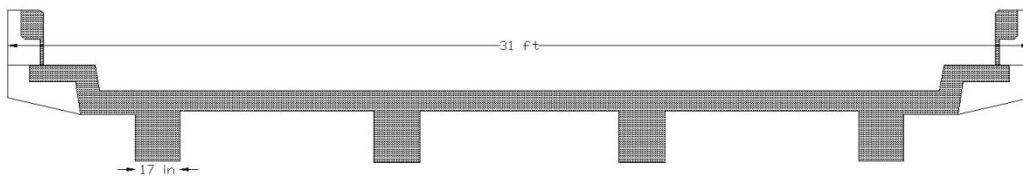


Figure 3.9 Cross section of BIN 4289

The first installation of SiWIM on BIN 4289 took place on March 1st 2011. This installation was carried out with the assistance of the CESTEL representative and allowed ALDOT staff to become familiar with installation procedures of the SiWIM sensors and cabinet. Influence line generation and calibration methodologies were introduced. FAD installation was chosen as the preferred method of installation and as such a number of the sensors were designated solely for axle detection purposes. All 24 strain sensors supplied with the system were used in the installation. Alternative weighing sensor and axle detection sensor locations were investigated. Figure 3.10 shows the location and orientation of all sensors. Calibration was completed for this installation, but no random trucks were statically weighed. After calibration had concluded the system was removed from the bridge.

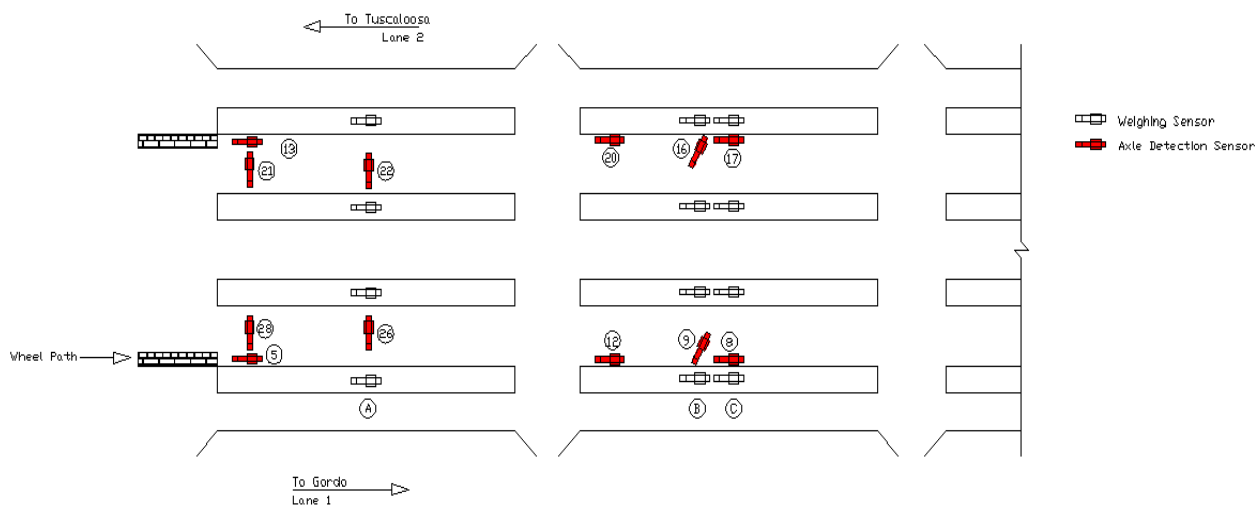


Figure 3.10 Initial Sensor Layout

SiWIM was installed on BIN 4289 for a second time on March 10th 2011. The second installation was planned and carried out solely by ALDOT staff. A set up using 8 sensors on the

second span of the bridge was configured, as shown in Figure 3.11 and Figure 3.12. The second span was selected as the ground beneath the second span was more level than the first and it was hoped that dynamic oscillations in strain induced from the joint between bridge and the abutment may have subsided before reaching the second span. The second installation was fully calibrated and readings from random traffic were taken.

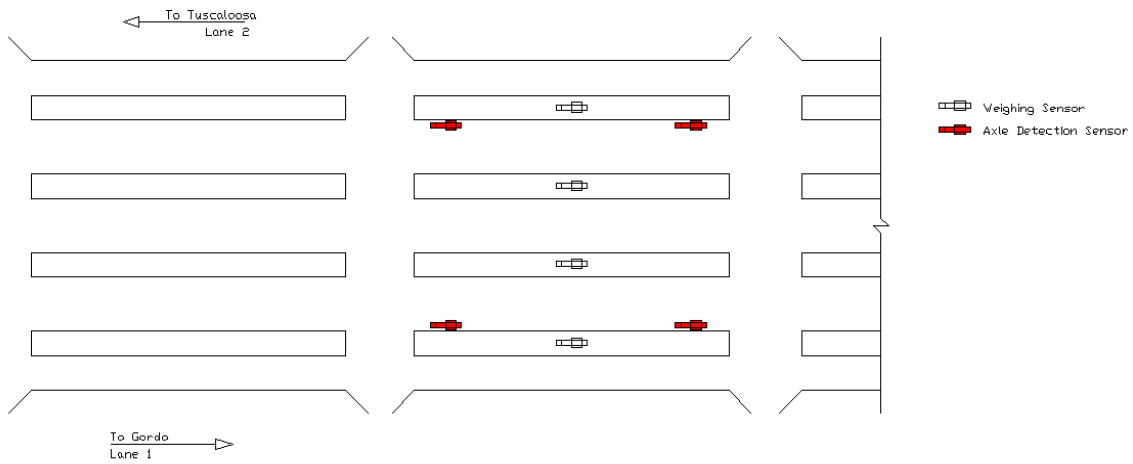


Figure 3.11 Second Installation Sensor Layout

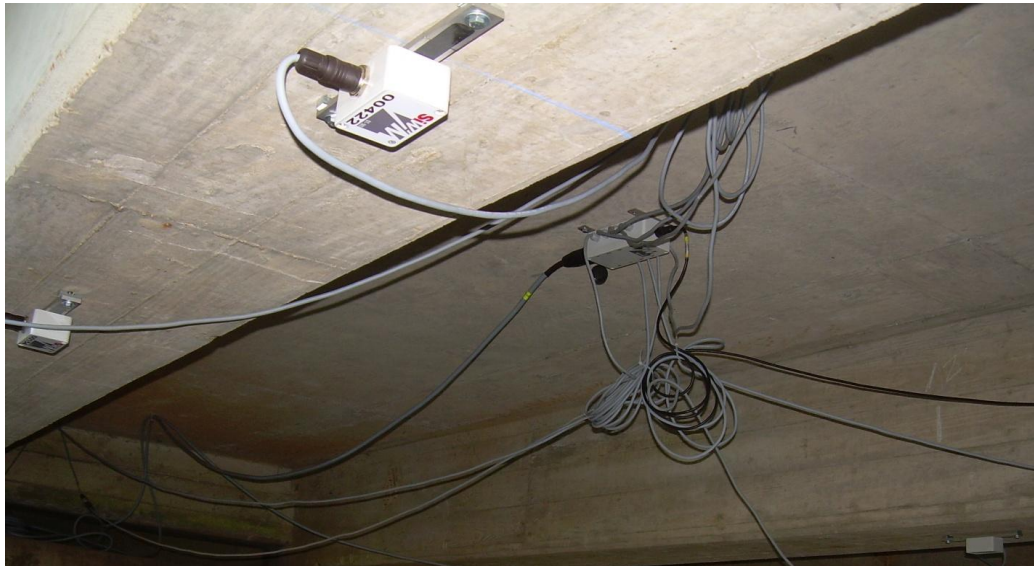


Figure 3.12 Photo of underside of BIN 4289

3.4.3 Positioning of Weighing Sensors

BIN 4289 is a tee beam reinforced concrete bridge. As all load is transferred to the beams, weighing sensors are orientated longitudinally and fixed to the underside of each beam to measure strain as the bridge is loaded by a passing vehicle. As BIN 4289 has four longitudinal beams, four weighing sensors are required. It was decided to compare the strain signals obtained from the first and second span of the bridge using the sensor configuration from the initial installation. Four weighing sensors were fixed at the mid span of both the first and second spans. On the second span, an additional set of weighing sensors were located at a distance of 3.7m (12ft) (40%) from the beginning of the span (Figure 3.10). This sensor configuration would allow for a comparison of the signals obtained from the middle of the first and second spans and from the two locations on the second span. On a continuous multiple span bridge, theory suggests that the maximum bending moment should occur at 40% of the span.

3.4.4 Positioning of Axle Detection Sensors

Axle detectors are only concerned with the identification of the exact time of an axle crossing the location where they are fixed. As such, sensors should be fixed to the underside of the slab, directly below the wheel path of the truck so that a definite, sharp peak can be observed in the strain signal. This sharp peak identifies the passing of an axle over the sensor location. Using two sensors a known distance from each other, an exact time for the axle to travel between the sensor locations is calculated. This time is then used to calculate velocity of the vehicle, and distances between axles. A clear strain signal with definite peaks is required to count the number of axles of the vehicle and to accurately determine the vehicle velocity. As noted in Chapter 2 high B-WIM accuracies are highly reliant on the accuracy of these calculations.

Traditionally, axle detectors have been orientated longitudinally to the bridge span. Recent thinking however, has suggested that orientating the sensors at an angle or transverse to the span could provide cleaner signals with more pronounced peaks. To investigate the effects of orientating the axle detector sensors in different ways, three different configurations were installed on BIN 4289 during the first installation. Figure 3.10 shows the position and orientation of all 12 AD (Axle Detector) sensors. One set were orientated longitudinally, one transversely and one at a 60 degree angle to the span. As well as having three configurations, signals were obtained at the beginning and the center of a span. Originally, sensors 5 and 13 were located at the center of span 2 at a 60 degree angle. Initial analysis of the signals on site showed that the longitudinal sensors at the beginning of the span provided the cleanest signal. The angled sensors at the beginning of the span produced poor signals and a decision was made to move these sensors to the beginning of the first span. It is important that upon installation of AD sensors that all are seen to provide clean peaks suitable for axle detection purposes. If this is not the case, it is necessary to move the sensors either longitudinally or to line them up with the truck wheel path. Figure 3.13 shows the distance to the wheel path being measured at the bridge site and the placement of an axle detector sensor below the bridge deck.



Figure 3.13 Measuring Distance to wheel path/Longitudinal axle detector sensor

3.4.5 Calibration

Two calibration vehicles were used to calibrate the SiWIM system on BIN 4289 as shown in Figure 3.14. The first truck was a 5-axle, 18 wheel flatbed truck which had been loaded with steel. This type of truck is the most common overweight vehicle in Alabama. The GVW of this truck was 78,850lbs. The second calibration truck was a 3-axle load test truck used by ALDOT with a GVW of 73,900lbs. The axle loads and configurations of both calibration trucks are outlined in Table 3.4. The trucks were statically weighed by an ALDOT weigh crew before arriving onsite. The weights were obtained with full fuel loads. To maintain consistency, the trucks were refueled upon arrival on site so that the same weights would be achieved. A minimum of 10 runs by each truck in each lane are required for calibration. As the possibility of a multiple presence event is a distinct possibility it is recommended that extra runs be carried out so that outliers can be disregarded and there are 10 usable runs for calibration in each lane. The speed limit at the bridge site is 45mph. Calibration was conducted by completing 6 runs of each truck at 45mph in each lane, 2 runs at 35 mph and 2 runs at 55mph. This calibration process was used for both the first and second installations of the system.



Figure 3.14 SiWIM photos of Calibration Trucks

Table 3.4 Calibration Truck Static Weights and Axle Configuration

	3-Axle Rigid Truck	Dist from Prev Axle	5-Axle Tractor Trailer	Dist from Prev Axle
Axle 1	21,200 lbs	-	10,400 lbs	-
Axle 2	26,350 lbs	224"	15,900 lbs	170"
Axle 3	26,350 lbs	56"	15,300 lbs	51"
Axle 4	-	-	18650 lbs	441"
Axle 5	-	-	18650 lbs	51"
GVW	73,900 lbs		78,850 lbs	

3.4.6 Influence Line Generation

“Influence lines of the bridge are the most important parameters of a B-WIM installation as they describe bridge behavior under the moving load” (Znidaric et al, 2011). The influence line is defined as the bending moment at the point of measurement induced by a unit axle load moving along the bridge. An influence line for the bridge can be generated using signals from random vehicles, or from the calibration vehicles. It is recommended that loaded trucks, similar in configuration to those which are envisaged to be weighed be used for the influence line generation. Signals from multiple vehicle types can be combined to form a single influence line which is an average response of the bridge to loading from alternative vehicle types.

Once the bridge configuration has been inputted, a default influence line must be generated. The strain signals from the selected trucks are smoothed using a FFT (Fast Fourier Transformation) in the SiWIM software. The software automatically creates an influence line from the smoothed signal as shown in Figure 3.15. It is essential that when creating the influence line that it returns and stays at zero at each end of the span. If this is not the case, the span append and prepends must be extended, default influence line generated and the process repeated. The influence line must also incorporate the location of the AD’s being used for that installation. It is recommended that a minimum of two signals from each lane are used and the influence line is generated from the average of these.

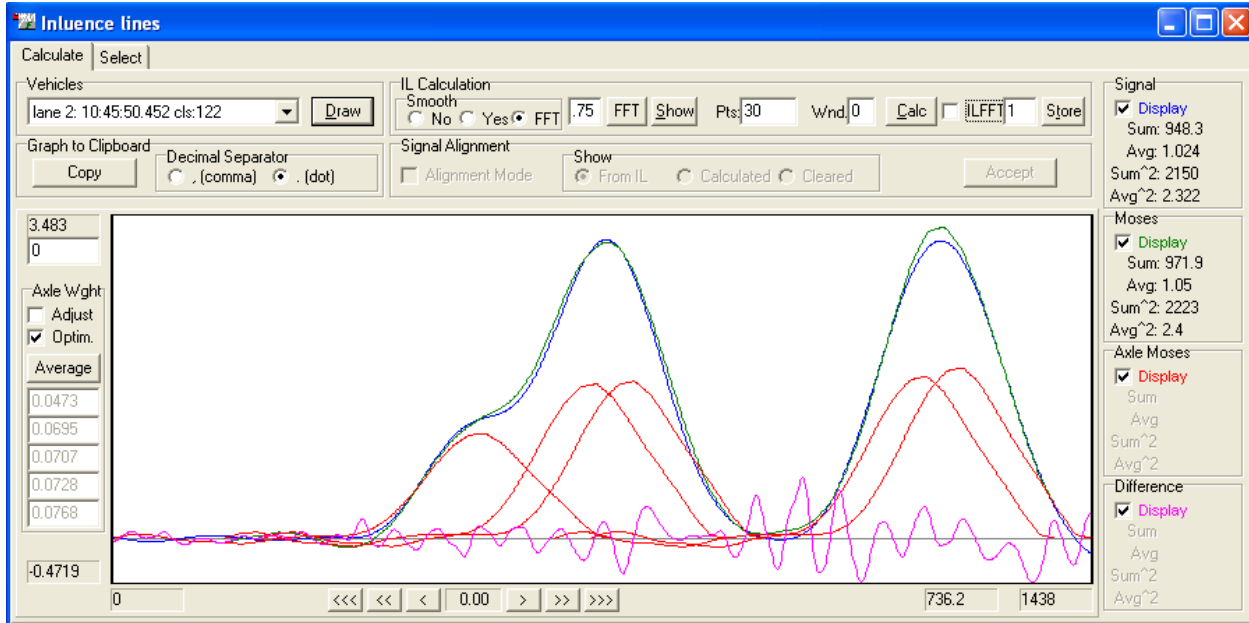


Figure 3.15 Screenshot from SiWIM influence line generation window

The first installation used the weighing sensors fixed to the first span. Sensors 13, 20, 5 and 12 (Figure 3.10) were used to detect axles and calculate vehicle velocity. This required that the influence line extend to include the position of sensors 20 and 12 on the second span. Initially a large (same length as bridge span) prepend and append were assigned and default influence lines generated. Large appends and prepends allow the user to determine where the influence line reaches zero, and the append and prepend can be adjusted accordingly. A long influence line has no adverse effects on accuracy but does increase the possibility of multiple presence events. Five random loaded trucks were selected in each lane. The signals were then smoothed using FFT and a low-pass filter of 4.75 Hz. Influence lines were calculated and stored for each vehicle. The two smoothest influence lines in each lane were chosen and these were averaged to produce the final influence lines.

The procedure for generating the influence lines for the second installation was identical to that of the first. Influence lines were generated for the second span. An influence line generated for BIN 4289 is shown in Figure 3.16.

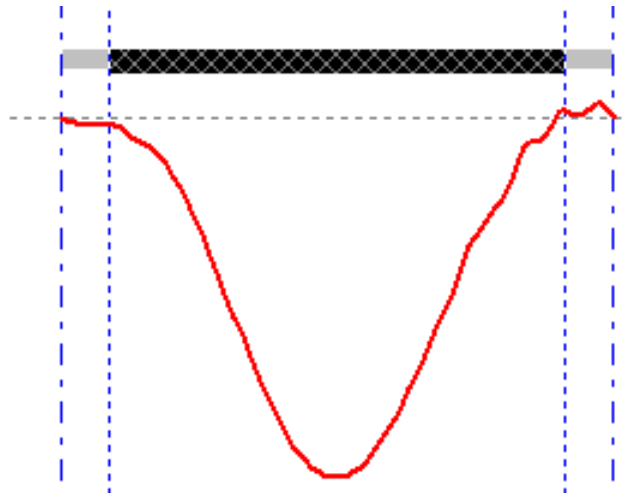


Figure 3.16 Influence line for BIN 4289

3.4.7 Calibration Factors

After influence lines have been generated for each lane, the calibration runs must be weighed. The static weights and measured axle distances are coded into the SiWIM software for the calibration trucks. Calibration factors are then calculated. Two separate calibration factors were used: one for rigid trucks and one for tractor trailer style trucks. After calibration factors are determined, the data is checked for possible outliers due to multiple presence events. Outliers are removed and calibration factors are readjusted. The removal of an outlier must be justified. Strain signals are examined to check for multiple presence during the strain reading, or for possible failure of a strain sensor. Further adjustments to calibration factors can be made using the following settings:

- Front Axle Correction

- Redistribution Within Group
- Temperature Compensation
- Front-Axle Velocity Compensation
- Velocity Compensation

Once calibration factors have been finalized the system is ready to weigh random traffic.

3.5 Accuracy Test

SiWIM systems can be managed remotely from a PDA (Personal Digital Assistant) device using μ SiWIM F software. This is of particular usefulness when using the system for pre selection, as the system can send a photo to the PDA of an overweight truck along with its weight to the weigh crew. The weigh crew can be located downstream from the bridge with the PDA and can pull over offending trucks as they pass. A good data connection is required for the system to communicate with the PDA device. It was discovered at the site that a sufficient data signal was not available at the bridge. Measures were taken to try improving the signal at the bridge location but the background signal was too low to transfer data.

An accuracy test of the installation took place on the morning of March 11th 2011. Testing was carried out on vehicles travelling on Lane 2 of the bridge, i.e., towards Tuscaloosa. As μ SiWIM F could not be used it was decided to locate an ALDOT member at the bridge site who was connected to the system. His job was to communicate with the downstream weigh crew when a heavy truck crossed the bridge. CB (Citizen's Band) radio was used to communicate to the State Trooper. A description of the truck, the load type and the GVW as indicated by the SiWIM system were given to the weigh crew. When the State Trooper identified the vehicle, he motioned for it to pull over and the weigh crew obtained the truck weight using portable static scales. Figure 3.17 shows a state trooper pulling over a pre selected truck and the truck being

statically weighed. Individual axles were weighed on their own while tandem or triaxles were weighed collectively. A total of 10 trucks were weighed using this method. Axle configurations were also measured using a standard measuring tape. Once testing had concluded on March 11th, the system was removed from the bridge and taken by ALDOT.



Figure 3.17 State Trooper puling over pre selected truck/Static weighing of truck

3.6 Power Setup

During the training installation and accuracy test, power was supplied to the system using a single dry cell boat battery. Each fully charged battery can supply the SiWIM system with power for approximately 30 hours. As it was never the intention to permanently install the system on BIN 4289, a permanent power setup was not installed at the bridge site. The system collected data until the battery power dissipated. The battery was replaced each morning.

The SiWIM system pulls a constant 3A with the camera connected. For quasi permanent installations the power setup in Figure 3.18 has been tested and has been found to be sufficient to continuously provide power to the SiWIM cabinet. The solar panels provide 20V to the regulators. The regulators control the voltage and supply the batteries with 12V. The regulators are designed to ensure batteries are not over charged. Every component is wired in parallel to

increase the current output. One battery lasts approximately 30 hours with the camera connected. This setup can provide up to 7 days of power with no sunlight. The schematic in Figure 3.18 illustrates how the system is wired.

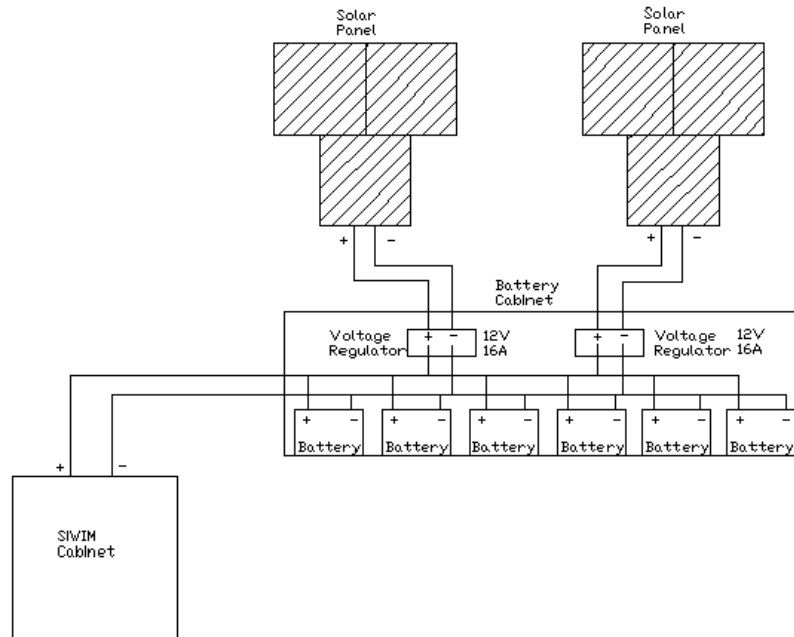


Figure 3.18 Power setup for long term installations

CHAPTER 4

ANALYSIS OF BRIDGE SELECTION TOOL

This chapter describes the results obtained from the development of Alabama B-WIM Bridge Selection Tool (ABST). The number of bridges which fall into each ranking are analyzed. Comparisons of results using different scoring schemes for the criteria and alternative ranking systems will be presented. Highly ranked bridges along routes with high volumes of truck traffic will be identified. The potential of this tool for use by ALDOT will be presented and it shall be shown how candidate bridges can be easily chosen using ABST.

4.1 Alabama Bridge Inventory

The bridge file showed a total of 19,146 bridges in the state of Alabama, as shown in Figure 4.1. A large percentage of these bridges were immediately dismissed as they were not suitable for B-WIM installation. Five criteria were used and the intersections of these 5 fields were the only bridges of interest within ABST. ALDOT is only interested in installation of the system on state owned bridges. The bridge must be operational and carry highway traffic. Only steel and concrete structures are suitable for installation and structure types such as a truss or arch are not suitable. Culverts were not considered for installation as they are generally pipe culverts, have spans too short for FAD installation or the depth of fill is too large to acquire sufficient strain signals. Using a query by attribute the number of bridges in each of the five categories was determined, as represented in Figure 4.2.

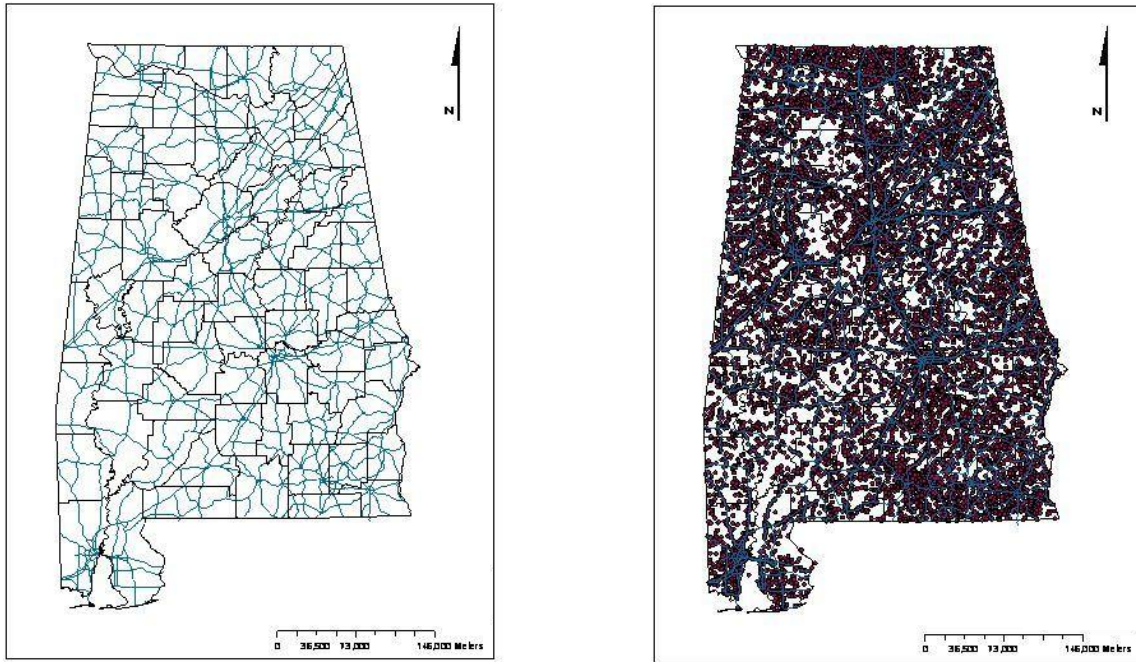


Figure 4.1 ABST maps showing Alabama highways/bridges

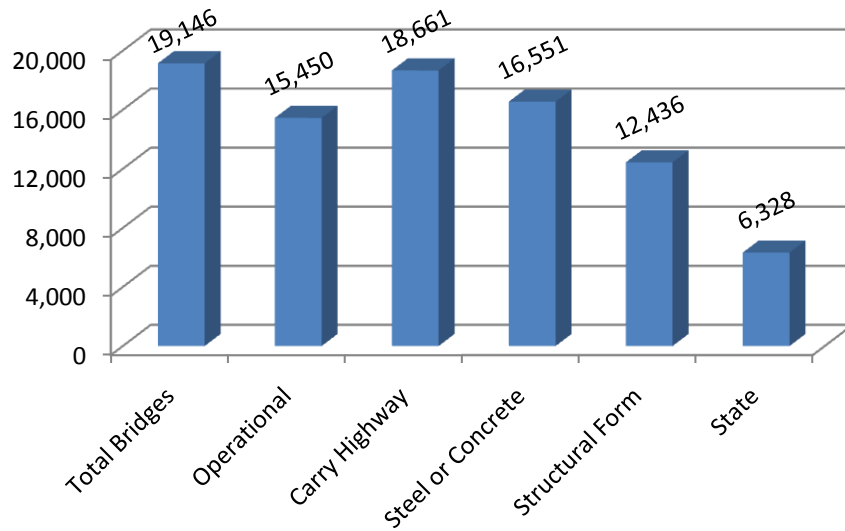


Figure 4.2 Breakdown of bridges in Alabama

To determine the intersection of the five categories, attribute queries were used. After each query, a new layer was created from the selected data. New layers were then immediately exported and saved as shapefiles. The first query selected state owned bridges. State owned bridges account for exactly one third of all bridges in Alabama. From state owned bridges, all operational bridges were selected and exported to their own shapefile. Approximately 5,695 (90%) of state owned bridges are operational. It was then necessary to verify which of these operational bridges carry a highway service. Only 12 of the operational state owned bridges do not carry a highway and out of these 5,683 bridges, it was noted that 5,659 of them were steel or concrete structures. Span type was used to select all bridges which were not an arch, culvert or truss. Finally, 3,554 bridges in the state of Alabama were classified as being ‘instrumentable’ (See Figure 4.3). This represents over half (56%) of state owned bridges.

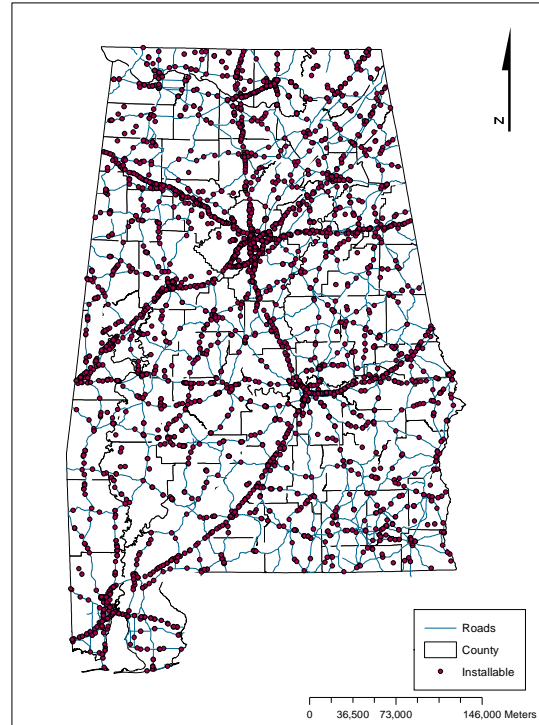


Figure 4.3 ABST map showing ‘instrumentable’ bridges in Alabama

4.2 Ranking of Bridges Using ABST

Each of the 3,554 suitable bridges was assigned a score based on 9 fields from the ABIMS database as per Table 3.1. Four alternative scoring schemes were considered. The weight assigned to each criterion was adjusted to attempt to provide a fair representation of the significance of that information. For example, it was important that if a bridge had one significant issue which would negatively affect the accuracy which could be obtained at that site, e.g., skew > 45, that that bridge would be assigned a negative score and be automatically classified as being unsuitable. The four scoring schemes vary by the importance which each attribute is assigned. Basis for the scores was obtained from reviewing literature from previous installations and from experience from the installation on BIN 4289. However, these scores are highly subjective and may require further adjustments.

As well as four alternative scoring schemes, three different ranking systems were tested. Four ranks were used for the first ranking system, five in the second and six in the third and these are described in Chapter 2. The number of bridges falling into each rank using the four scoring schemes is presented in Tables 4.1, 4.2 and 4.3.

Table 4.1 Bridges in each rank using ranking system 1

	Rank 1	Rank 2	Rank 3	Rank 4
Score 1	448	1015	1517	574
Score 2	448	698	1725	683
Score 3	763	723	1200	868
Score 4	448	1279	1438	389

Table 4.2 Bridges in each rank using ranking system 2

	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
Score 1	448	1315	1217	342	232
Score 2	448	1255	1168	419	264
Score 3	763	792	1131	502	366
Score 4	448	1750	967	181	208

Table 4.3 Bridges in each rank using ranking system 3

	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6
Score 1	448	281	1462	789	309	265
Score 2	448	191	1272	960	360	323
Score 3	763	94	1111	718	467	401
Score 4	448	401	1567	749	164	225

After review of the ranking systems it was determined that the first ranking system was most appropriate for use in the tool. Assigning bridges to a large number of categories could confuse users of the tool. Definitions for each category would have to be known by the user. Four categories can provide useful information while also being user friendly.

Four ranking categories were used; Rank 1 - Ideal, Rank 2 - Suitable, Rank 3 - Sufficient, Rank 4 - Unsuitable. Ideal bridges should provide the most accurate results. Suitable bridges should still provide accurate results but have some issue which makes them less appealing for installation. Sufficient bridges should provide usable results but high accuracies are likely not to be obtained. Sufficient bridges should be avoided if at all possible. Unsuitable bridges have one or more significant issues which will cause inaccurate results to be obtained. These bridges are unsuitable for pre-selection readings to be measured and should not be instrumented. Ranks of each of the 3,554 bridges are shown in Figure 4.4.

Choice of a scoring system is highly subjective. Assigning importance to a particular attribute is a difficult task. Efforts were made in each scoring scheme to heavily penalize,

attributes which are known to cause complications or poor accuracy. From Tables 4.1, 4.2 and 4.3 it is seen that the majority of bridges fall into Rank 2 or Rank 3 for all schemes. Score 4 appears to be the most lenient of all, with only 389 bridges classified as 'Unsuitable' for installation. Scoring scheme 3 has the greatest number of ideal bridges, while also the greatest number of unsuitable.

Scoring scheme 1 was selected for use within the prototype tool. It was determined that this scheme fairly assigned scores to the ABIMS data and recognized the importance of each attribute with relation to installation accuracy. The three candidate bridges for the accuracy test were checked using the tool. It was seen that the selected bridge, BIN 4289, was assigned a rank of 2 by Score 1, while the other candidates obtained a rank of 3. Score 3 and Score 4 assigned all three bridges the same rank.

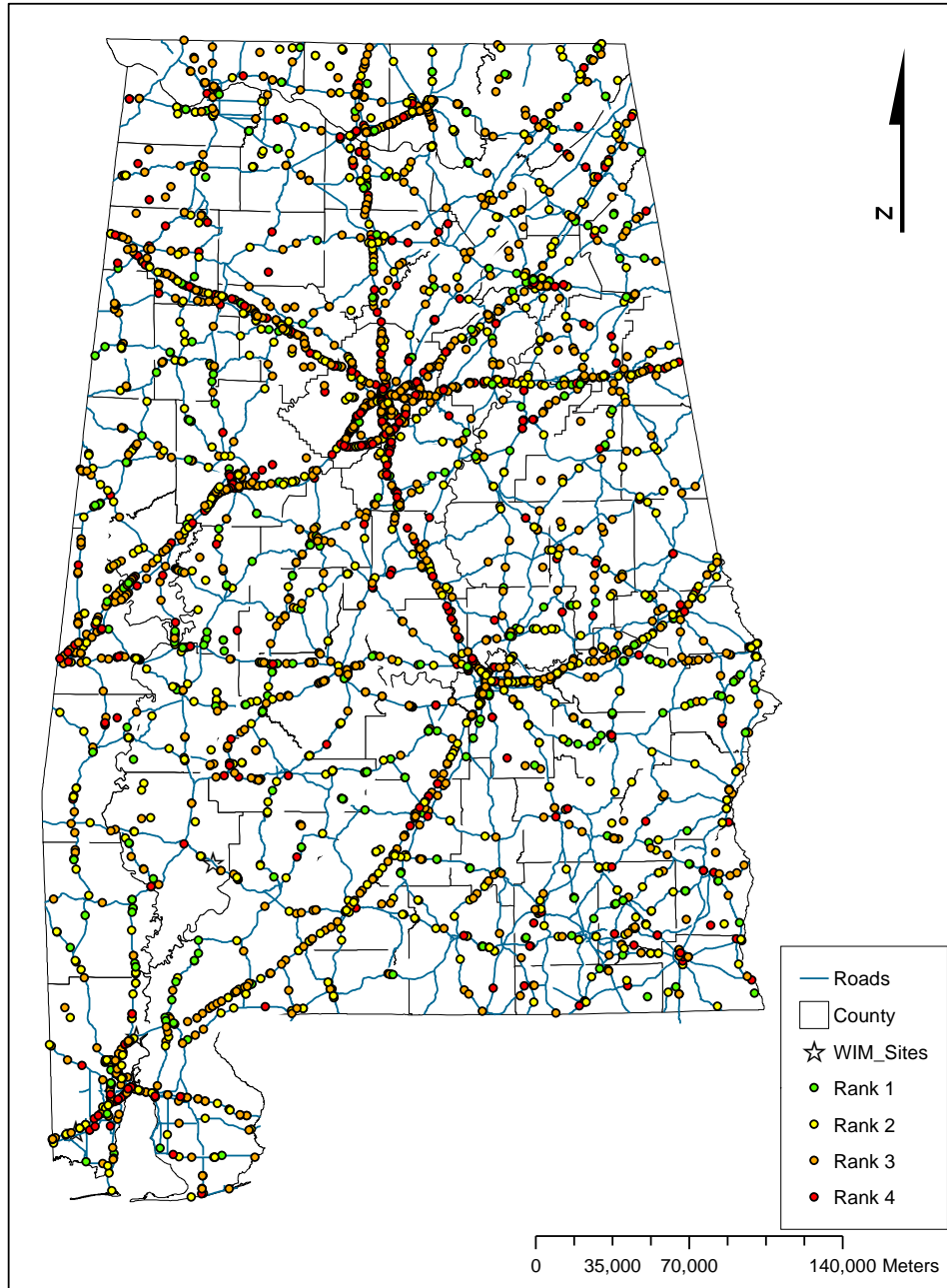


Figure 4.4 Ranking of all instrumentable bridges using ABST

4.3 FAF Route Selection

A bridge with characteristics for high accuracy is of no use for pre-selection needs if truck flow volumes are very low over it. FAF truck flow data for 2007 was used to select routes with truck volumes over a desired threshold. Figure 4.5 shows routes within the state with truck flows greater than 500, 1,000 and 2,000 per day.

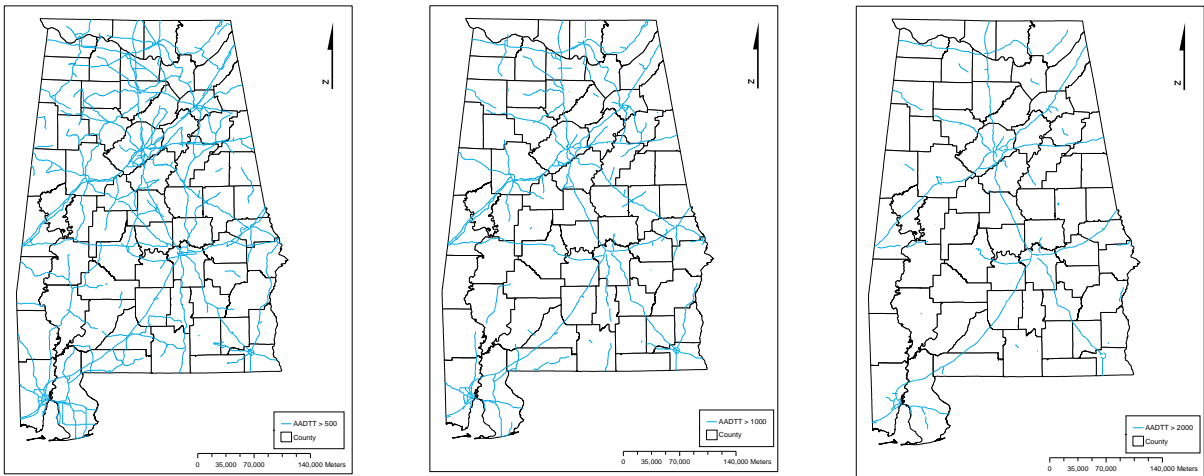


Figure 4.5 Maps of routes with more than 500, 1,000 and 2,000 trucks per day respectively

After setting a desired threshold, users can select the route on which they wish to install the system. Bridges of a certain ranking can then be selected to be shown on the map. Upon examination of the map, a user can select a number of candidate bridges along the selected route which are to be visited in person. The final selection of a bridge should be made in the field and should be based upon ease of installation, verification of bridge and road attributes which contribute to B-WIM accuracy, and the provision of a location nearby where it is safe to pullover and statically weigh pre-selected trucks.

By setting a threshold for truck flows and choosing particular ranks which a user is interested in viewing, a map can easily be produced showing bridges and routes which are of

interest. Where the road shapefile overlaps the bridge shapefile, shows locations where high truck volumes cross bridges which should be able to provide the level of accuracy required.

Figure 4.6 shows Ideal and Suitable bridges as well as routes with over 1,000 trucks per day.

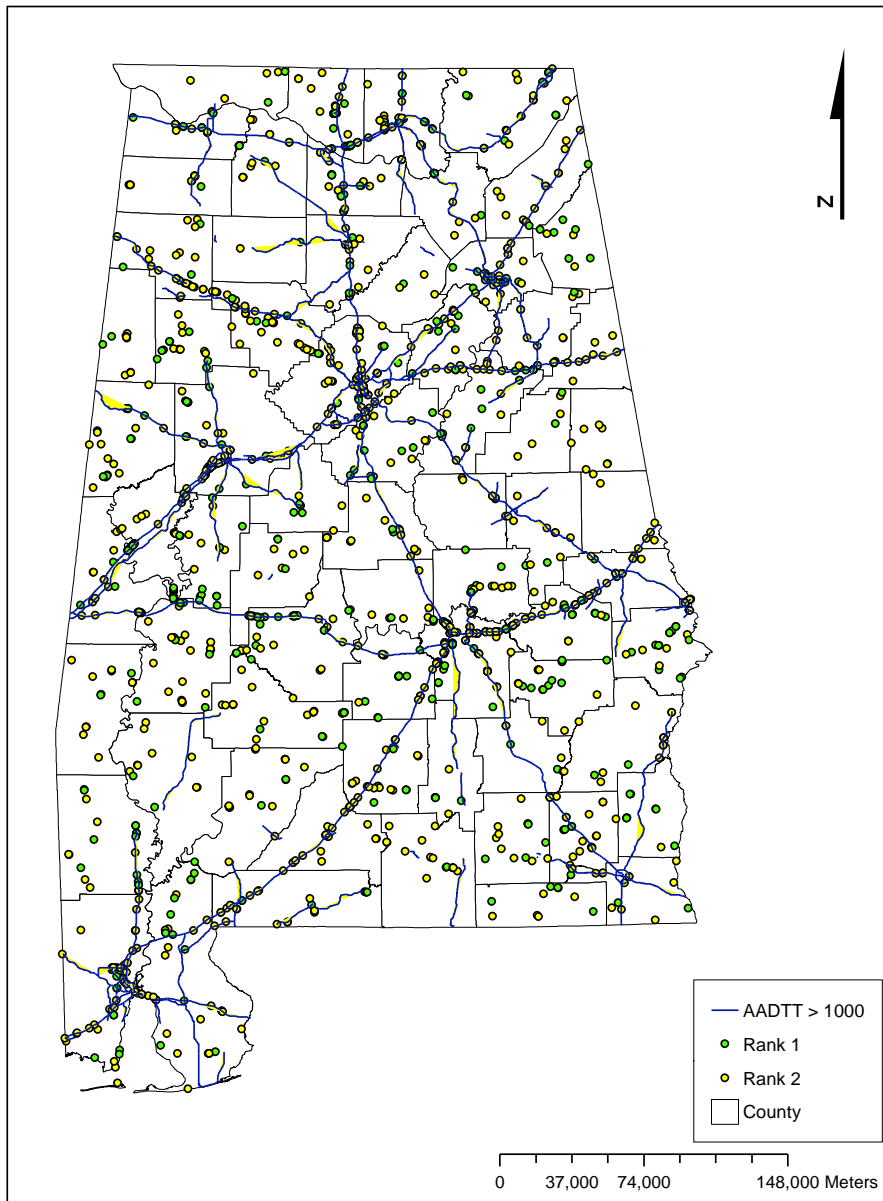


Figure 4.6 ABST map of 'Ideal' & 'Suitable Bridges' and routes with AADTT > 1000

4.4 Cellular Data Coverage

Rasters, showing coverage maps from the four main cellular providers, were added rescaled and shifted to the correct coordinates within ArcGIS. Any shapefile can be overlaid onto these rasters to approximate whether sufficient data signal can be obtained at a bridge site. B-WIM system uses cellular data signals to transfer data during the pre selection of overweight vehicles. It appears from Figure 4.7 that Verizon provides the most widespread coverage within Alabama.

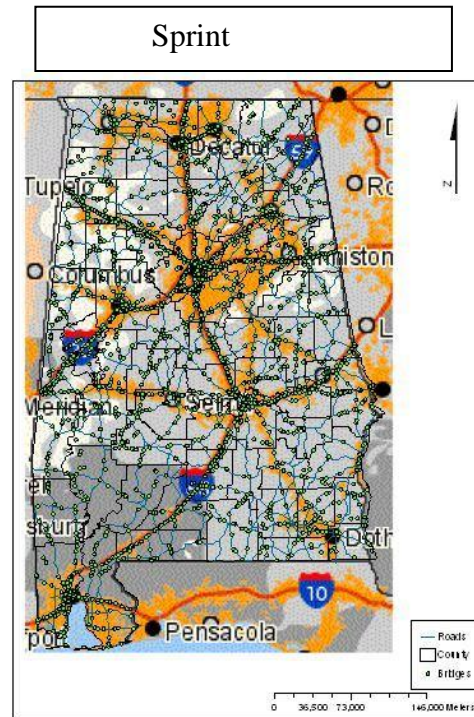
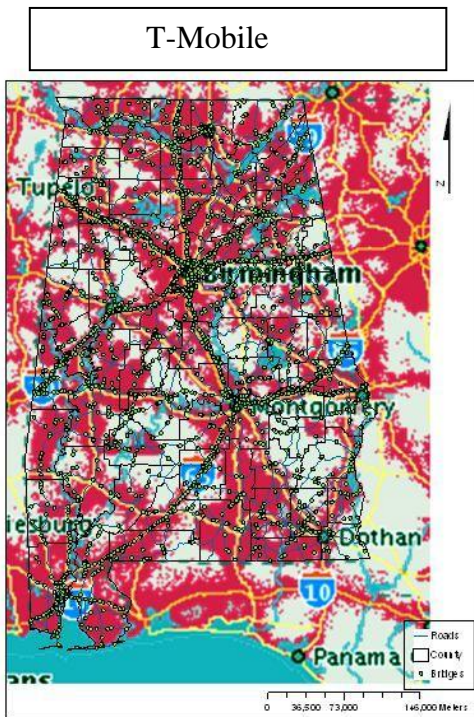
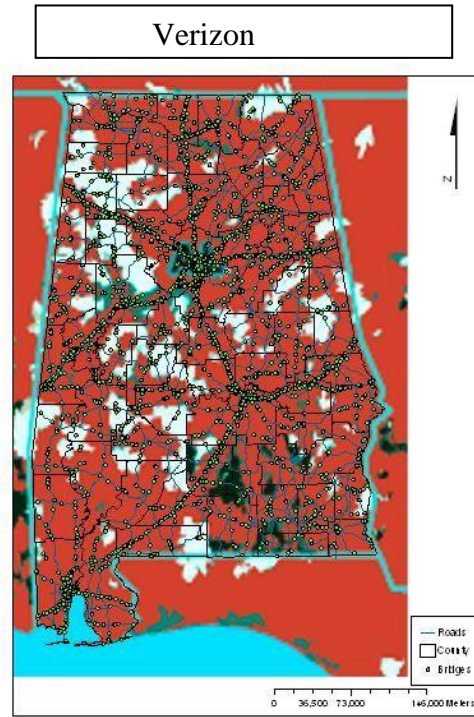
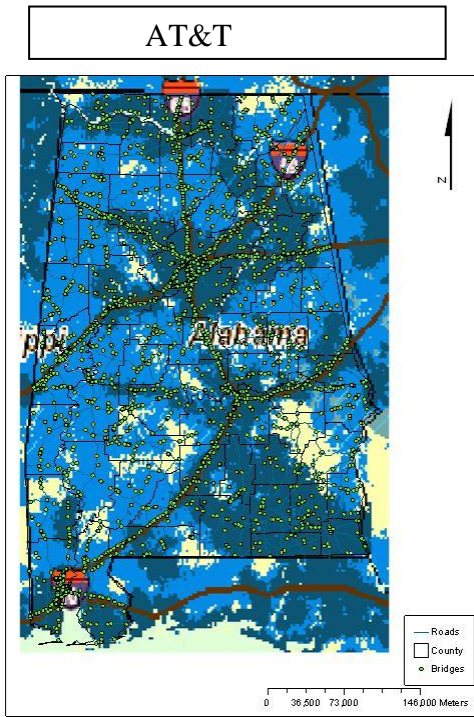


Figure 4.7 Data signal strength maps within ABST

4.5 Summary

ABST was developed as a prototype to show that the development of a tool for selecting bridges suitable for B-WIM application is possible. Additional data may be used in the future to improve the tool. It was determined that 3,554 bridges within the state were potential candidates for installation. Each of these bridges was assigned a score and a ranking based on attributes obtained from ABIMS. As stated, the scores assigned to each attribute are highly subjective and may need adjustment as seen fit in the future. The tool aims to determine how suitable a bridge is to obtain a high level of B-WIM load measurement accuracy. It does not take into account how easy an installation in the field will be. Candidate bridges should be identified using the tool, and the final decision should come after a field inspection. A comments field is available in the tool which allows users to add a comment as to the installation ease of a particular structure based on personal knowledge or after a site visit. FAF provides AADTT data which is used to select possible routes. Once a route or section of road is selected, it can be determined which, if any, of the cell providers can provide sufficient coverage for data transfer.

CHAPTER 5

ANALYSIS OF B-WIM INSTALLATION AND TESTS

This chapter analyzes the data collected during the testing of the SiWIM system on BIN 4289 near Gordo, Alabama. Two installations of the system were carried out and an accuracy test using random traffic was conducted using the second installation. Alternative sensor locations were compared for both axle detector and weighing sensors. The data from both installations will be presented and analyzed.

5.1 Sensor Locations

All 24 strain sensors were installed on the first and second spans of BIN 4289 for the initial installation. Different configurations, locations and orientations were used so that the signals obtained could be compared.

5.1.1 *Weighing Sensors*

Weighing sensors were installed on the four longitudinal beams in three different locations. Comparisons were made between strain signals located at the middle of span two and at 40% of the span. The first span was also instrumented at the mid span so signals could be compared with those from the second span.

The signals obtained from the 5 axle truck calibration truck travelling in lane one and lane two are shown in Figure 5.1 and 5.2 respectively. In lane 1, the largest strain is achieved at the center of the second span, with a peak voltage of 4.8 V. This is significantly larger than the center of the first span with a peak of 3.2 V. Span one is stiffer, likely due to material properties

or construction methods. A signal of magnitude 2.5 V was obtained at 40% of the second span. Theory suggests that for a continuous span bridge, maximum strain should occur at 40% of the span length. At almost half of the mid span strain, it is clear that this is not the case, and this suggests that BIN 4289 is simply supported.

Figure 5.2 contains the strain signals from the same truck travelling in lane 2 for the three sensor locations. The results from lane 2 are different from those in Lane 1. Once again, the largest signal is received from the sensors at the middle of span 2. The signal from the 40% location is roughly 1V smaller than the max at the mid span. The signal from span 1, however, is of a much lower magnitude than both signals from span 2. The signal has a maximum of 1.3V compared to 4.2V at the same location on span 2. A number of possible causes for this low strain were considered. The improper installation of sensors 23 and 24 could have caused the low signal. This is considered unlikely though as all other sensors appeared to be functioning as expected and the likelihood of both those sensors being poorly installed is low. Vehicle dynamics was also not thought to be a factor, as the sensors receive strains for the entire time the truck is on the instrumented span. The most likely reason is considered to be increased stiffness in span 1 and in particular the beams instrumented with sensors 23 and 24.

The positioning of the weighing sensors does not have a big role in the accuracy of the installation, once adequate strain signals are obtained. Both of the instrumented spans provided signals which are sufficient for weighing vehicles. As a general rule, the center of the span will provide the greatest signals and should provide sufficient signals regardless of bridge type. As expected, max strain for a simply supported structure occurs at the middle of the span.

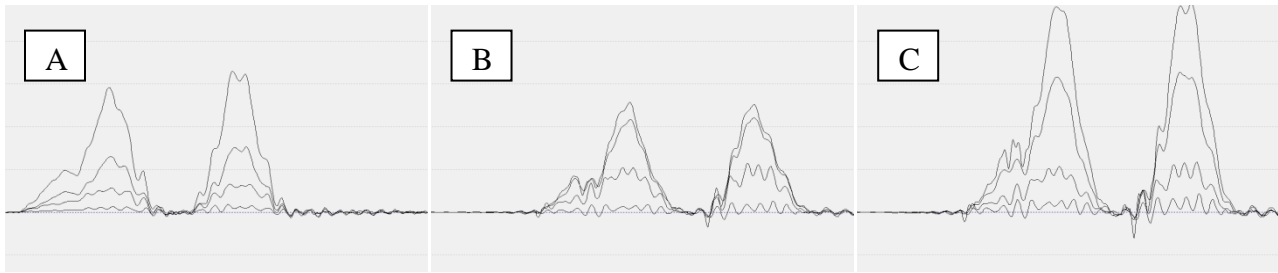


Figure 5.1 Strain signals from weighing sensors at ‘A’, ‘B’ and ‘C’ (as per Figure 3.10)-Lane 1

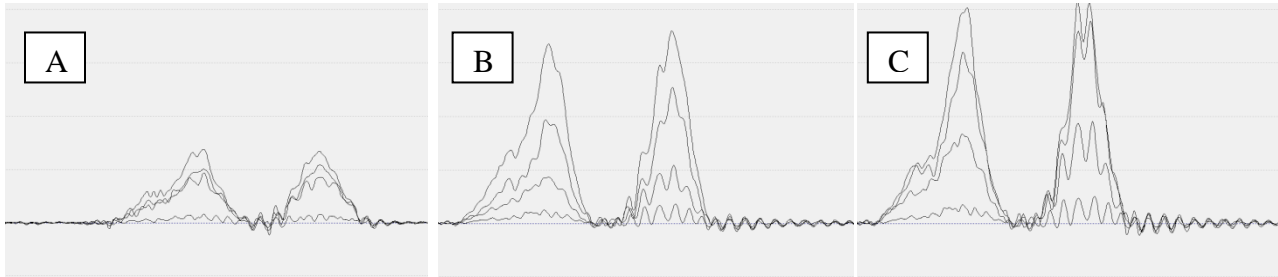


Figure 5.2 Strain signals from weighing sensors at ‘A’, ‘B’ and ‘C’ (as per Figure 3.10)-Lane 2

To verify that there is little interaction between bridge spans two influence lines were generated within SiWIM as shown in Figure 5.3. The first influence line is solely for span 1. A small append and prepend are included and it can be see that the influence line goes to zero. This is the influence line used during the calibration of the system. The second influence line was generated solely to demonstrate that the second span has little or no affect on the first span. It incorporates the entire length of the second span as an append. In the second span, the line is practically zero. It can be concluded that loading of the second span has a negligible effect on the first span. As such, it is appropriate to conclude that the bridge acts as a simply supported structure. When generating influence lines for a simply supported structure, preceding and following spans can be generally ignored.

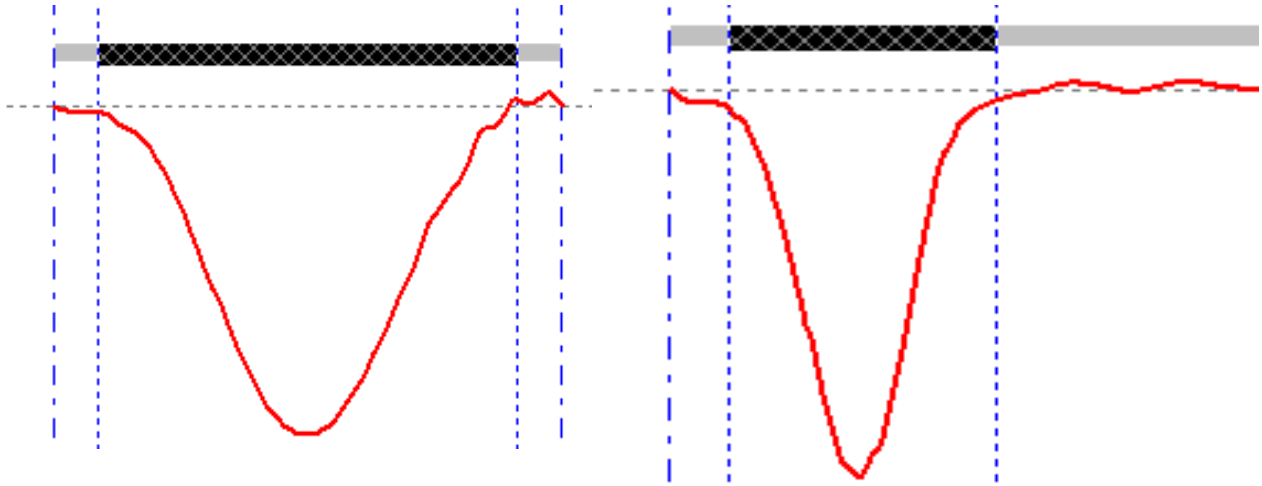


Figure 5.3 Influence line of Lane 1 (1st span) / Lane 1 (1st and 2nd spans)

5.1.2 Axle Detection Sensors

Axle detectors were laid out as per Figure 3.10. The strain signals from the 12 sensor locations will now be analyzed, compared and discussed.

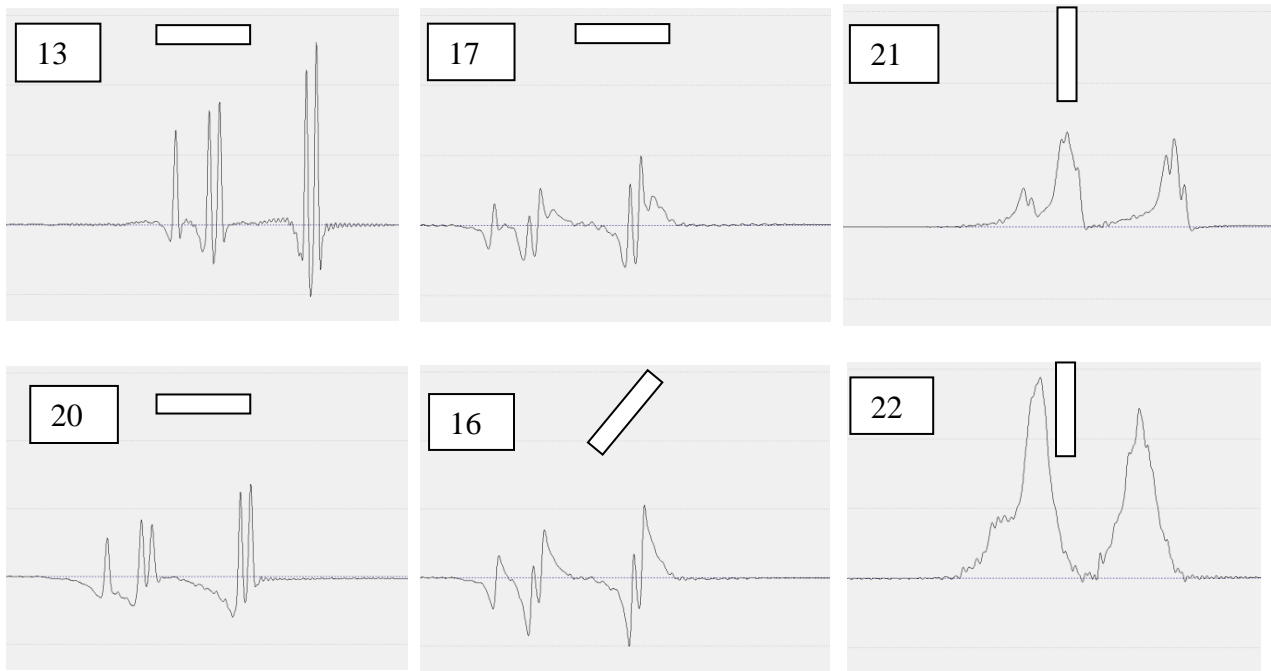


Figure 5.4 Axle detection signals from sensors 13,21,22,20,16 & 22

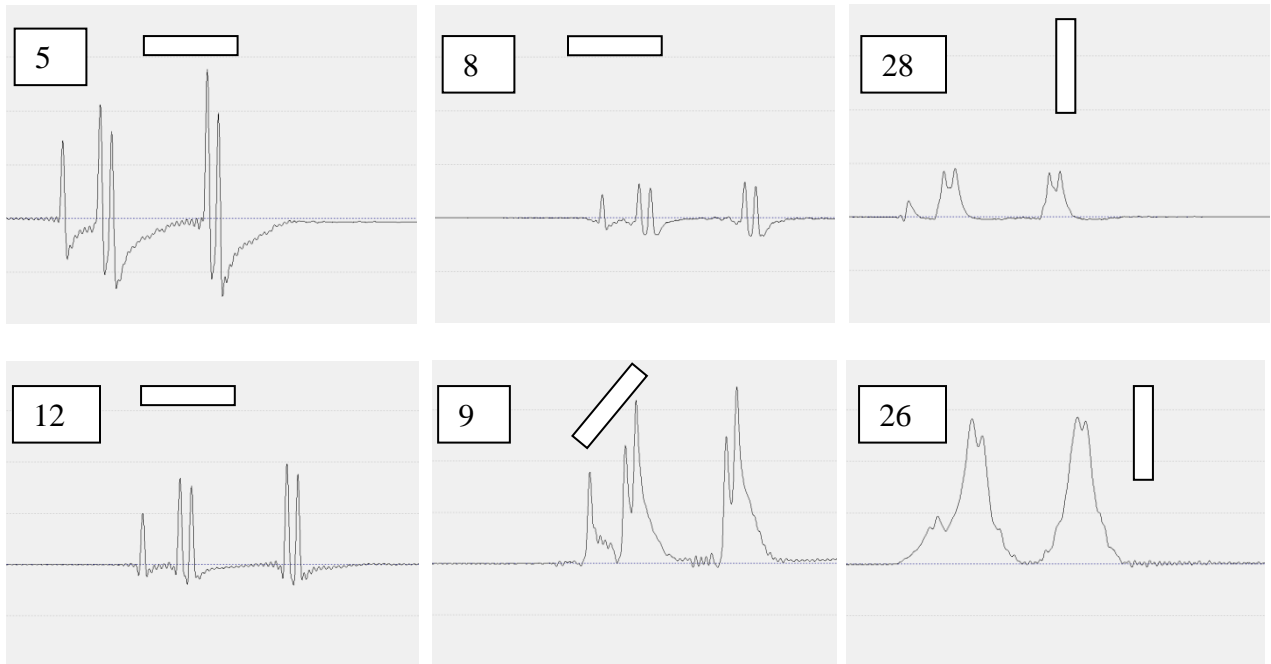


Figure 5.5 Axle detection signals from sensors 5,28,26,12,9 & 8

The strain signals in Figure 5.4 and 5.5 are for the 5-axle truck used during calibration. Figure 5.4 shows signals obtained for lane 2 while lane 1 signals are shown in Figure 5.5.

Longitudinal AD sensors (13, 20, 5 and 12) were all located roughly 0.9m (3ft) from the beginning of their respective spans. Clean signals, with sharp peaks for each of the five axles were obtained for all of these sensors. These signals are ideal for FAD purposes. It can be clearly seen that these sensors provide the best axle detection signals.

Using the signals in Figures 5.4 and 5.5 the following axle configurations in Table 5.1 were obtained. The 5-axle truck has a total axle length of 713 inches.

Table 5.1 Number of Axles detected by each sensor

Sensor	Lane	Identified Axles
5	1	5
13	2	5
12	1	5
20	2	5
8	1	5
17	2	7
9	1	5
16	2	6
26	1	6
22	2	6
28	1	5
21	2	7

Sensors 8 and 17 were also orientated longitudinally but at the center of the span. The magnitudes of both signals are much lower than those achieved at the beginning of a span. From Table 5.1 sensor 8 identifies all 5 axles, while sensor 17 calculated 7. Apart from the longitudinal sensors at the beginning of the span, only sensors 8, 9 and 28 correctly identified the 5 axles. These have the cleanest strain signals.

The bridge is stiffer closer to the beginning and end of each span. It is believed that this contributed to the definite peaks being obtained at these locations. The dynamic load induced by the truck crossings is not such an issue at the stiffer section. The transverse AD sensors provided poor signals for axle detection. Instead of providing definite peaks where axles cross the sensor location the signal is more dispersed. As the truck crosses the bridge, strain begins to occur in the beam. In the tee beam construction, this beam strain induces strain in the deck. As such, strain is induced transversely in the deck prior to the axle reaching the sensor location. This causes the peaks to be more spread out. This phenomenon is not such an issue in the longitudinal direction. Longitudinally mounted sensors near the beginning and end of spans provided the best identification of axles.

5.2 Calibration Results

Calibration runs were conducted using two calibration trucks as described in Chapter 3. The results for the first and second installations are shown in Tables 5.2 and Table 5.3 respectively.

Table 5.2 Calibration runs from first installation (SiWIM Results)

Calibration Run	Speed	3 axle truck 73,900 lbs		5 axle truck 78,850 lbs	
		Lane 1	Lane 2	Lane 1	Lane 2
1	45 mph	74,907	70,184	78,798	80,220
2	45 mph	75,098	73,259	80,603	78,349
3	45 mph	74,237	74,031	81,495	78,312
4	45 mph	74,676	72,143	80,734	77,061
5	45 mph	74,737	74,343	78,813	78,378
6	45 mph	-	-	78,790	77,652
7	35 mph	73,396	76,357	78,769	80,227
8	35 mph	72,661	-	74,286	-
9	55 mph	72,587	77,473	78,698	80,765
10	55 mph	72,906	-	77,984	-

Table 5.3 Calibration runs from second installation (SiWIM Results)

Calibration Run	Speed	3 axle truck 73,900 lbs		5 axle truck 78,850 lbs	
		Lane 1	Lane 2	Lane 1	Lane 2
1	45 mph	73,520	74,301	78,173	86,347
2	45 mph	73,949	75,168	80,841	82,397*
3	45 mph	75,032	72,460	79,060	80,257
4	45 mph	75,664	72,391	79,886	79,010
5	45 mph	74,520	73,703	80,360	78,471
6	45 mph	74,210	70,986	78,727	83,040*
7	45 mph	-	72,376	78,555	77,473
8	35 mph	69,696	76,251	80,120	80,411
9	35 mph	70,608	73,589	79,131	78,096
10	55 mph	76,079	74,401	76,519	79,101
11	55 mph	75,723	73,849	75,976	74,736

* not used due to multiple presence events

Accuracy of the calibration for both lanes was determined using the COST 323 criteria as shown in Tables 5.4 and 5.5. An accuracy classification of C(15) and D+(20) were obtained for Lane 1 and Lane 2 calibrations. Accuracy of B+(7) was obtained in both lanes for GVW. This

accuracy is more than sufficient for the pre selection of overweight vehicles based on GVW. The calibration procedure was classified as having ‘Limited Reproducibility’ (two to ten different trucks under changing traffic conditions) and ‘Environmental Repeatability’ (short measurements in mostly constant environmental conditions-weather).

Table 5.4 COST 323 Accuracy classification of calibration of lane 1

	Count	Mean (%)	Std. dev. (%)	δ (%)	δ_{\min} (%)	δ_{crit} (%)	δ_{class}	π_o (%)	π (%)	π_{crit} (%)	Class
GVW	21	0	2.33	5.6	5.22	6.52	7	91.08	91.08	93.49	B+(7)
Group	32	0.2	5.58	14.4	12.4	12.48	15	92.73	92.73	96.6	C(15)
Single	21	0	6.59	16	14.8	12.7	15	91.08	91.08	93.74	C(15)

Table 5.5 COST 323 Accuracy classification of calibration of lane 2

	Count	Mean (%)	Std. dev. (%)	δ (%)	δ_{\min} (%)	δ_{crit} (%)	δ_{class}	π_o (%)	π (%)	π_{crit} (%)	Class
GVW	21	0	2.45	5.6	5.49	6.87	7	91.08	91.08	91.79	B+(7)
Group	30	0.1	5.04	14.4	11.2	10.98	15	92.52	92.52	98.11	C(15)
Single	21	0.3	7.4	20	16.6	15.74	20	91.08	91.08	96.39	D+(20)

5.3 Static Weighing of Random Vehicles

On the morning of March 11th 2011 an accuracy test was carried out. 10 trucks travelling in Lane 2 were statically weighed after being pre-selected using SiWIM. Figure 5.6 shows how verification was carried out to ensure the correct vehicle had been statically weighed while Table 5.6 compares the GVW measured and obtained using the SiWIM system.



Figure 5.6 Photo of pre selected truck from SiWIM/Photo of truck being statically weighed

Table 5.6 Comparison of SiWIM to static weights

Description	Static GVW (lbs)	SiWIM GVW (lbs)	% Difference
Log Truck, 5 axles	90,972	88,850	2.39
Flatbed (Lumber), 5 axles	83,620	80,800	3.49
Scrap Steel, 5 axles	75,348	79,700	5.77
Scrap Steel, 5 axles	86,393	83,300	3.71
Flatbed (steel coil),6 axles	100,487	104,750	4.24
Black Box Truck, 5 axles	80,108	78,800	1.66
Log Truck, 5 axles	88,283	87,000	1.47
Log Truck, 5 axles	90,229	86,850	4.69
White Box Truck, 5 axles	74,052	77,600	4.79
Log Truck, 5 axles	88,883	89,600	1.01

Table 5.7 COST 323 accuracy classification of random traffic weighing

	Count	Mean (%)	Std. dev. (%)	δ (%)	δ_{min} (%)	δ_{crit} (%)	δ_{class}	π_0 (%)	π (%)	π_{crit} (%)	Class
GVW	10	0.2	3.45	10	7.27	7.27	10	80.11	80.11	94.26	B(10)
Group	20	0.4	6.52	18	13.5	10.52	15	87.45	87.45	96.63	C(15)
Single	10	-3	5.58	15	12.7	8.29	10	80.11	80.11	89.12	B(10)

An overall accuracy of C(15) was obtained for the testing, while a GVW accuracy of B(10) was achieved. This accuracy level is very good and is more than sufficient for pre-

selection use. As can be seen from Table 5.6, the maximum discrepancy in GVW was 5.77%. Only one truck which SiWIM weighed to be over the 80,000lbs legal limit was actually below the limit, and the SiWIM weight for this truck was only 1.66% from the static weight obtained by the weigh crew. It is evident that B-WIM can be a valuable tool for pre-selection of overweight vehicles. The possibility of flooding meant that the system was not left installed on BIN 4289. Once testing had concluded on March 11th, the system was removed from the bridge and taken by ALDOT.

5.4 Conclusion

The exact positioning of weighing sensors was not found to be an issue on a tee beam type structure. Placement of the sensors in a line perpendicular to the direction of traffic at any location close to the mid span should provide adequate signals for the weighing of heavy vehicles. Once a distinctive strain signal which is repeatable is obtained, the sensor location will suffice.

Axle detection signals, however, must meet certain criteria to be adequate. There are no set rules for the positioning of these sensors, but the comparisons of the signals obtained from different orientations and locations have provided some insight into optimum positioning of sensors. In practice, B-WIM installation crews should locate sensors where they believe the best signals may be received. Upon installation the signals should be reviewed and if not adequate, the sensors must be repositioned.

From the comparison conducted it was found that axle detection sensors should be located directly below the truck wheel path, on the bridge slab. Sensors should be orientated longitudinally and positioned close to the beginning or end of the bridge span. Transverse sensors were found to provide poor signals and axles were not identified correctly. Sensors

located at the center of the span were seen to be not as clean and to have less definite peaks, possibly due to reduced stiffness of the structure at the mid span, and thus allowing dynamic loading effects to interfere with the signal.

Results from both calibration procedures were very impressive, especially with regards to GVW. Citations by weigh crews are predominantly due to GVW offences and so GVW accuracy was the primary concern during both installations. Accuracy of B+(7) was obtained in both lanes for the calibration procedure for GVW. High calibration accuracy is important as it is very unlikely to obtain a better accuracy when weighing random vehicles. The opposite is most often the case.

The accuracy test of random traffic was also very promising and an overall accuracy of C(15) was obtained with an accuracy of B(10) obtained for GVW. This accuracy is more than sufficient for pre-selection use and the installation confirmed the potential of B-WIM for pre-selection use in Alabama.

CHAPTER 6

CONCLUSIONS & RECOMMENDATIONS

Upon completion of this project a number of conclusions have been arrived at. These conclusions and recommendations for future work shall be outlined in this chapter.

6.1 Feasibility of a Bridge Selection Tool

It has been shown that the development of a tool for selection of bridges for optimum B-WIM deployment is feasible. A prototype tool was developed which uses freely available data to select optimum bridges for installation. ABST provides a user with the potential of a bridge to achieve high truck weight measurement accuracy. Bridges are ranked by assigning scores to attributes obtained from ABIMS. Selection of routes for installation is carried out by looking at truck flow volumes from FAF. Data coverage maps are also provided to supply users of guideline information of cellular service at a particular bridge location. WIM sites are also presented, which further allows the user to make an informed decision as to best location for B-WIM deployment. By using simple queries, a user of the tool can select bridges of any rank, or having any other attribute in the subdatabase.

The scores assigned to attributes in the ABIMS database are very subjective. Efforts were made to calibrate the scores to achieve a realistic representation as to the importance of each attribute in obtaining accurate results. However, the scores may require further calibration as the tool is used and bridges visited. The ranking of a bridge is highly dependent on the scoring scheme employed. Future use of the tool may determine that certain attributes may be required to

be added or removed to improve the realism of the tool. A comments field is added to the bridge file to allow users to input comments related to the bridges suitability once inspections have been completed. After a number of bridges have been inspected and instrumented, knowledge will be gathered as to locations which have been able to provide accurate results.

6.2 Location of Sensors

A comparison was made of weighing sensor locations. It was seen that for a simply supported structure that a greater strain signal was obtained at the mid span as opposed to 40% of the span length. It was concluded that weighing sensors should by default be located at the mid span of a bridge regardless of the bridge type or support conditions. Strain signals at the mid span should always be sufficient enough for the weighing of vehicles, if the bridge is suitable for B-WIM installation.

A comparison of axle detector locations and orientations was also carried out. Sensors were placed at the center of a span and also at 0.9m (3ft) from the beginning of the span. Longitudinal, transverse and sensors placed at 60 degrees to the span direction were also compared. It was found for all sensor orientations that those located at the beginning of the bridge span produced cleaner signals than those at the mid span and they had more definite axle peaks. It is thought that the bridge is stiffer at this location than at the mid span. The dynamics of a trucks axle do not induce oscillations as pronounced in the structure at this stiffer section and so a cleaner signal is obtained. Transverse axle detectors were seen to provide very poor signals and miscalculated the number of axles of a crossing truck.

6.3 Accuracy of B-WIM

The calibration and accuracy tests of the B-WIM system provided very encouraging results. Calibration accuracy of B+(7) was obtained in both lanes for GVW while B(10) was

obtained when random traffic was statically weighed. The second installation of the system was completely coordinated and carried out by ALDOT staff, showing, that after sufficient training, the installation and calibration of the system can be competently carried out and good accuracy obtained. These accuracies are more than sufficient for pre-selection use and provide evidence to verify ALDOT's purchase of the system and usage for overweight vehicle enforcement.

6.4 Recommendations for Future Work

Truck flow information is available for all state routes through the FAF database. During the development of ABST, efforts were made to obtain a breakdown of truck flows per commodity type. It is believed that this information is available but was not obtained for this project. Future work should make efforts to obtain this data and utilize it to make more informed bridge selection decisions. Certain industries such as logging, mining and steel manufacturing are known by authorities to heavily load trucks. Efforts can be made to target routes with high volumes of trucks from these industries.

Data maps were obtained for this project from the websites of the various cell carriers. These maps are simply rasters and the resolutions of many are not very high. Also, it is highly probable that the carriers over-estimate the extent of their coverage range for marketing reasons. A request was made to the FCC (Federal Communications Commission) to obtain a map readable in ArcGIS showing the coverage areas of carriers. This was not available at the time of this project but it is understood that work is in progress to produce a map of this sort. If such a map becomes available, it should be integrated into the tool to provide accurate information regarding cell coverage at each bridge site.

A future cost/benefit analysis study should be conducted. This study could examine the financial benefits of deploying B-WIM systems in an effective manner. The cost of a B-WIM

system could be compared to that of a WIM site. The cost of an overweight vehicle in terms of pavement damage should be determined and an estimate of the total mileage of overweight vehicles in the state obtained. This would allow the total cost of overweight vehicles in Alabama to be determined. Then, the number of miles traveled by overweight vehicles, which a B-WIM system can remove from the network, can be estimated and the cost savings associated with the system can be determined.

REFERENCES

- Bouteldja, M., Jacob, B., and Dolcemascolo, V., (2008) 'Test of a B-WIM System on Integral and Steel Orthotropic Deck Bridges in France', in Proceedings of the 5th International Conference on Heavy Vehicles (ICWIM '08), Paris, France pp. 205-213.
- Bushman, R., and Pratt, A., J., (1998) 'Weigh In Motion Technology – Economics and Performance' Presented at NATMEC 1998, Charlotte, North Carolina.
- Chatterjee, P., OBrien, E. J., Li, Y.-Y. and González, A., (2006) 'Wavelet Domain Analysis for Identification of Moving Loads from Bridge Measurements', *Computers & Structures*, 84, 28, pp 1792-1801.
- COST_323, 1999. 'European Specification on Weigh-in-Motion of Road Vehicles', EUCO-COST/323/8/99, LCPC, Paris, August, 66pp.
- Dempsey, A.T., Jacob, B. and Carracilli, J. (1998a) 'The use of Instrumented Orthotropic Bridges for Determining Vehicle Weight/Dimensions/Parameters' in Proceedings of 5th International Symposium on Heavy Vehicle Weights and Dimensions, pp.188-209.
- Dempsey, A. Znidaric, A. and O'Brien, E. (1998b), 'Development of a Dynamic Bridge Weigh in Motion Algorithm', in Proceedings of 5th International Symposium on Heavy Vehicle Weights and Dimensions, Australia, pp.95-113.
- Dempsey A., Jacob B., and Carracilli J. (1999) 'Development and Experimental Testing of Orthotropic Bridge Weigh-in-Motion for Determining Axle and Gross Vehicle Weights', in *Weigh-in-motion of Road Vehicles*, B.Jacob ed., Proceedings of the Final Symposium of the project WAVE, Paris, 6-7 May 1999, hermes science publications, pp. 227-238.
- Gonzalez, A. and OBrien, E.J. (1998) 'The Development of a Dynamic Bridge Weigh-in-Motion Algorithm' in *Pre-proceedings of 2nd European Conference on Weigh-in-Motion of Road Vehicles* Luxembourg, pp.445-452.
- González, A., Brady, S.P. and OBrien, E.J. (1999) 'A Dynamic Multi-Sensor Bridge Weigh-In-Motion Algorithm'.in Ed. B. Jacob, Hermes Science Publications eds. Proceedings of the Final Symposium of the project WAVE Paris, France, , 06-07 May-99 , pp.209-216.

- Jacob, B., 1998. 'Action COST 323: Weigh-In-Motion of Road Vehicles'. Pre-Proceedings of 2nd European Conference on Weigh-in-Motion of Road Vehicles, Lisbon 14-16 September. Luxembourg: European Commission, pp.25-33.
- Jacob, B., O' Brien, E., J., and Newton, W., (2000) 'Assessment of the Accuracy and Classification of Weigh-in-Motion Systems; Part 2. European Specification' Heavy Vehicle Systems, 7, 2, pp.153-168.
- Jacob, B., and Feypell-de La Beaumelle, V. (2010) 'Improving Truck Safety: Potential of Weigh-in-Motion Technology', IATSS Research 34, pp.9-15.
- Kalin, J., Znidaric, A., and Lavric, I., (2006) 'Practical Implementation of Nothing-On-The-Road Bridge Weigh-In-Motion System' 9th International Symposium on Heavy Vehicle Weights and Dimensions.
- Krupa C., and Kearney T., (2009), 'Truck Size and Weight Enforcement Technology, Task 2 Deliverables – State of the Practice of Roadside Technologies' FHWA.
- McNulty, P., and OBrien, E.J., (2003), 'Testing of Bridge Weigh-In-Motion System in Sub-Arctic Climate', Journal of Testing and Evaluation, Vol. 31, No. 6, Nov. 2003, pp. 1-10.
- Moses, F. (1979), 'Weigh-in-Motion System Using Instrumented Bridges', Transportation Engineering Journal, ASCE, 105, TE3, pp.233-249.
- Moses, F. and Ghosn, M., (1981), 'Weighing Trucks in Motion Using Instrumented Highway Bridges', Final Report to Ohio DOT, Dec. 1981.
- O'Brien, E.J., and Kealy, N.J., (1998) 'Development of a Novel Bridge Weigh-In-Motion System' in Proceedings of 5th International Symposium on Heavy Vehicle Weights and Dimensions, pp.222-235.
- O'Brien, E.J., Žnidarič, A. and Dempsey, A.T., (1999) 'Comparison of Two Independently Developed Bridge WIM Systems', Heavy Vehicle Systems, Int. J. of Vehicle Design, Vol. 6, Nos ¼, pp.147-161.
- O' Brien, E. J., Quilligan, M. J. and Karoumi, R., (2006), 'Calculating an Influence Line from Direct Measurements', Bridge Engineering, Proceedings of the Institution of Civil Engineers, 159(BE1), Mar. 2006, pp.31-34.
- OECD (1998), Dynamic Interaction between Vehicle and Infrastructure Experiment, Technical report, DSTI/DOT/RTR/IR6(98)1/FINAL, OECD, Paris, 151 pp.
- Peters, R.J.,(1984) 'AXWAY - A System to Obtain Vehicle Axle Weights', Proceedings 12th Australian Road Research Board Conference, Vol. 12 , No. 1, pp.17-29.

- Peters, R.J. (1986), 'CULWAY - an Unmanned and Undetectable Highway Speed Vehicle Weighing System', in Proc. 13th AARB Conference, Australian Road Research Board, Vol. 13, No. 6, pp70-83.
- Quilligan M, Karoumi R, and O'Brien EJ. (2002) 'Development and Testing of a 2-Dimensional Multi-Vehicle Bridge-WIM algorithm' In: Proceedings of the third international conference on weigh-in-motion, pp. 199-208.
- Quilligan, M. (2003) 'Bridge Weigh-in-Motion: Development of a 2-D Multi-Vehicle Algorithm' Licentiate Thesis, Royal Institute of Technology, Stockholm, Sweden.
- Rowley, C., Gonzalez, A., O'Brien, E., and Znidaric, A., (2008) "Comparison of conventional and regularized bridge weigh-in-motion algorithms," in Proceedings of the 5th International Conference on Heavy Vehicles (ICWIM '08), Paris, France, May 2008, pp. 221–230.
- Rowley, C.W., O'Brien, E.J., González, A. and Žnidarič, A., (2009), 'Experimental Testing of a Moving Force Identification Bridge Weigh-in-Motion Algorithm', *Experimental Mechanics*, Vol. 49, Issue 5, 2009, pp. 743-746.
- Sanders, L., (1960), 'A Short History of Weighing' <<http://www.averyweightronix.com/main.aspx?p=1.1.3.4>>, (Oct. 8, 2010).
- SDDOT Briefing- (2003), 'Truck Weights and Highways', SDDOT Office of Research, September 24.
- Straus, S.H, and Semmens, J. (2006), 'Estimating the Cost of Overweight Vehicle Travel on Arizona Highways-Final Report 528'.
- Tikhonov, A. N. and V. Y. Arsenin, *Solutions of Ill-posed Problems*, New York: Wiley, 10–21, 1977.
- WAVE, (2001), 'Weighing-in-Motion of Axles and Vehicles for Europe (WAVE): Report of Work Package 1.2', June 2001.
- Znidaric, A. and Baumgärtner, W., (1998), 'Bridge Weigh-in-Motion Systems — an Overview' in Pre-Proceedings of 2nd European Conference on Weigh-in-Motion of Road Vehicles, Lisbon 14-16 September. Luxembourg: European Commission, pp.139-152.
- Žnidarič, A., Lavrič, I. and Kalin, J. (1999), 'Bridge WIM Measurements on Short Slab Bridges', in Proceedings of the Final Symposium of the project WAVE, Ed. B. Jacob, Hermes Science Publications, Paris, France, pp.217-226.
- Žnidaric, A., Lavric, I. and Kalin, J. (2002), "Free-of-Axle Detector Bridge WIM Measurements on Short Slab Bridges" in Proceedings of the 3rd International WIM Conference, Orlando, Florida, USA, pp.231-239.

Znidaric, A., Lavric, I. and Kalin, J., (2008), 'Measurement of Bridge Dynamics with a Bridge Weigh-in-Motion System', in Proceedings of 5th International Symposium on Heavy Vehicle Weights and Dimensions, pp.388-397.

Znidaric. A., Lavric, I., Kalin, J., and Kulauzovic, B. (2011), 'SiWIM Bridge Weigh-in-Motion Manual', Fourth Edition, ZAG Ljubljana.